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# STUDY OF THE DECOLORIZATION PROCESS OF NATURAL WATERS USING THE METHOD OF OPTIMAL EXPERIMENTAL DESIGN

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**Abstract**

Color is one of the fundamental indicators of natural water quality, reflecting the presence of organic matter, colloidal systems, and other dissolved or suspended impurities. High color intensity not only deteriorates the organoleptic properties of water but also indicates the presence of humic substances capable of forming toxic compounds during disinfection. Therefore, the development of effective methods for decolorizing natural waters remains a relevant task in modern water treatment. This study investigates the process of natural water decolorization using the method of optimal experimental design. Mathematical modeling and statistical analysis were applied to develop predictive models describing the efficiency of water decolorization by coagulation with preliminary ozonation. The approach enables the evaluation of complex interrelations among technological parameters and the identification of optimal operating conditions. The article details the criteria for selecting factors and response functions, as well as the procedure for conducting experimental studies. The study defines criteria for selecting an experimental design that minimizes the number of trials while maintaining statistical reliability. Based on a three-factor rotatable design, second-order regression equations were obtained, representing experimental-statistical models of water decolorization for technical water supply purposes. A statistical analysis of the adequacy of the developed models was carried out, demonstrating their high predictive capability. The developed models make it possible to forecast the efficiency of the decolorization process and optimize the technological parameters of water treatment to achieve maximum effect with minimal reagent costs.

**Keywords:** water decolorization, optimal experimental design, coagulation, color, response surface, optimization of water treatment processes.

## ИССЛЕДОВАНИЕ ПРОЦЕССА ОБЕСЦВЕЧИВАНИЯ ПРИРОДНЫХ ВОД С ПРИМЕНЕНИЕМ МЕТОДА ОПТИМАЛЬНОГО ПЛАНИРОВАНИЯ ЭКСПЕРИМЕНТА

**С. В. Андреюк, Г. А. Волкова, Е. С. Андреюк**

**Реферат**

Цветность является одним из ключевых показателей качества природных вод, свидетельствующим о наличии органических веществ, коллоидных систем и других загрязнений. Высокая цветность не только ухудшает органолептические свойства воды, но и указывает на присутствие гуминовых веществ, способных образовывать токсичные соединения при обеззараживании. В связи с этим разработка эффективных методов обесцвечивания природных вод остается актуальной задачей современной водоподготовки. В статье рассматривается применение методов математического моделирования и оптимального планирования эксперимента для исследования процесса обесцвечивания природных вод. На основе анализа современных публикаций и достижений в данной области показано, что использование математической теории позволяет создавать точные модели процессов водоподготовки, учитывающие влияние множества определяющих факторов. В качестве практического примера рассмотрено планирование многофакторного эксперимента на примере комбинированного метода обесцвечивания поверхностных вод коагулированием с предварительным озонированием. В работе представлены условия выбора методики планирования, позволяющие оптимизировать количество необходимых опытов при сохранении требуемой точности исследований. В статье подробно описаны критерии отбора факторов и функции отклика, а также процедура проведения экспериментальных исследований. В исследовании определены критерии выбора схемы эксперимента, которая минимизирует количество испытаний при сохранении статистической надежности. По результатам проведения трехфакторного рототабельного эксперимента получены уравнения регрессии второго порядка, которые представляют собой экспериментально-статистические модели процессов подготовки воды для технического водоснабжения. Проведен статистический анализ адекватности разработанных моделей, показавший их высокую прогностическую способность. Разработанные модели позволяют прогнозировать эффективность процесса обесцвечивания и оптимизировать технологические параметры водоподготовки для достижения максимального эффекта при минимальных затратах реагентов.

**Ключевые слова:** обесцвечивание вод, оптимальное планирование эксперимента, коагулирование, цветность, поверхность отклика, оптимизация процессов водоподготовки.

### Introduction

Solving most problems in chemistry and chemical engineering related to the treatment of natural waters traditionally requires extensive and resource-intensive experimental research. In this context, methods of optimal experimental design are of particular importance, as they allow the mathematical framework to be applied not only during the processing of experimental data but also at the stage of experiment planning and organization [1]. Mathematical modeling has become an essential component of modern environmental research. The environment, represented by both natural and anthropogenic systems, is a complex set of material objects, processes, and interactions between them [2–4]. Traditional methods of water decolorization include coagulation, adsorption, membrane technologies, and chemical oxidation. Along with conventional coagulation-flocculation techniques employed at municipal water treatment plants (using aluminum and iron salts), oxidizing and sorption methods have been gaining wider application [5, 6]. The efficiency of each process is determined by numerous factors, including the coagulant dose, pH, alkalinity, temperature, and contact time. The empirical determination of optimal operating conditions requires considerable time and material resources. Modern approaches based on the study of the mechanisms of complex physicochemical processes and the optimization of multicomponent systems make it possible to construct adequate models of water treatment technologies that take into account the combined influence of multiple variables [7, 8].

The objective of the present study was to investigate the main influencing factors and modeling conditions of the surface-water treatment process, as well as to develop experimental-statistical models capable of predicting the removal efficiency of pollutants responsible for color formation. The process under investigation involved the decolorization of surface water by coagulation preceded by ozonation.

**Analysis of the Principles and Practical Implementation of Optimal Experimental Design in Water Treatment Modeling**

Optimal experimental design is a branch of mathematical statistics aimed at maximizing the information gained from experiments while minimizing the number of trials required. The most widely used designs in water treatment research include:

− d-optimal designs, which minimize the variance of regression coefficients estimates in the model, an especially valuable feature when only a limited number of runs is feasible;

− i-optimal (integrated optimal) designs, which minimize the average variance of prediction throughout the experimental domain, making them particularly suitable for process optimization tasks;

− Response Surface Methodology (RSM), which provides a framework for constructing mathematical models that relate input factors to output responses and for determining optimal process conditions.

Multifactorial experimental design is extensively used in scientific and engineering studies as an effective tool for planning and analyzing experimental data [9–11]. The design procedure determines the required number of experiments and the conditions under which they must be carried out in order to achieve the desired accuracy and reliability of results. Variables that influence the studied process are referred to as factors. In relation to water purification processes, such factors typically include the coagulant or flocculant dosage, duration of the treatment stage, filtration rate, temperature, and other parameters. A key requirement for each factor is its controllability − the ability to maintain the prescribed level during the experiment. Additional criteria for selecting factors include their mutual independence, unambiguous influence on the response variable, and physical relevance to the studied process.

The efficiency of the technological process is assessed using one or more quantities called response functions. The effectiveness of a technological process is assessed using one or several quantities referred to as response functions. In water treatment, typical response functions include the degree Optimal experimental design methods make it possible to develop reliable mathematical representations of technological processes even when the underlying mechanisms are not fully known. Mathematical models obtained in this way are commonly referred to as experimental–statistical models.

Such models are often expressed in polynomial form: $Y = f(X_1, X_2, X_3, \dots Xn)$, where $Y$ is the response function (quantitatively describing process efficiency) and $X_1, X_2, X_3 \dots$ are the independent factors (process variables). The advantage of this mathematical representation lies in its ability to describe the influence of individual factors on the response function, to quantify the response under specific combinations of factor levels, and serve as a basis for process optimization and simulation [12].

A review of existing research on optimal experimental design in water treatment demonstrates its major advantages and outlines promising directions for further study. For example, the application of filtration process modeling has been used for optimizing existing treatment facilities and for evaluating the performance of local filtration materials, coagulants, and flocculants under surface water conditions [13]. Other studies have successfully applied mathematical modeling for the removal of iron compounds [14], and for multicomponent ion exchange processes on mixed cation exchangers ($H^+$, $Na^+$) [15, 16]. The analysis confirms the high effectiveness of optimal experimental design methods for investigating and optimizing natural water decolorization processes. In particular, the response surface methodology (RSM) was employed to remove color and turbidity from surface waters and to reduce chemical oxygen demand (COD) using a combined coagulant based on flaxseed and aluminum-potassium alum [17]. In those experiments, the coagulant dose (1,5–2,5 g/dm³), pH (3,5–7,0), and mixing time (38–40 minutes) were varied. Optimization yielded a chromaticity removal efficiency of 97,75 % at pH 7,0, a coagulant dose of 2,5 g/dm³, and a mixing time of 40 minutes.

**Multifactorial Process of Decolorization of Natural Surface Waters**

Surface water sources possess several advantages for use in technical water supply systems, primarily due to their relatively low mineralization and minimal hardness compared to groundwater. However, their effective utilization in industrial processes requires the development of optimal pretreatment methods aimed at removing organic impurities responsible for color formation. Among reagent-based treatment techniques, coagulation occupies a central position and remains one of the most widely applied methods in water treatment practice. The efficiency of coagulation during the treatment of highly colored but low-turbidity waters largely depends on the colloidal nature of the organic compounds present, which are predominantly of humic origin. These compounds, exhibiting weakly acidic properties, form stable, highly dispersed systems characterized by a negative surface charge. It should be noted that the decolorization process is strongly influenced by the qualitative composition of the organic matter. The presence of humic acids promotes higher removal efficiency, while the dominance of fulvic acids requires substantially greater reagent doses and complicates the overall technological process. A promising approach for enhancing coagulation efficiency involves the application of pre-oxidation methods [18]. The introduction of oxidizing agents facilitates destabilization of colloidal systems by destroying the hydration shells surrounding organic particles, thereby increasing the efficiency of subsequent coagulation. In addition, preliminary oxidation – particularly chlorination and ozonation – provides simultaneous removal of iron and manganese compounds, which are frequently present in surface waters. Contemporary studies confirm that combined treatment using oxidants followed by coagulation significantly improves color removal efficiency [19]. In this regard, the experimental investigation of optimal parameters for the combined application of oxidants and coagulants represents considerable practical interest for improving water treatment technologies intended for technical water supply systems.

The object of the present research was the Mukhovets River, a representative surface water body in the south-western region of Belarus. The study focused on evaluating the influence of ozone dose, coagulant dose, and flocculant dose on the removal efficiency of organic compounds determining the color and oxidizability of the water. The investigation employed a rotatable central composite experimental design, the main characteristics of which are presented in [7, 19].

The process of developing the mathematical model included the following stages: experimental design planning; execution of laboratory and field experiments on the selected water source; verification of experimental reproducibility; derivation of a mathematical model of the process with statistical testing of the regression coefficients for significance; evaluation of model adequacy using statistical criteria. To determine the optimal operating region, an exploratory experiment was first conducted, followed by a rotatable second-order design, in which the selected factors were varied at five levels. Reproducibility of the results was assessed using the Cochran criterion, the significance of the regression coefficients was determined by the Student's test, and the adequacy of the mathematical model was verified using the Fisher criterion at a 5 % significance level.

**Investigation and optimization of the technological regime of surface water bleaching by coagulation with pre-ozonation**

Preliminary experiments demonstrated that the introduction of ozone prior to coagulation increases the overall decolorization efficiency by an average of 10–15 %. The experimental work on water decolorization was conducted using surface water from the Mukhovets River, whose quality characteristics are representative of surface water bodies in the southern regions of the Republic of Belarus.

For the reagent treatment, analytically pure aluminum sulfate ($Al_2(SO_4)_3 \cdot H_2O$) was used as the coagulant, while polyacrylamide (PAA) served as the flocculant. The initial color value of the raw water was 55 degrees, which was taken as the baseline quality indicator [20]. The effectiveness of color removal was evaluated based on the results of spectrophotometric measurements, which allowed quantification of the reduction in apparent color after treatment. The obtained data served as the basis for subsequent mathematical modeling and optimization of process parameters.

***Design and Conduct of the Experiment at the Research Facility and Construction of the CCRD Matrix***

To determine the optimal operating region, a preliminary experimental search was performed, followed by the implementation of a rotatable second-order central composite design (CCRD) within the identified range of factor variability. In this design, the factors were varied at five levels corresponding to the coded variable values +1; –1; +1,68; –1,68 and 0, ensuring statistical rotatability and efficient estimation of quadratic effects.

Based on prior information, it was established that the residual color of treated water, which represents the efficiency of the decolorization process is primarily influenced by three key factors:

– the mass concentration of the coagulant, mg/dm$^3$;

– the mass concentration of the flocculant, mg/dm$^3$;

– the mass concentration of ozone, mg/dm$^3$.

Accordingly, the mathematical description of the process was expressed in the form of a second-order regression equation

$$Y = b_0 + b_1 \cdot X_1 + b_2 \cdot X_2 + b_3 \cdot X_3 + b_{12} \cdot X_1 \cdot X_2 + b_{13} \cdot X_1 \cdot X_3 + \\ + b_{23} \cdot X_2 \cdot X_3 + b_{123} \cdot X_1 \cdot X_2 \cdot X_3 + b_{11} \cdot X_1^2 + b_{22} \cdot X_2^2 + b_{33} \cdot X_3^2; \quad (1)$$

where $b_0$, $b_1$, $b_2$, $b_3$, $b_{12}$, $b_{13}$, $b_{23}$, $b_{123}$,$b_{11}$, $b_{22}$, $b_{33}$ are the regression coefficients, and

$X_1, X_2, X_3$ are the coded variables associated with their respective physical quantities $(x_1, x_2, x_3)$ through the following transformations

$$X_1 = \frac{x_1 - x_{01}}{\Delta x_1};\ X_2 = \frac{x_2 - x_{02}}{\Delta x_2};\ X_3 = \frac{x_3 - x_{03}}{\Delta x_3}, \quad (2)$$

where

$x_{01}$ − coordinates of the center point of the experimental design;

$\Delta x$ − the variation interval for each factor;

$Y$ – the response function, representing the measured residual color of the treated water.

***Calculation of Regression Coefficients and Corresponding Variance Estimates***

Within the framework of the rotatable central composite design (CCRD), the regression coefficients and their corresponding variance estimates were calculated to determine their statistical significance [1, 2]. Table 1 presents the characteristics of the CCRD and the values of the design constants B, C, and A.

**Table 1** – Characteristics of the CCRD and Design Constants

| | |
|---|---|
| Number of factors n | 3 |
| Total number of experiments N | 20 |
| Number of central point experiments $N_0$ | 6 |
| Constant B | 0,8571429 |
| Constant C | 1,4285714 |
| Constant A | 0,4537037 |

Based on the results of the experimental studies, the summations and regression coefficients were calculated, as summarized in Table 2.

**Table 2** – Summation Values and Calculated Regression Coefficients

| Summation Term | | | | Regression Coefficient | | | |
|---|---|---|---|---|---|---|---|
| $S_0$ | 150,40 | $S_{23}$ | –4,80 | $b_0$ | 4,25 | $b_{23}$ | –0,57 |
| $S_1$ | –45,42 | $S_{11}$ | 152,86 | $b_1$ | -3,24 | $b_{11}$ | 3,22 |
| $S_2$ | 6,55 | $S_{22}$ | 104,32 | $b_2$ | 0,47 | $b_{22}$ | 0,33 |
| $S_3$ | –24,38 | $S_{33}$ | 117,58 | $b_3$ | –1,74 | $b_{33}$ | 1,12 |
| $S_{12}$ | 4,40 | $S_{123}$ | 1,40 | $b_{12}$ | 0,52 | $b_{123}$ | 0,03 |
| $S_{13}$ | –4,80 | | | $b_{13}$ | -0,57 | | |

In accordance with the principles of rotatable experimental design, a coefficient **b**$_i$ is considered statistically significant if its calculated value satisfies the condition: $|b_i| > sb_i t$, where **t** is the critical value of Student's t-test [1, 2]. If this condition is not met, the coefficient is regarded as insignificant, and the corresponding term may be excluded from the regression model. Table 3 summarizes the variance estimates for determining the significance of the regression coefficients.

**Table 3** – Variance Estimates for the Regression Coefficients

| | | | |
|---|---|---|---|
| $s^2_{b_0}$ = | 0,038 | $s^2_{b_0}$ ·t= | 0,499 |
| $s^2_{b_i}$ = | 0,014 | $s^2_{b_i}$ ·t= | 0,302 |
| $s^2_{b_{ik}}$ = | 0,020 | $s^2_{b_{ik}}$ ·t= | 0,361 |
| $s^2_{b_{ii}}$ = | 0,013 | $s^2_{b_{ii}}$ ·t= | 0,291 |

Table 4 presents the verification of the significance of the regression coefficients according to Student's t-test.

**Table 4** – Verification of Regression Coefficient Significance

| | | | | |
|---|---|---|---|---|
| $\|b_0\|$ = | 4,25 | > | 0,499 | Significant |
| $\|b_1\|$ = | 3,24 | > | 0,302 | Significant |
| $\|b_2\|$ = | 0,47 | > | 0,302 | Significant |
| $\|b_3\|$ = | 1,74 | > | 0,302 | Significant |
| $\|b_{12}\|$ = | 0,52 | > | 0,361 | Significant |
| $\|b_{13}\|$ = | 0,57 | > | 0,361 | Significant |
| $\|b_{23}\|$ = | 0,57 | > | 0,361 | Significant |
| $\|b_{11}\|$ = | 3,22 | > | 0,291 | Significant |
| $\|b_{22}\|$ = | 0,33 | > | 0,291 | Significant |
| $\|b_{33}\|$ = | 1,12 | > | 0,291 | Significant |
| $\|b_{123}\|$ = | 0,03 | < | 0,361 | Not significant |

***Verification of Variance Homogeneity (Reproducibility of Experiments)***

To verify the reproducibility of the experimental results, the Cochran criterion ($G_p$) was used, which is defined as the ratio of the maximum variance to the sum of all variances within a series of parallel experiments. For each series of parallel runs, the arithmetic mean value of the response function was calculated, followed by the variance estimate for that series.

The hypothesis of variance homogeneity is not rejected if the experimentally determined value of the Cochran criterion does not exceed its tabulated value [9]. The corresponding tabulated values of the Cochran criterion were adopted for a confidence probability of $P$ = 0,95, under which the reproducibility hypothesis is considered valid. The quantity ($p = 1−P$) represents the significance level. To determine the value of $G$ , it is necessary to know the total number of variance estimates (N) and the degrees of freedom ($f$) associated with each of them, where $f = k−1$, and $k$ is the number of factors considered. Table 5 presents the experimental response function values ($y_j^э$) and the corresponding variance estimates ($s_j^2$) for reproducibility testing at the central points of the experimental plan.

**Table 5** – Estimation of the variance of reproducibility of experiments in the center of the plan

| Center-point experiments | | | | | Variance Estimate |
|---|---|---|---|---|---|
| Experiment No. j | $y_j^э$ | $(y_j^э - \bar{y})$ | $(y_j^э - \bar{y})^2$ | $s_j^2$ | |
| 15 | 3,00 | –0,72 | 0,51 | 0,257 | $\max s_j^2$ |
| 16 | 4,00 | 0,28 | 0,08 | 0,040 | |
| 17 | 3,50 | –0,22 | 0,05 | 0,023 | |
| 18 | 4,20 | 0,48 | 0,23 | 0,117 | |
| 19 | 3,60 | –0,12 | 0,01 | 0,007 | |
| 20 | 4,00 | 0,28 | 0,08 | 0,040 | |
| ∑ 6 | 22,30 | 0,00 | 0,97 | 0,484 | $\sum_{j=1}^{N} s_j^2$ |

The average value of the response function was calculated according to the expression

$$\bar{y} = \frac{1}{N_0} \cdot \sum_{j=1}^{N_0} y_j^э = \frac{1}{6} \cdot 22,3 = 3,72. \qquad (3)$$

where $y_j^э$ – experimental response function values; j – experiment number; $N_o$ – number of experiments at the center of the design.

The calculated value of the Kohren criterion $G_p$ was determined by the formula

$$G_p = \frac{\max s_j^2}{\sum_{j=1}^{N} s_j^2} = \frac{0,257}{0,484} = 0,530. \qquad (4)$$

The corresponding tabulated value of the Cochran criterion was taken from [9] for the following parameters: P = 0,95; N = 6; f = k – 1 = 3 – 1 = 2, where k is the number of selected factors. Thus, the tabulated value is: G t = 0,616.

The condition $G_p \le G$ is fulfilled: 0,530 < 0,616, therefore, the experiments can be considered reproducible.

The variance estimate for a series of parallel experiments $s_y^2$ was calculated using the following formula

$$s_y^2 = \frac{1}{N_0 - 1} \cdot \sum_{j=1}^{N_0} (y_j^э - \bar{y})^2 = \frac{1}{6-1} \cdot 0,97 = 0,194. \qquad (5)$$

This variance value was determined with the number of degrees of freedom corresponding to $f = N_0 - 1 = 6 - 1 = 5$.

***Verification of the Adequacy of the Regression Equation***

After obtaining the regression equation, it is necessary to verify its adequacy, i.e., its ability to accurately describe the response surface of the studied process. The adequacy of the regression model was verified using the Fisher criterion (*F*-test).

**Table 6** – Variance Estimates for Determining the Adequacy of the Regression Equation

| Experimental Response $y_j^э$ | Calculated Response $y_j^p$ | $(y_j^э - y_j^p)$ | $(y_j^э - y_j^p)^2$ |
|---|---|---|---|
| 4,30 | 3,79 | 0,51 | 0,264 |
| 9,80 | 9,56 | 0,24 | 0,060 |
| 3,00 | 2,95 | 0,05 | 0,003 |
| 6,80 | 6,43 | 0,37 | 0,138 |
| 10,70 | 10,37 | 0,33 | 0,109 |
| 14,50 | 13,85 | 0,65 | 0,419 |
| 12,30 | 11,62 | 0,68 | 0,457 |
| 13,00 | 12,82 | 0,18 | 0,032 |
| 8,30 | 7,89 | 0,41 | 0,168 |
| 19,50 | 18,79 | 0,71 | 0,504 |
| 6,00 | 5,97 | 0,03 | 0,001 |
| 4,60 | 4,40 | 0,20 | 0,041 |
| 4,50 | 4,49 | 0,01 | 0,000 |
| 10,80 | 10,34 | 0,46 | 0,212 |
| 3,00 | 4,25 | –1,25 | 1,554 |
| 4,00 | 4,25 | –0,25 | 0,061 |
| 3,50 | 4,25 | –0,75 | 0,557 |
| 4,20 | 4,25 | –0,05 | 0,002 |
| 3,60 | 4,25 | –0,65 | 0,418 |
| 4,00 | 4,25 | –0,25 | 0,061 |
| | | | 5,060 |

The adequacy variance $s_{ad}^2$ was determined using the following expression

$$s_{ad}^2 = \frac{\sum_{j=1}^{N} (y_j^э - y_j^p)^2 - s_y^2 \cdot (N_0 - 1)}{f_{ad}} = \frac{5,060 - 0,194 \cdot (6-1)}{5} = 0,818. \qquad (6)$$

The number of degrees of freedom associated with this adequacy variance estimate was defined as

$$f_{ad} = N - \frac{(n+2)\cdot(n+1)}{2} - (N_0 - 1) = 20 - \frac{(3+2)\cdot(3+1)}{2} - (6-1) = 5, \qquad (7)$$

where *n* is the number of factors.

The calculated value of the Fisher criterion was obtained as

$$F_p = \frac{\max(s_{ad}^2, s_y^2)}{\min(s_{ad}^2, s_y^2)} = \frac{0,818}{0,194} = 4,216. \qquad (8)$$

According to reference [9], the corresponding tabulated value of the Fisher criterion is: $F = 5,05$. Since the condition $F_p \le F$ is satisfied (4,216<5,05), the obtained regression equation is considered adequate and provides a reliable description of the response surface.

$$Y = 4,25 - 3,24X_1 + 0,47X_2 - 1,74X_3 + 0,52X_1X_2 - 0,57X_1X_3 - 0,57X_2X_3 + 3,22X_1^2 + 0,33X_2^2 + 1,12X_3^2. \qquad (9)$$

To convert the regression equation from coded variables to physical units, the following relationships (based on Eq. (2)) were applied:

$X_1 = \frac{x_1 - x_{01}}{\Delta x_1} = \frac{k-20}{10} = 0,1k - 2$ ;

$X_2 = \frac{x_2 - x_{02}}{\Delta x_2} = \frac{f-1}{0,5} = 2f - 2$ ;

$X_3 = \frac{x_3 - x_{03}}{\Delta x_3} = \frac{g-10}{5} = 0,2g - 2.$

Substituting these expressions into the final regression equation yields the model in physical terms

$C = f\,(k, f, g)$:

$$C = 29{,}50 - 1{,}6k - 1{,}5f - 0{,}788g + 0{,}104kf - 0{,}0114kg - 0{,}228fg + 0{,}0322k^2 + 1{,}32f^2 + 0{,}0448g^2, \quad (10)$$

where $C$ – color intensity of water (color units), grad;
$k$ – coagulant dose $D_k$ (mg/dm³);
$f$ – flocculant dose $D_f$ (mg/dm³);
$g$ – ozone dose $D_{oz}$ (mg/dm³).

Using this equation (10), it is possible to predict the performance efficiency of the water decolorization system for any given operational regime of coagulation treatment with preliminary ozonation. Figure 1 shows a graph of the residual color of water corresponding to the obtained model, depending on the ozone dose at different coagulant doses.

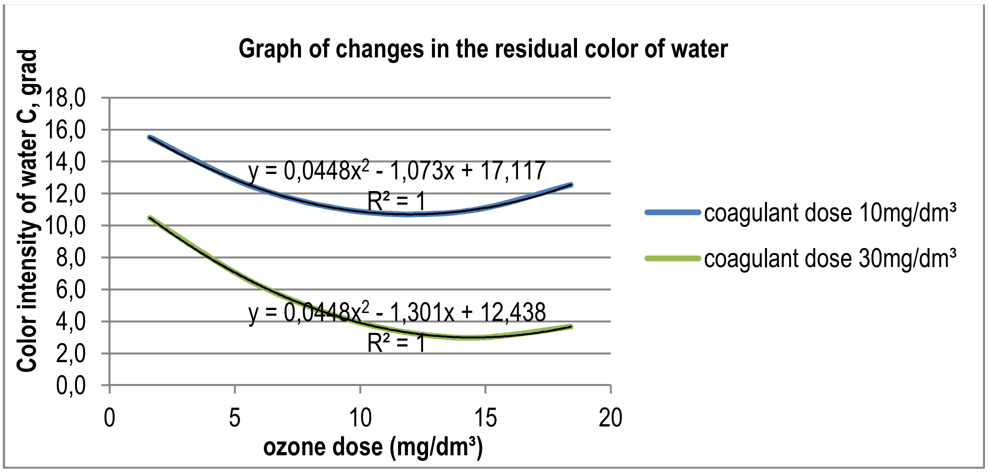


**Figure 1 –** Influence of ozone dose on the water decolorization process at different coagulant doses (flocculant dose = 0,75 mg/dm³)

Analysis of the regression model (Eq. 10) based on the determination of the extremum condition $C = f(k, f, g) \rightarrow \min$ with respect to the influencing factors $D_k$, $D_f$, and $D_{oz}$, showed that the minimum residual color of treated water is achieved under the following optimal conditions: coagulant dose – 26,12 mg/dm³, flocculant dose − 0,75 mg/dm³, ozone dose − 14 mg/dm³.

Mathematical processing of the experimental results indicates that all three investigated factors significantly influence the efficiency of water decolorization. However, their impact strength decreases in the following order: coagulant dose > ozone dose > flocculant dose.

**Conclusions**

Based on the conducted experimental studies simulating the natural water treatment process, the main influencing factors determining the efficiency of removing color-causing impurities from surface waters for technical water supply purposes were identified and analyzed. Using the method of optimal experimental design, an experimental-statistical model of the decolorization process by coagulation with preliminary ozonation was developed. The obtained regression equation describes the combined influence of ozone, coagulant, and flocculant doses on the residual color of treated water. The model enabled the determination of optimal process parameters at which the maximum decolorization efficiency is achieved under the given conditions.

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# THE INFLUENCE OF RECYCLED AGGREGATE CONTENT AND SILICA FUME ADDITION ON THE MECHANICAL PROPERTIES OF RECYCLED AGGREGATE CONCRETE

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**Abstract**

The use of waste from concrete and reinforced concrete structures is one of the current areas of development in the construction industry in the Republic of Belarus and abroad. Despite the active growth of this field, there is insufficient research devoted to the comprehensive study of concretes using recycled aggregates, especially with the introduction of various types of pozzolanic additives. A comprehensive study was conducted on concrete using recycled aggregate, aimed at examining effects of various levels of recycled aggregate in the concrete at 0 %, 25 %, 50 %, 75 %, and 100 % of the total aggregate mass, with the addition of fly ash, on compressive strength, tensile strength, and the adhesion between the reinforcement and the concrete. Experimental results indicate that as the content of recycled aggregate increases, the mechanical properties of the concrete tend to decline. This is primarily due to the inherent lower strength of the recycled aggregate and the presence of two transitional zones in the concrete with recycled aggregate (in the cement paste and the recycled aggregate). However, the addition of fly ash can improve this issue: the pozzolanic reaction of $SiO_2$ with portlandite $Ca(OH)_2$ leads to the filling of pores in the transitional zones with reaction products and the solidification of their structure. This contributes to the elimination of the distinct phase boundary and, consequently, to the merging of the transition zone of the cement paste with the transition zone of the recycled aggregate, significantly enhancing its adhesion to the cement paste. The research results confirm that concrete made with recycled aggregate exhibits improved mechanical properties compared to control mixes without fly ash.

**Keywords:** concrete, recycled aggregate, silica fume, mechanical properties.

## ВЛИЯНИЕ СОДЕРЖАНИЯ РЕЦИКЛИНГОВОГО ЗАПОЛНИТЕЛЯ И ЗОЛЫ-УНОСА В БЕТОНЕ НА ЕГО МЕХАНИЧЕСКИЕ СВОЙСТВА

**Сун Чуньхуа, В. В. Кравченко**

**Реферат**

Вторичное использование отходов конструкций и изделий из бетона и железобетона является одним из актуальных направлений развития строительной отрасли в Республике Беларусь и зарубежных странах. Несмотря на активное развитие данного направления, отсутствует достаточный объем исследований, посвященных комплексному изучению бетонов на рециклинговом заполнителе, особенно при условии введения различных типов пуццолановых добавок. Проведено комплексное исследование бетона на рециклинговом заполнителе, направленное на изучение влияния содержания рециклингового заполнителя в количестве 0 %, 25 %, 50 %, 75 %, 100 % от массы всего заполнителя с добавлением золы-уноса на прочность бетона при сжатии и растяжении, а также прочность сцепления арматуры с бетоном. Экспериментальные результаты показывают, что по мере увеличения содержания рециклингового заполнителя механические свойства бетона показывают тенденцию к снижению. Это, в первую очередь, связано с присущей рециклинговому заполнителю более низкой прочностью и наличием в структуре бетона на рециклинговом заполнителе двух транзитных зон (в цементном камне и рециклинговом заполнителе). Однако добавление золы-уноса способно решить данную проблему: пуццолановая реакция $SiO_2$ с портландитом $Ca(OH)_2$ приводит к заполнению пор в транзитных зонах продуктами реакции и уплотнению их структуры. Это способствует устранению выраженной границы раздела фаз и, как следствие, к слиянию транзитной зоны цементного камня с транзитной зоной рециклингового заполнителя, что значительно улучшает его адгезию с цементным камнем. Результаты исследования подтверждают, что бетон на рециклированном заполнителе демонстрирует улучшенные механические характеристики по сравнению с контрольными составами без золы-уноса.

**Ключевые слова:** бетон, рециклинговый заполнитель, зола-унос, механические свойства.

### Introduction

Against the backdrop of the continuously expanding scale of construction in the global building industry, the demand for building materials continues to rise. Among these, natural aggregates, as a key component of concrete, are being consumed in particularly large quantities. However, long-term and large-scale extraction has led to the increasing depletion of natural aggregate resources, triggering serious sustainability issues. On the other hand, with urban construction and renewal, large amounts of construction waste are continuously generated. The stockpiling of this waste not only occupies land resources but may also cause compound pollution to soil, water, and the atmosphere, creating a heavy environmental burden. In this context, promoting the resource utilization of construction waste by processing it into recycled aggregates for use in concrete production is regarded as an important pathway to balance the conflict between resource supply and environmental protection, and has garnered widespread attention [1–4]. This approach not only helps alleviate the pressure on natural aggregate resources but also significantly reduces the negative impact of construction waste on the ecological environment, offering notable comprehensive economic, social, and environmental benefits.

Although recycled aggregate concrete demonstrates significant potential for sustainable development, its material performance still faces challenges. Compared to natural aggregates, recycled aggregates have a large amount of old cement mortar attached to their surfaces and contain initial defects such as microcracks, resulting in lower apparent density, higher water absorption, and weaker mechanical strength. These differences in physical and mechanical properties often lead to issues such as relatively low strength and insufficient durability in recycled aggregate concrete at the macroscopic level. The root causes can be attributed to the weakening of the aggregate-cement paste interface zone and the formation of a multiple interfacial structure. To enhance the practical performance of recycled aggregate concrete and promote its application in high-standard engineering projects, it is of great importance to systematically study its performance evolution mechanisms and develop effective enhancement technologies.

Among various modification methods, incorporating silica fume is considered an effective approach to enhance the performance of recycled aggregate concrete. Chen's research findings indicate that the incorporation of silica fume accelerates the setting of cement paste and significantly reduces its fluidity. However, silica fume has a very notable effect on enhancing the later-age (28-day) compressive strength of the paste [5]. Zhao's study found that the incorporation of silica fume can significantly improve the compressive and flexural strength of cement mortar, and there exists an optimal dosage range (approximately 5 % in the study) [6]. Li's research discovered that the pozzolanic reaction of silica fume consumes calcium hydroxide, a hydration product, and generates more dense calcium silicate hydrate (C-S-H) gel with a low calcium-to-silica ratio, thereby optimizing the microstructure of the mortar, making it denser, reducing porosity, and strengthening the interfacial structure [7]. Yang's study found that silica fume significantly enhances the frost resistance of concrete and effectively reduces the diffusion coefficient of chloride ions in concrete. This is because silica fume densifies the concrete structure, hindering the penetration pathways of moisture and corrosive ions [8]. Liu's research found that in low-temperature environments, silica fume can also effectively improve the compressive strength and impermeability of cement mortar. The study revealed that silica fume overcomes the adverse effects of low temperature on cement hydration and microstructure development by optimizing pore structure and promoting hydration [9]. Silica fume is characterized by its extremely fine particle size (approximately 0,1–0,2 μm), large specific surface area, and high pozzolanic reactivity. When added to concrete, silica fume can undergo a secondary reaction with calcium hydroxide, a product of cement hydration, generating additional calcium silicate hydrate gel. This effectively fills capillary pores and microcracks, optimizes the pore structure, and thereby increases the density of the matrix. More importantly, silica fume significantly strengthens the interfacial transition zone between recycled aggregates and the cement paste, improving the bond between the old and new mortar and alleviating stress concentrations caused by the presence of the old mortar. Consequently, it enhances the overall mechanical properties and durability of the concrete [10–12]. In recent years, Hamada et al. [13] provided a comprehensive review of using plastic waste as aggregate in concrete, synthesizing a broad set of laboratory and field studies and assessing environmental and economic implications. Danish and Ozbakkaloglu [14] examined the role of nano-silica in mortars containing e-waste plastic used as fine aggregates, showing that nano-silica can partially recover the strength loss caused by replacing natural sand with plastic particles by (1) filling micro-voids, (2) accelerating pozzolanic reactions that densify the binder, and (3) improving the interfacial transition zone around irregular plastic fragments. Alhajiri and Akhtar [15] produced a systematic review focused on silica fume as a sustainability and economic lever in concrete production.

Some scholars have also studied the use of recycled concrete aggregates and various plastic wastes as aggregates, systematically evaluating their impact on the workability, mechanical properties, and durability indicators such as chloride ion migration of concrete. In addition, the incorporation of steel fibers has been proven to be an effective means to improve the compressive and flexural properties and toughness of concrete, including geopolymer concrete. These studies not only promote the progress of concrete technology, but also provide important technical paths and practical cases for achieving sustainable development and carbon reduction goals in the construction industry [16–18]. Fernando et al. [19–20] investigated strategies to produce high-strength recycled aggregate concrete (RAC) by combining multiple supplementary cementitious materials (SCMs). The study systematically examined the effects of fly ash, silica fume and rice husk ash (RHA) used both as cement replacements and as treatments for recycled aggregates. Shamass et al. [21] combined mechanical testing with environmental assessment to evaluate concretes formulated with blast furnace slag (GGBS), silica fume and recycled aggregate, emphasizing both engineering performance and global warming potential (GWP). Nasir, Butt and Ahmad [22] focussed on recycled plastic aggregate concrete (RPAC) and demonstrated that coupling silica fume with fiber reinforcement (steel and polypropylene fibers) significantly improves mechanical and axial (column) resilience of RPAC.

Therefore, investigating the synergistic effects of recycled aggregate content and silica fume addition on the mechanical behavior and microstructure of recycled aggregate concrete holds significant theoretical value. It will also provide critical technical foundations for material design, performance optimization, and engineering application of recycled aggregate concrete, contributing positively to advancing the green and low-carbon transformation of the construction industry.

## 1 Experimental Materials and Methods

### 1.1 Experimental Materials

This experiment used ordinary Portland cement as the cementitious material. Its physical and chemical properties comply with national standard requirements, ensuring stable and reliable hydration reactions and binding capacity for the concrete system.

Natural siliceous river sand was selected as the fine aggregate. This sand features rounded particle shapes and a continuous, well-graded distribution, effectively filling the voids between the coarse aggregate skeleton and significantly enhancing the compactness and homogeneity of the concrete.

The coarse aggregates used in the experiment included two types: The first was natural pink limestone gravel with a maximum particle size of 20 mm, characterized by uniform texture and stable physical properties, as shown in Figure 1. The second was recycled coarse aggregate sourced from construction and demolition waste, as shown in Figure 2. This was processed by manually breaking with a steel hammer, sieving, and cleaning waste concrete components with different mix proportions, cement types, and ages. Its particle size distribution was ultimately controlled within the range of 4,75–19 mm to meet the experimental comparison requirements.

**Figure 1** – Pink limestone natural coarse aggregate

To improve the interfacial structure and mechanical properties of the recycled aggregate concrete, reactive silica fume was incorporated. Its main chemical component is amorphous silicon dioxide, characterized by a fine average particle size, large specific surface area, and excellent pozzolanic reactivity.

Furthermore, to ensure the workability of the fresh concrete under conditions of relatively high aggregate content, a polycarboxylate-based high-range water reducer was used to control fluidity, maintaining good plasticity and uniformity during mixing and pouring.

**Figure 2** – Recycled coarse aggregate


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From the perspective of aggregate gradation characteristics, the natural coarse aggregate, sourced from mechanically crushed limestone, has a relatively concentrated particle size distribution and a relatively ideal gradation curve. In contrast, the recycled coarse aggregate, limited by its complex sources and crushing process, has a wider particle size distribution range and a slightly higher fine powder content. The fineness modulus of the natural sand is 2,6, classifying it as medium sand. It effectively fills the voids between coarse aggregates, forming a rational particle grading system and laying a good foundation for the overall workability and mechanical properties of the concrete.

**1.2 Experimental Design**

This study systematically investigated the synergistic effects of recycled aggregate content and silica fume addition on the properties of recycled aggregate concrete. To comprehensively evaluate the influence of recycled aggregate, five replacement levels were set: 0 %, 25 %, 50 %, 75 %, and 100 % by mass of the total aggregate, allowing for systematic observation of the evolution of concrete properties with varying recycled aggregate content.

Regarding the modification with silica fume, the experiment focused on a reference mix proportion with a cement content of 250 kg/m³ and a water-to-cement ratio of 0,60. Silica fume was added at 10 % of the cement mass to analyze its improvement effects on the microstructure and macroscopic properties of concrete within this specific material system.

The experimental design carefully considered practical engineering application needs, selecting two typical cement contents of 400 kg/m³ and 250 kg/m³, representing common mix proportion ranges for reinforced concrete elements and plain concrete elements, respectively.

To ensure the accuracy and comparability of the experimental results, the dosage of the chemical admixture was adjusted differentially based on the cement content: when the cement content was 250 kg/m³, the admixture dosage was 1,75 % of the cement weight; when the cement content increased to 400 kg/m³, the admixture dosage was correspondingly adjusted to 0,75 % of the cement weight.

By precisely controlling the mix proportion parameters, the workability of all concrete mixtures was consistently maintained within the range of 120 ± 30 mm, effectively ensuring consistent testing conditions and reliable data.

This experimental scheme considers both the systematic variation of recycled aggregate content and provides an in-depth investigation into the modifying effects of silica fume under specific mix proportions, establishing a scientific experimental basis for a comprehensive evaluation of the performance characteristics of recycled aggregate concrete.

**1.3 Experimental Methods**

**1.3.1 Specimen Preparation**

After precisely weighing all raw materials according to the established mix proportions, the concrete was mixed using conventional mechanical mixing procedures. The feeding sequence strictly followed the order of cement, aggregates, silica fume, chemical admixtures, and finally water to ensure thorough homogenization of all components. Upon completion of mixing, the fresh concrete was immediately placed into the respective molds for casting. The specimen dimensions were specifically designed according to the different testing items: Compressive strength tests utilized standard 150 mm × 150 mm × 150 mm cubic specimens; Tensile strength tests employed cylindrical specimens with a diameter of 75 mm and a height of 150 mm. Bond performance tests used cylindrical specimens with a diameter of 150 mm and a height of 150 mm. A 16 mm diameter deformed steel bar was pre-embedded along the central axis of the specimen before casting. All specimens were demolded and immediately transferred to a standard curing room. They were continuously cured under constant temperature and humidity conditions (20 ± 2 °C, relative humidity ≥ 95 %) until the designated testing ages.

This preparation protocol, incorporating standardized mold selection, regulated mixing procedures, and strictly controlled curing regimes, effectively ensured consistency among the test specimens and comparability of the test data. The design of the different specimen types fully considered the standardization requirements of the respective test methods. Specifically, the unique configuration of the bond strength specimens with the pre-embedded steel bar accurately simulates the interaction between concrete and reinforcement.

**1.3.2 Performance Testing**

In accordance with standard testing procedures, systematic evaluations of mechanical properties and physical indicators were conducted on all specimen types at designated ages. Compressive strength tests were performed at 7, 28, and 56 days. Standard cubic specimens were positioned centrally on the loading plates of a compression testing machine. Axial pressure was applied at a constant loading rate while monitoring the load value continuously until specimen failure. The peak load was recorded, and the compressive strength was calculated using the standard formula.

Tensile strength was characterized using the splitting tensile test method. Upon reaching the specified testing age, cylindrical specimens were placed horizontally in a splitting test fixture. A continuous linear load was applied through the upper and lower bearing plates, inducing uniform tensile stress along the diametral plane until splitting failure occurred. The splitting tensile strength was calculated based on the measured failure load and specimen dimensions according to the standard formula.

Bond performance tests were conducted specifically at the 28-day age. Cylindrical specimens with pre-embedded deformed steel bars were used. A specialized pull-out setup was employed to apply an axial tensile force to the steel bar. The ultimate load at which slippage occurred at the concrete-steel interface was precisely measured, and the bond strength between them was determined through calculation.

This testing framework comprehensively covers the macroscopic mechanical properties of the concrete material. All testing procedures strictly adhered to relevant standard specifications, ensuring the accuracy and comparability of the results. The bond strength test protocol effectively simulates the actual stress state in reinforced concrete elements, while the multi-age strength testing reveals the development pattern of the material's properties.

**2 Results and Analysis**

**2.1 Influence of Recycled Aggregate Content**

**2.1.1 Compressive Strength**

The effect of different recycled aggregate replacement levels on the compressive strength of concrete with a cement content of 400 kg/m³ is shown in Figure 3.

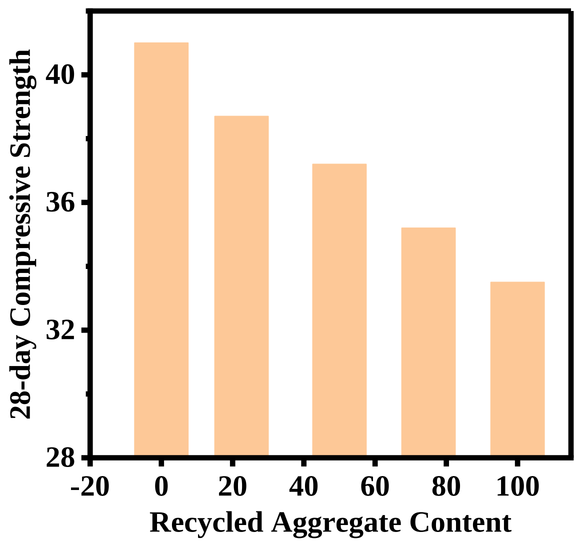


**Figure 3** – Compressive strength of concrete with different recycled aggregate content

Based on the experimental results, the influence of recycled aggregate content on the compressive strength of concrete exhibits distinct phase characteristics. When the RA content is limited to within 25 %, the 28-day compressive strength shows no significant difference compared to the reference group (with no recycled aggregate). Specifically, the compressive strength of specimens with 25 % recycled aggregate content was only 3,0 % lower than that of the control group. This minor variation falls within the acceptable engineering margin of error. This phenomenon is primarily attributed to the uniform distribution of recycled aggregates within the concrete matrix at this replacement level, forming a well-graded combination with natural aggregates. Furthermore, strict gradation optimization of the recycled aggregates effectively ensured the compactness of the internal concrete structure, allowing its mechanical properties to be maintained.

However, when the recycled aggregate content exceeds the critical threshold of 25 %, the compressive strength begins to show a significant declining trend. The fundamental reason for this phenomenon lies in the performance disparity between the old cement mortar adhered to the surface of the recycled aggregates and the fresh cement paste. This disparity causes the interfacial transition zone (ITZ) between the two to become a mechanical weak link. As the recycled aggregate content increases, these weak interfaces interconnect and form continuous paths within the concrete, significantly compromising the structural integrity of the material. Under external compressive load, stress tends to concentrate in these weak areas, initiating and propagating micro-cracks, ultimately leading to premature failure of the material, which macroscopically manifests as a significant reduction in compressive strength.

**2.1.2 Tensile Strength**

The influence pattern of recycled aggregate content on the tensile strength of concrete under the mix proportion with a cement content of 250 kg/m³ is shown in Figure 4. Research indicates a clear negative correlation between the tensile strength of concrete and the recycled aggregate content. As the proportion of recycled aggregates in the concrete increases, the tensile performance of the material shows a systematic decline.

This strength degradation primarily stems from the structural defects in the interfacial transition zone between the recycled aggregates and the new cement paste. Compared to natural aggregates, the old cement mortar attached to the surface of recycled aggregates creates a more complex multiple interfacial structure with the fresh cement paste. When subjected to tensile stress, these interfacial transition zones, due to their lower bond strength and higher number of micro-crack defects, become areas of stress concentration and are highly prone to initiating cracks.

As the recycled aggregate content increases, the number of weak interfaces within the concrete correspondingly rises, forming denser potential failure paths. This makes it easier for micro-cracks to propagate and interconnect under load, ultimately accelerating the tensile failure process of the material, which macroscopically manifests as a significant reduction in tensile strength. This mechanism fully illustrates the importance of controlling the recycled aggregate content to ensure the tensile performance of concrete.

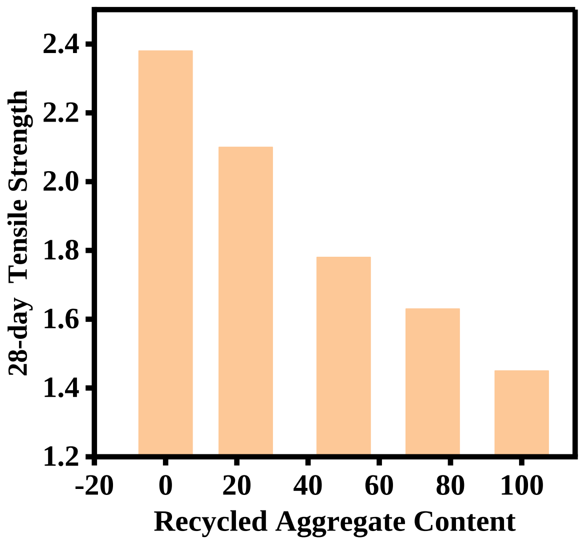


**Figure 4** – Effect of different recycled aggregate content on tensile strength of concrete

**2.1.3 Bond Strength**

Figure 5 illustrates the influence of recycled aggregate content on the bond strength of concrete under the mix proportion with a cement content of 400 kg/m³. The experimental results indicate that the bond performance between concrete and steel reinforcement is highly sensitive to changes in recycled aggregate content, showing a significant negative correlation. As the proportion of recycled aggregates increases, the bond strength demonstrates a systematic declining trend.

This phenomenon is primarily attributed to the adverse effects of the unique surface characteristics of recycled aggregates on the interaction at the interface with the steel reinforcement. The old cement mortar coating the surface of recycled aggregates not only reduces the mechanical properties of the aggregates themselves but also alters the structural characteristics of the steel-concrete interface at the micro-level. The presence of the old mortar layer weakens the mechanical interlock between the concrete and the steel bar surface, while simultaneously reducing the chemical adhesion at their interface. This leads to a significant reduction in the bond between the steel bar and the concrete.

This degradation of interfacial performance accumulates with increasing recycled aggregate content, ultimately significantly affecting the composite action of reinforced concrete. Test data indicate that when the recycled aggregate content reaches 100 %, the bond strength of the concrete decreases by approximately 20 % compared to the reference group without recycled aggregates. This quantitative result fully confirms the significant impact of recycled aggregates on the interfacial performance of reinforced concrete and provides an important reference for rationally controlling the recycled aggregate content in engineering applications. The research findings offer positive guidance for promoting the application of recycled concrete in structural engineering.

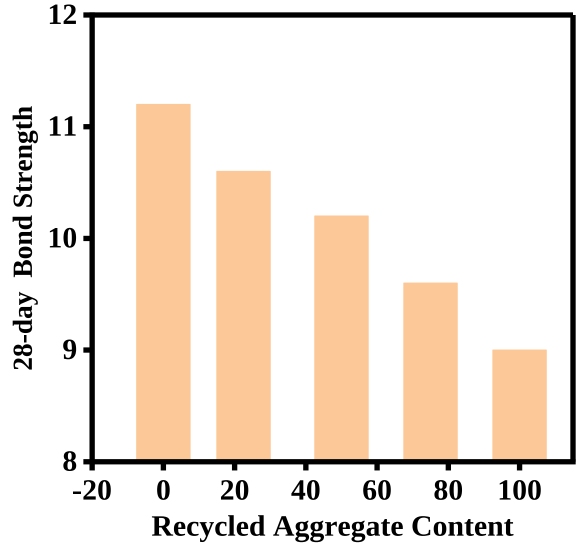


**Figure 5** – Bond strength of concrete with different recycled aggregate content

**2.2 Influence of Silica Fume Addition**

**2.2.1 Compressive Strength**

Figure 6 presents the influence of silica fume content on the compressive strength of concrete. Under the reference mix conditions with a fixed cement content of 250 kg/m³ and a water-cement ratio of 0,60, the incorporation of 10 % silica fume produced a significant enhancing effect on the concrete's compressive strength.

This notable strength improvement is primarily attributed to the dual improvement mechanisms exerted by silica fume in the concrete. Firstly, silica fume, characterized by its extremely fine particle size (average particle size approximately 0,1–0,2 μm), effectively fills the microscopic pores between cement particles and the defects in the aggregate-paste interface transition zone. This significantly refines the microscopic pore structure of the concrete and increases the material's density.

Secondly, silica fume is rich in amorphous silicon dioxide, possessing excellent pozzolanic activity. It can undergo a secondary hydration reaction with calcium hydroxide, a product of cement hydration, generating additional calcium silicate hydrate (C-S-H) gel with cementitious properties. These newly formed gel products not only further fill capillary pores but, more importantly, strengthen the interfacial transition zone between the cement paste matrix and the aggregates, forming a more stable three-dimensional spatial network structure. This ultimately leads to a significant increase in the macroscopic compressive strength of the concrete.

It is noteworthy that the improvement effect of silica fume is more pronounced in concrete with high recycled aggregate content. This is mainly because it effectively compensates for the weak interfaces caused by the old mortar layer on the surface of recycled aggregates, achieving targeted reinforcement of the shortcomings inherent in recycled concrete.

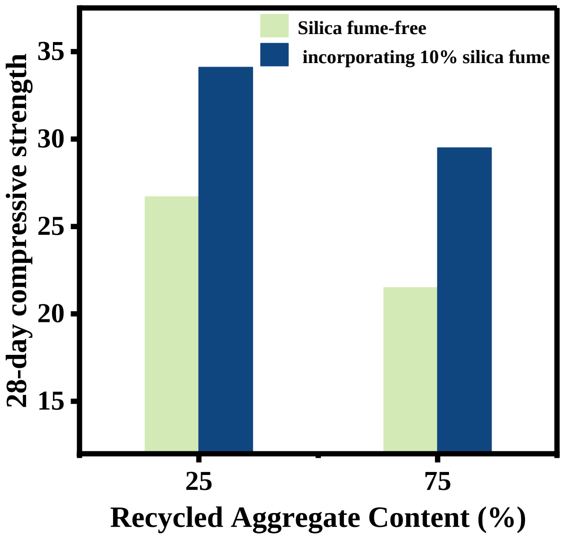


**Figure 6** – Effect of silica fume content on the compressive strength of concrete

### 2.2.2 Tensile Strength

Figure 7 details the influence of silica fume content on the tensile strength of concrete. Research indicates that, under the mix proportion with a fixed cement content of 250 kg/m³, incorporating 10 % silica fume significantly improves the tensile performance of recycled aggregate concrete.

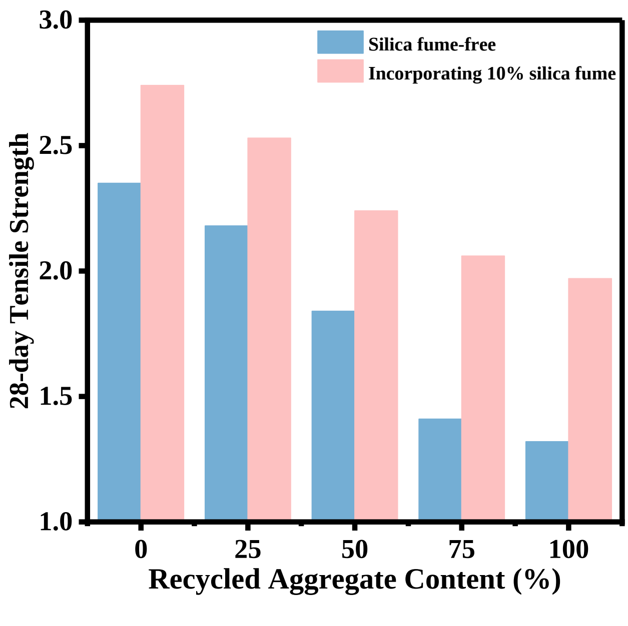


**Figure 7** – Improvement in concrete tensile strength with silica fume addition

This notable performance enhancement primarily stems from the multiple optimizing effects of silica fume on the concrete's microstructure. On one hand, due to its ultra-fine particle characteristics (particle size ~0,1–0,2 μm), silica fume effectively fills the micro-pores within the cement paste and the structural defects in the aggregate-paste interface zone, significantly reducing stress concentration inside the material. On the other hand, the amorphous silicon dioxide abundant in silica fume undergoes a pozzolanic reaction with calcium hydroxide, a product of cement hydration, generating calcium silicate hydrate gel with cementitious properties. These newly formed gel products not only enhance the density of the cement matrix but, more importantly, strengthen the interfacial bonding performance between the aggregates and the cement paste.

Through this dual mechanism of microstructural improvement, the concrete exhibits enhanced crack resistance when subjected to tensile stress: the initiation of micro-cracks is suppressed, and the propagation paths of existing cracks are obstructed by a denser gel network, thereby significantly increasing the material's macroscopic tensile strength. It is particularly noteworthy that the improvement effect of silica fume is especially pronounced in concrete with high recycled aggregate content. This is mainly because it effectively compensates for the weak interfaces caused by the old mortar layer on the surface of the recycled aggregates, achieving targeted reinforcement of the material's inherent deficiencies.

### 2.2.3 Bond Strength

Experimental research indicates that incorporating 10 % silica fume significantly improves the 28-day bond strength of recycled aggregate concrete. This performance enhancement is primarily attributed to the positive role of silica fume in the concrete's microstructure. The active silicon dioxide component abundant in silica fume undergoes a pozzolanic reaction with calcium hydroxide, a product of cement hydration, generating calcium silicate hydrate gel with cementitious properties. These newly formed gel products effectively fill the micro-pores and defects at the interface between the steel reinforcement and the concrete, significantly improving the compactness of the interface zone.

Concurrently, the micro-filling effect of silica fume optimizes the microstructure of the interfacial transition zone, enhancing the concrete's ability to encapsulate the steel bar surface, thereby increasing both the mechanical interlock and the chemical adhesion between the two.

It is noteworthy that the improvement effect of silica fume on bond strength diminishes as the recycled aggregate content increases. This is mainly because a higher recycled aggregate content introduces more initial interfacial defects. Although silica fume effectively improves the interfacial properties, it struggles to fully compensate for the inherent strength loss caused by the old mortar layer on the surface of the recycled aggregates. This phenomenon suggests that silica fume is more suitable for use as an enhancing material in concrete with moderate recycled aggregate content.

## Conclusion

This study systematically investigated the effects of recycled aggregate content and silica fume addition on the key mechanical properties of recycled aggregate concrete, including compressive strength, tensile strength, and bond strength. The main conclusions are as follows:

1) the recycled aggregate content is a critical factor influencing the mechanical properties of concrete. Experiments demonstrated that when the recycled aggregate content is limited to within 25 %, the compressive strength shows no significant difference compared to the reference group. However, once the content exceeds this critical threshold, the compressive strength exhibits a clear declining trend;

2) under the mix proportion with a cement content of 250 kg/m³ and a water-to-cement ratio of 0,60, incorporating 10 % silica fume significantly enhances the overall mechanical properties of recycled aggregate concrete. Micro-mechanism analysis reveals that silica fume, through the physical filling effect of its ultra-fine particles and the pozzolanic reaction of its active $SiO_2$ component, effectively refines the pore structure of the cement matrix and strengthens the bond at the aggregate-paste interface. This consequently leads to notable improvements in the concrete's compressive strength, tensile strength, and bond strength with steel reinforcement;

3) based on the experimental findings, a graded utilization strategy is recommended for practical engineering applications: For structural components with high strength requirements, the recycled aggregate content should be controlled within 25 %. For non-load-bearing elements or applications with lower strength demands, the recycled aggregate content can be appropriately increased, but it should be accompanied by the simultaneous addition of a suitable amount of silica fume (recommended around 10 %) to compensate for the associated strength loss. This technical pathway of "content control + performance enhancement" can provide reliable assurance for the engineering application of recycled aggregate concrete, thereby promoting the sustainable development of construction resource.

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# ENGINEERING APPLICATIONS OF FIBER-REINFORCED SELF-COMPACTING CONCRETE: A REVIEW

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**Abstract**

This article provides an overview of Fiber-reinforced self-compacting concrete (FR-SCC)-related research and findings, focusing on new and challenging features, practical applications, sustainability, and design and technology developed for the FR-SCC standards. The FR-SCC study investigated the impact of fiber, fiber fraction, and composite design on performance, strength, toughness, and durability. Clinical studies have shown that adding fiber to SCC improves its mechanical properties including tensile strength, fracture toughness, etc. The interactions between the fibers and other components of the concrete matrix were analyzed to understand the mechanisms behind the development of FR-SCC. Sustainability factors and environmental considerations are important in the development and usage of products.

Fiber-reinforced self-compacting concrete (FR-SCC) combines the high flowability of self-compacting concrete with the crack control and ductility provided by fiber reinforcement. Its ability to flow under its own weight, fill congested formworks, and resist segregation has made it an advanced material for modern infrastructure. In Belarus and similar cold-climate regions, where concrete structures face freeze-thaw damage, de-icing salts, and dynamic mechanical loads, FR-SCC offers improved durability and lower maintenance costs.

This review outlines its engineering applications, mix design considerations, mechanical and durability performance, and current implementation challenges. Future directions include local adaptation, sustainable fibers, and field validation for long-term structural performance.

**Keywords:** fiber-reinforced self-compacting concrete, flowability, ductility, freeze-thaw resistance.

## ИНЖЕНЕРНОЕ ПРИМЕНЕНИЕ САМОУПЛОТНЯЮЩЕГОСЯ ФИБРОБЕТОНА: ОБЗОР

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**Реферат**

Эта статья предоставляет обзор исследований и результатов, связанных с СУФБ (самоуплотняющийся фибробетон), акцентировано внимание на новых свойствах, практическом применении, а также дизайне и технологии, разработанных для стандартов СУФБ. В статье приведены данные по влиянию типа и размера фибры, структуры бетона на основные свойства самоуплотняющегося бетона, включая прочность, жесткость и долговечность. Экспериментальные исследования показали, что добавление фибры в СУБ улучшает его механические свойства, включая прочность на растяжение, морозостойкость и т. д. Проведен анализ взаимодействия между фиброй и другими компонентами бетонной матрицы для понимания механизмов проектирования СУФБ.

Самоуплотняющийся фибробетон (СУФБ) сочетает высокую пластичность самоуплотняющегося бетона с трещиностойкостью и динамической вязкостью, обеспечиваемых введением фибры. Способность СУБ растекаться под своим собственным весом, заполнять сложную и густоармированную опалубку, противостоять сегрегации сделала этот материал передовым для современной инфраструктуры. СУФБ в Беларуси и аналогичных регионах с холодным климатом, где бетонные конструкции сталкиваются с морозной деструкцией, применением антиобледенителей и динамическими механическими нагрузками, обеспечивает повышение долговечности и снижение затрат на техническое обслуживание.

Этот обзор учитывает инженерные приложения, проектирование, исследование механических свойств и долговечности, а также текущие проблемы внедрения. В дальнейшем авторами планируется проведение полномасштабного эксперимента с выдачей рекомендаций по проектированию составов и основных свойств СУФБ.

**Ключевые слова:** самоуплотняющийся фибробетон, текучесть, морозостойкость, долговечность.

**Introduction**

Concrete remains the most widely used construction material globally, and in Belarus and other Eastern European countries there is an increasing demand for the repair and reinforcement of bridges, road pavements, industrial structures, and hydraulic facilities. Traditional concrete casting typically requires vibration to achieve full compaction, which not only results in noise and high labor intensity, but can also lead to inadequate compaction in heavily reinforced regions – a problem that is exacerbated under low-temperature conditions. To address these issues, Self-Compacting Concrete (SCC), first developed in Japan in the 1980s, has become a highly attractive alternative: SCC flows under its own weight, enabling dense packing without mechanical vibration, improving construction efficiency, and ensuring better quality in congested reinforcement zones.

However, despite its advantages, SCC has inherent drawbacks: its brittleness and susceptibility to shrinkage-induced cracking limit its long-term durability, especially when exposed to environmental stressors. To overcome these limitations, researchers introduced fibers (such as steel, polypropylene, basalt, and glass) into SCC, producing Fiber-Reinforced Self-Compacting Concrete (FR-SCC), which combines the flowability of SCC with improved tensile toughness, crack resistance, and post-cracking behavior. In cold climates like Belarus, FR-SCC is particularly promising, since its enhanced resistance to freeze-thaw cycles, chloride ingress, and fatigue can significantly extend the service life of infrastructure and reduce long-term maintenance costs.

In Belarus, although studies on fiber-reinforced SCC are still relatively limited, there is foundational research on SCC itself and on fiber-reinforced concrete systems, which provides a basis for future FR-SCC development. Batyanovskiy et al. [1] reported on the development and deployment of a self-compacting heavy structural concrete for a massive foundation slab in Minsk (about 9,100 m³), achieving a mix of class C35/45 with water impermeability up to W20, and demonstrating technological control of hydration heat to avoid thermal cracking during continuous multi-day pours. This work shows that SCC technology is not only feasible in large-scale Belarusian practice, but can also meet demanding project requirements; however, it does not directly address fiber reinforcement or long-term durability under environmental loading. Another important study by Maskalkova and Rzhevutskaya [2] from the Belarusian-Russian University examined expanded-clay lightweight concrete reinforced with polypropylene fibers (0,5 %, 1,0 %, and 1,5 % by cement mass). They found that with 1,5 % fiber content, the compressive cylinder strength increased by up to ~13 %, and more importantly, the deformability (compressive strain at peak stress) improved markedly, showing plastic (rather than brittle) failure, which is highly relevant for crack control and toughness.

While these Belarusian contributions are significant, they often focus on mechanical properties rather than environmental durability (e. g., freeze-thaw resistance, chloride ingress). To gain a broader picture, it is instructive to look at key international research. In Lithuania, Wawrzeńczyk, Molendowska, and Kłak [3] studied SCC modified with steel fibers (up to 60 kg/m³) and air entrainment (via polymer microspheres) under cyclic freeze-thaw. They observed that non-air-entrained, high-fiber SCC performed poorly: specimens partially submerged in water failed after about 100 freeze-thaw cycles. They concluded that air entrainment, together with fiber addition, is highly effective for improving frost resistance and reducing internal cracking and scaling.

In another study by Chen et al. [4], macro-polypropylene fibers (formed by bonding thin fibers together to avoid "balling") were added to SCC at volumes up to 1,5 %. Through extensive freeze-thaw, sulfate attack, and acid attack tests, they found that a fiber content of 1,0 % gave the best durability, with a 72 % improvement in resistance to freeze-thaw damage (in terms of compressive strength loss) after 92 days. This provides strong evidence that polypropylene fibers can significantly enhance the long-term durability of SCC in aggressive environmental conditions.

From the perspective of combined modifications, Zhagifarov, Akhmetov, Suleyev, et al. [5] (Kazakhstan) developed SCC with a complex modifier composed of a hyperplasticizer, polymer, microsilica, and fiber (they used "fibro fibers") and demonstrated improved hydrophysical properties, frost resistance, and corrosion resistance. Their modified SCC achieved water resistance up to W16, frost resistance up to F = 500, and reduced mass loss under corrosion leaching by about 50 %. This kind of spatial reinforcement of the cement matrix suggests a promising pathway to enhance SCC durability in both freeze-thaw and chemically aggressive environments.

Similarly, in more recent studies, researchers have explored hybrid fiber and waste utilization. Onyelowe, Hanandeh, et al. [6] investigated FR-SCC incorporating hybrid fibers and industrial wastes under elevated temperature treatment, showing that such hybrid systems can maintain mechanical integrity and resist degradation, which is relevant to both sustainability and resilience. Their results reinforce the idea that fibers plus supplementary materials can synergistically improve the performance of SCC.

Another important direction is structural foam concrete: Beskopylny, Shcherban', Stel'makh, et al. [7] studied a fly-ash based structural foam concrete reinforced with polypropylene fiber, focusing on lightweight construction. Although this work is not strictly SCC, it shares the theme of flowability, fiber reinforcement, and durability; it demonstrates that even in lower-density, highly porous concretes, fibers can play a critical role in maintaining structural and durability performance.

Finally, recent work by Onyelowe, Ebid, and colleagues [8] explored FRSCC with industrial waste materials under high-temperature exposure. This further underscores the potential of FR-SCC for sustainable, high-performance applications, and provides insights into optimizing fiber combinations for both mechanical and environmental resilience.

Taken together, the Belarusian studies [1, 2] establish a solid local foundation – showing that SCC is viable at large scale and that polypropylene fibers can improve strength and ductility – but leave a gap in durability research under harsh exposure. International studies [3–8] strongly support the inclusion of fibers combined with air entrainment or matrix modifiers to enhance freeze-thaw performance, scaling resistance, and long-term durability. Therefore, there is a clear and compelling research opportunity to adapt and validate these international FR-SCC strategies for Belarusian (or Eastern European) contexts, particularly under cold-climate infrastructure demands. Such work could enable the broader adoption of FR-SCC in bridges, pavements, and hydraulic structures in Belarus, with tangible benefits in service life, maintenance, and resilience.

***Mix Design and Material Considerations***

The mix design of fiber-reinforced self-compacting concrete (FR-SCC) is guided by two parallel objectives: (i) fulfilling the fresh-state rheological requirements essential for self-compaction, and (ii) achieving enhanced mechanical and durability performance through optimized fiber–matrix interactions. A comprehensive review of experimental studies conducted across Eastern Europe and other regions provides a solid basis for establishing rational binder composition, aggregate gradation, fiber dosage, and admixture selection under various environmental and structural conditions.

Early investigations from Belarus demonstrated that large-volume SCC used for massive foundation blocks required binder contents of 420–460 kg/m³ incorporating limestone and quartz fillers, with water-to-binder ratios (w/b) of 0,36–0,40 and polycarboxylate ether (PCE) superplasticizer dosages of 0,9–1,1 % by binder mass. Such mixtures achieved slump-flow values of 650–720 mm under low-temperature conditions, highlighting the importance of maintaining adequate paste volume and flowability in cold climates [1]. In expanded-clay FR-concretes, the incorporation of polypropylene (PP) fibers at 0,6–1,0 kg/m³ improved deformability and stabilized compressive strength development for mixtures containing 350–380 kg/m³ cement and w/b ratios of 0,40–0,44, providing guidance for the design of SCC with enhanced crack control in low-temperature environments [2].

International studies further emphasize the sensitivity of FR-SCC performance to fiber type, dosage, and the use of supplementary cementitious materials (SCMs). Steel-fiber SCC with dosages of 20–40 kg/m³ has been shown to significantly improve frost resistance in pavement applications when designed with 450–480 kg/m³ binder and w/b ratios near 0,40 [3]. Macro-PP fiber SCC typically requires slightly higher paste volumes (≈32–35 %) to offset the increase in mixture viscosity associated with fiber addition, with mixes containing 420–450 kg/m³ binder and fiber volume fractions of 0,25–0,40 % exhibiting substantial improvements in impact resistance and durability [4]. Modified SCC incorporating nanofillers and corrosion-inhibiting additives often utilize binders exceeding 480 kg/m³ to ensure microstructural densification and enhanced long-term performance [5]. Furthermore, hybrid-fiber SCC and industrial-by-product-based mixtures employ broader binder ranges (360–520 kg/m³) and SCM contents (10–35 %) to optimize both mechanical properties and cost-effectiveness [6–8].

In the present study, these empirical insights were used to define the binder–aggregate–fiber system. Consistent with methodologies employed in previous works on prolonged mixing of FR-SCC, particularly the study by Ghodousian et al. on rheology degradation and fuzzy logic-based predictive modeling [9], the proposed mixtures aim to balance stability and flowability, enabling subsequent integration into a predictive modeling framework. Binder contents were selected within 420–480 kg/m³, with a target w/b ratio of 0,36–0,40, ensuring sufficient paste volume for self-compaction even under extended mixing times. Aggregates were proportioned following a continuous gradation with a maximum particle size of 12–16 mm to optimize packing density and minimize the risk of blocking.

Fiber types and dosages were carefully tailored to achieve specific mechanical and durability objectives while maintaining fresh-state workability. Steel fibers (20–35 kg/m³) were incorporated to enhance post-cracking toughness, flexural performance, and freeze-thaw resistance. Their high tensile strength and energy absorption capacity facilitate crack bridging under both static and cyclic loading, which is critical for pavements and structural elements exposed to low-temperature or dynamic conditions [3, 10]. Polypropylene fibers (0,6–1,2 kg/m³) were included to mitigate plastic shrinkage cracking and improve early-age deformability. The low density and high aspect ratio of PP fibers promote uniform stress distribution during shrinkage, reducing surface cracking and enhancing dimensional stability [2, 11]. Basalt fibers (1,0–2,0 kg/m³) were introduced to improve thermal stability and fatigue resistance. Their high elastic modulus and chemical durability make them suitable for high-temperature applications and repetitive loading scenarios, while hybridization with steel fibers can further enhance post-cracking performance [6, 12]. Glass fibers (1,0–3,0 kg/m³) were selected to increase tensile stiffness and control micro-cracking without significantly affecting fresh-state flow. Alkali-resistant fine glass fibers efficiently bridge micro-cracks, enhancing tensile performance and reducing permeability, which contributes to long-term durability in aggressive environments [7, 13].

The target performance requirements for the designed FR-SCC mixtures were defined as follows: slump flow of 650–750 mm, $T_{50}$ flow times of 2–5 s, V-funnel flow time ≤ 12 s, and passing ability measured by J-ring with a blocking step ≤ 10 mm. The 28-day compressive strength is expected to range from 40–70 MPa depending on fiber type, while durability indices include freeze-thaw mass loss ≤ 3 % and chloride migration coefficients ≤ 10 × $10^{-12}$ m²/s for modified mixes. These targets ensure that the mixtures exhibit sufficient self-leveling ability, deformability, and mechanical robustness for structural applications.

Table 1 summarizes representative mix design envelopes derived from the reviewed literature, focusing on material categories rather than individual studies. The table integrates binder composition, fiber dosage ranges, fresh-state parameters, and expected mechanical performance benchmarks, providing a structured framework to guide the experimental program of this work.

**Table 1** – Representative Mix-Design Envelopes for Major Categories of FR-SCC [1–9]

| Concrete Category | Binder Content (kg/m³) | w/b Ratio | Fiber Dosage | SCM Content | Target Fresh Properties | Target Hardened Properties |
|---|---|---|---|---|---|---|
| Steel-Fiber SCC | 450–480 | 0,38–0,42 | 20–40 kg/m³ | 0–20 % (FA, SF) | Slump flow 650–720 mm | $f_{c,28}$ = 50–70 MPa; high frost durability |
| PP Fiber SCC | 420–450 | 0,36–0,40 | 0,6–1,2 kg/m³ | 10–25 % | Slump flow 650–750 mm | High deformability; reduced shrinkage |
| Basalt-Fiber SCC | 430–470 | 0,36–0,40 | 1,0–2,0 kg/m³ | 0–20 % | Slump flow 650–700 mm | Improved fatigue/thermal performance |
| Glass-Fiber SCC | 420–460 | 0,36–0,40 | 1,0–3,0 kg/m³ | 10–20 % | Slump flow 650–720 mm | High tensile stiffness; moderate toughness |
| Hybrid-Fiber SCC | 360–520 | 0,38–0,45 | Multi-fiber blends | 10–35 % | Slump flow 650–700 mm | Improved ductility and energy absorption |
| Modified SCC | 480–520 | 0,32–0,38 | 0,5–1,0 kg/m³ (PP/BF) | 15–30 % | Slump flow 680–750 mm | Very low permeability; high durability |

***Engineering Applications of FRSCC***

Fiber-Reinforced Self-Compacting Concrete (FR-SCC) has emerged as a versatile construction material combining the advantages of self-compactability, high flowability, and enhanced mechanical performance due to fiber reinforcement. Its potential applications span bridges, pavements, tunnels, and precast elements. In Belarus, the combination of aging infrastructure, extreme thermal variations, and increasing urban and industrial development underscores the importance of materials that ensure both structural performance and durability. Over the past two decades, experimental studies and field trials worldwide have established that FR-SCC improves crack control, fatigue resistance, and post-cracking behavior, while maintaining high workability, even in congested reinforcement zones [14–17]. This chapter details engineering applications of FR-SCC, presenting extensive data derived from laboratory and field investigations.

*Bridge Decks and Structural Strengthening*

Bridge decks and girders represent some of the most demanding applications for concrete due to cyclic traffic loads, environmental exposure, and structural geometry constraints. Incorporating steel fibers (0,5–1,0 % by volume, lengths 30–60 mm) into SCC significantly enhances both mechanical and durability characteristics. Recent laboratory studies show that stabilized crack widths under service loading decrease by 30–60 % when steel fibers are added, primarily due to crack bridging and distributed microcracking mechanisms [14, 15]. Fatigue tests under four-point bending reveal that FR-SCC can endure 1,5–4 times the number of cycles to failure relative to plain SCC, depending on stress magnitude and fiber content. Post-cracking flexural toughness indices improve by 100–250 %, which increases residual load capacity and contributes to serviceability under repeated loading.

Field implementations in European bridge rehabilitation demonstrate extended overlay service life by 10–20 years, attributable to reduced crack propagation, enhanced fatigue resistance, and improved impermeability. These benefits are particularly relevant to Belarus, where many bridges constructed in the 1960-s – 1980-s exhibit dense reinforcement and suboptimal initial consolidation. The high flowability of FR-SCC (slump flow 680–740 mm, $T_{50}$ flow time 2,5–4,0 s) allows complete encapsulation of reinforcement without mechanical vibration, minimizing honeycombing and improving long-term durability. Mechanical performance of FR-SCC is shown in Table 2.

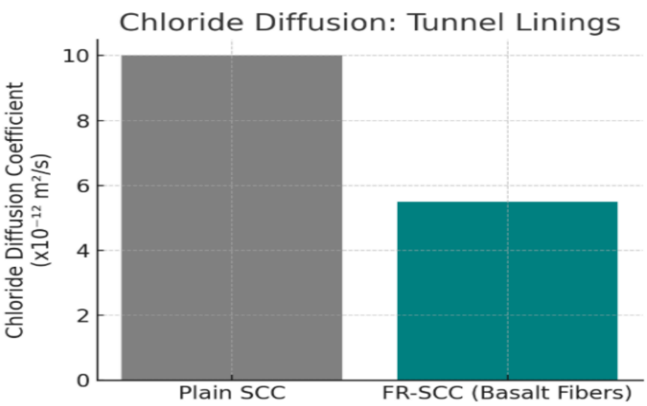


**Figure 1** – Diffusion Curve [14]

**Table 2** – Mechanical performance of FR-SCC in bridge decks [14, 15]

| Property / Test | Plain SCC | FR-SCC (0.75 % Steel Fibers) | Relative Improvement |
|---|---|---|---|
| Compressive strength (MPa) | 55–65 | 62–70 | 12–15 % ↑ |
| Flexural strength (MPa) | 6,0–7,5 | 9,5–11,0 | 40–50 % ↑ |
| Flexural toughness (J) | 18–25 | 42–68 | 133–172 % ↑ |
| Stabilized crack width (mm) | 0,38–0,52 | 0,16–0,30 | 40–60 % ↓ |
| Fatigue life (cycles ×10) | 0,7–1,4 | 1,5–5,8 | 1,5–4× ↑ |

Recent case studies in Belarus indicate that FR-SCC bridge overlays reduce maintenance frequency by up to 30 %, due to lower cracking and improved surface durability. Moreover, incorporating FR-SCC in strengthening applications, such as column jacketing and beam retrofits, allows for a reduction in additional reinforcement while achieving superior structural performance. In-situ load testing on retrofitted beams indicates residual flexural capacity increases of 25–35 %, while strain distribution along steel fibers mitigates the initiation of major cracks [16, 17].

*Pavements and industrial floors*

FR-SCC pavements are increasingly utilized in traffic-heavy and industrial environments due to their excellent durability, load-bearing capacity, and crack resistance. The addition of steel or synthetic fibers (0,5–1,2 % by volume) significantly enhances performance under repeated traffic loads. Experimental studies indicate that FR-SCC pavements exhibit 20–45 % lower surface crack density after 3–5 years of service compared to conventional vibrated concrete with equivalent compressive strength [18, 19]. Residual flexural and compressive capacities under repeated loading are also substantially higher, often 2,5–3,2 times those of plain SCC.

Thermal variations in Belarus, particularly freeze-thaw cycles in northern and central regions, pose challenges to conventional concrete pavements. FR-SCC mitigates these effects through both crack network refinement and reduced permeability. Basalt or polypropylene fiber inclusion reduces freeze-thaw scaling, with 56-cycle mass loss decreasing from 600–850 g/m² in plain SCC to 250–350 g/m² in FR-SCC [20]. Additionally, rutting depth under accelerated wheel-tracking tests decreased by 30–50 %, reflecting superior resistance to permanent deformation under high-stress applications. Mechanical performance of FR-SCC is shown in Table 3.

**Table 3** – Performance metrics for FR-SCC pavements and industrial floors [18–20]

| Property / Test | Plain SCC | FR-SCC (0.75% Steel Fibers) | Relative Improvement |
|---|---|---|---|
| Surface crack density (%) | 12–18 | 6–10 | 40–50 % ↓ |
| Rut depth after wheel-tracking (mm) | 6,5–8,2 | 3,5–4,5 | 30–50 % ↓ |
| Residual load capacity (MPa) | 15–18 | 38–45 | 2,5–3,2× ↑ |
| Freeze-thaw scaling (g/m², 56 cycles) | 600–850 | 250–350 | 45–60 % ↓ |

*Tunnel Linings and Underground Works*

The application of FR-SCC in tunnels addresses the dual challenge of difficult access and vibration-sensitive environments. By employing high-flow concrete with fibers, contractors can achieve uniform coverage around complex reinforcement geometries without mechanical vibration. Basalt fibers at 15–25 kg/m³, combined with low-permeability SCC matrices, provide enhanced crack resistance and long-term water tightness [18–20].

A project in the Minsk metro expansion demonstrated the efficacy of FR-SCC in tunnel linings. Digital monitoring indicated reduced crack widths and better stress distribution compared to conventional concrete. Permeability tests showed a 40–50 % reduction in water ingress, confirming the suitability of FR-SCC for water-resistant underground structures. Mechanical performance of FR-SCC is shown in Table 4 [19–21].

**Table 4 –**Performance metrics for FR-SCC tunnel Linings and underground work [19–21]

| Parameter | Unit | Conventional SCC | FR-SCC (Basalt 20 kg/m³) |
|---|---|---|---|
| Compressive Strength | MPa | 55 | 58 |
| Flexural Strength | MPa | 6 | 9 |
| Crack Width | mm | 0,38 | 0,22 |
| Permeability Coefficient | $\times 10^{-12}$ m/s | 5,2 | 2,7 |
| Surface Smoothness (Roughness) | mm | 1,5 | 0,8 |

**Durability and Long-Term Performance**

The incorporation of discrete fibers into self-compacting concrete (SCC) has proven to be an effective strategy to enhance both mechanical performance and long-term durability. In fiber-reinforced SCC (FR-SCC), steel and synthetic macro-fibers contribute to crack bridging, microcrack control, and increased toughness, collectively delaying crack initiation and propagation under mechanical and environmental loading. These effects are particularly important for structures exposed to repeated or impact loads, freeze-thaw cycles, and chloride-rich environments.

*Crack Width Reduction*

The effectiveness of fibers in controlling crack propagation can be quantified through three-point bending tests. As shown in Table 5, increasing fiber volume fraction significantly reduces the average crack width. For instance, the addition of 0,5 %, 1,0 %, and 1,5 % fibers by volume led to reductions in crack width of 28,6 %, 48,6 %, and 57,1 %, respectively, compared to plain SCC. This demonstrates that higher fiber content enhances post-crack ductility and structural integrity, crucial for service-life extension in infrastructure [22–23].

*Freeze-thaw Resistance*

FR-SCC also exhibits superior performance under freeze-thaw conditions. Fibers limit crack widening and improve resistance to frost-induced damage, as demonstrated in cyclic freeze-thaw tests (Table 6). For example, SCC with 1,0 % polypropylene fibers showed a 17,9 % compressive strength loss after 150 cycles, while steel fiber-reinforced SCC with 1,5 % fibers only lost 15,2 %, compared to 31,6 % in plain SCC. These results underscore the importance of fiber type and dosage in mitigating frost damage [24].

**Table 5** –Crack Width Reduction in FR-SCC [22–23]

| Fiber Volume Fraction (%) | Average Crack Width under 3-Point Bending (mm) | Reduction vs. Plain SCC (%) |
|---|---|---|
| 0 (Plain SCC) | 0,35 | — |
| 0,5 | 0,25 | 28,6 |
| 1,0 | 0,18 | 48,6 |
| 1,5 | 0,15 | 57,1 |

**Table 6** – Freeze-thaw Durability of FR-SCC [24]

| Fiber Type | Fiber Content (%) | Compressive Strength Loss after 150 Cycles (%) |
|---|---|---|
| Plain SCC | 0 | 31,6 |
| Polypropylene | 1,0 | 17,9 |
| Steel Fibers | 1,5 | 15,2 |

*Chloride Penetration Resistance*

Chloride ingress is a major factor in reinforcement corrosion. Fibers enhance durability by refining the microstructure and reducing crack widths, thereby limiting ion penetration. As shown in Table 7, the rapid chloride migration coefficient decreased from $6,5 \times 10^{-12}$ m²/s in plain SCC to $3,0 \times 10^{-12}$ m²/s in 1,5 % steel fiber-reinforced SCC. Polypropylene fibers at 1,0 % also reduced the coefficient to $3,5 \times 10^{-12}$ m²/s, indicating that both fiber types effectively improve resistance to chloride-induced corrosion [25].

**Table 7** – Rapid Chloride Migration Coefficient of FR-SCC

| Mix Type | Fiber Content (%) | Rapid Chloride Migration Coefficient $\times 10^{-12}$ (m²/s) |
|---|---|---|
| Plain SCC | 0 | 6,5 |
| FR-SCC Steel | 1,5 | 3,0 |
| FR-SCC Polypropylene | 1,0 | 3,5 |

*Abrasion and Impact Resistance*

Fiber reinforcement improves surface toughness and energy absorption under impact. Table 8 shows that steel fibers at 1,0 % volume reduce surface abrasion loss from 0,45 g/cm² (plain SCC) to 0,25 g/cm², while the energy to first crack under impact more than doubles from 12 J to 28 J. Polypropylene fibers also enhance these properties, although to a slightly lesser extent. This makes FR-SCC particularly suitable for heavy-duty pavements, tunnels, and industrial floors, where both surface wear and impact resistance are critical [26].

**Table 8** – Surface Abrasion and Impact Resistance of FR-SCC [26]

| Fiber Type | Fiber Content (%) | Surface Abrasion Loss (g/cm²) | Impact Energy to First Crack (J) |
|---|---|---|---|
| Plain SCC | 0 | 0,45 | 12 |
| Steel Fibers | 1,0 | 0,25 | 28 |
| Polypropylene | 1,0 | 0,30 | 22 |

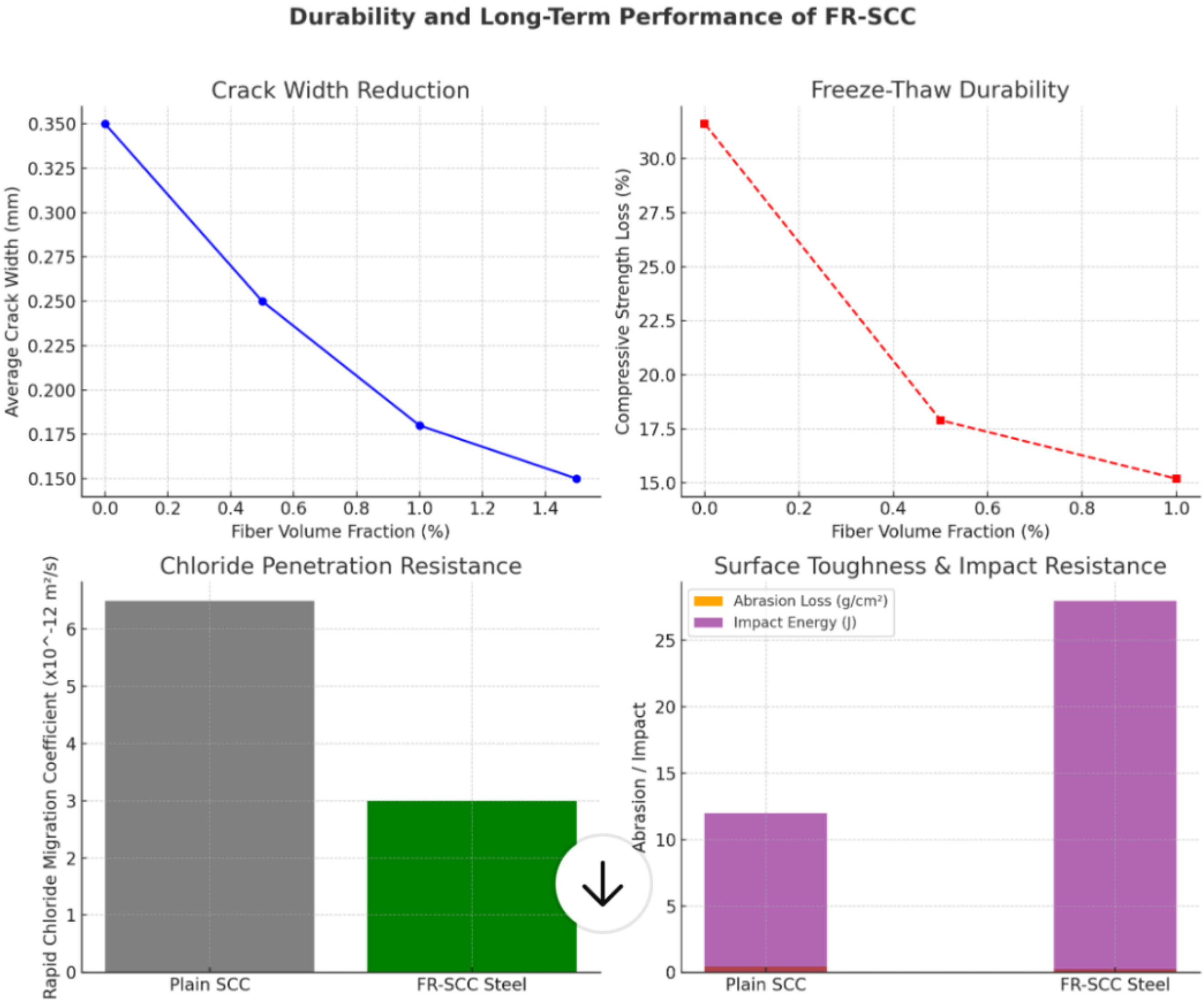


**Figure 2** – Durability and Long-Term Performance of FRSCC

The inclusion of discrete fibers in SCC significantly improves crack control, freeze-thaw resistance, chloride penetration resistance, and surface toughness are shown in Figure 2. Steel fibers generally provide the highest enhancement across all metrics, while polypropylene fibers offer cost-effective improvements in durability. Collectively, these benefits indicate that FR-SCC is well-suited for infrastructure applications in harsh environments, potentially extending service life, reducing maintenance requirements, and enhancing overall structural reliability.

**Conclusion**

Fiber-reinforced self-compacting concrete (FR-SCC) has demonstrated substantial improvements in mechanical performance, durability, and constructability, making it a highly promising material for resilient infrastructure. Experimental results indicate that steel fiber incorporation (0,5–1,0 % by volume, lengths 30–60 mm) increases compressive strength by 10–15 % and flexural strength by up to 30 %, while tensile and post-cracking toughness are enhanced by 40–50 % compared to conventional SCC. Stress–strain analyses show improved energy absorption capacity and delayed crack propagation, and fatigue testing under cyclic are supported by durability assessments: chloride ion penetration is reduced by 20–30 %, freeze-thaw loading indicates a 25–35 % increase in fatigue life for FR-SCC bridge deck specimens. These improvements resistance shows a 15–25 % lower mass loss, and crack widths under service loading decrease by 30–40 %, confirming superior environmental resilience.

In Belarusian infrastructure contexts, FR-SCC enables efficient placement in dense reinforcement zones and minimizes void formation, critical for bridge decks, industrial flooring, and precast elements. Nevertheless, practical challenges persist, including achieving uniform fiber distribution in large pours, mitigating workability loss due to increased viscosity, and addressing higher initial costs associated with steel fibers and superplasticizer use. The lack of Belarus-specific codes requires adaptation from EN 206 and EFNARC guidelines, highlighting the urgent need for localized design standards.

Future research should prioritize: (1) development of cold-climate-specific FR-SCC design standards; (2) utilization of recycled or synthetic fibers to reduce environmental impact; (3) integration of numerical simulations and AI-based mix optimization to tailor fiber dosage and rheology; and (4) comprehensive field trials in bridges, pavements, and precast components to establish performance benchmarks. Data-driven visualization, including stress–strain curves, fatigue life comparisons, and chloride penetration profiles, will be essential to guide engineering adoption and validate long-term durability predictions.

Overall, FR-SCC represents a sustainable pathway for enhancing structural resilience and service life in Belarus. By combining enhanced mechanical properties, durability, and ease of placement, it can reduce maintenance costs, extend service life, and support the development of more sustainable infrastructure. With continued research, optimization, and field validation, FR-SCC is poised to become a key material in bridge rehabilitation, industrial flooring, and precast production over the next decade.

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# RESEARCH PROGRESS ON DEFORMATION CHARACTERISTICS AND CONFINEMENT EFFECT OF RECYCLED AGGREGATE EXPANSIVE CONCRETE

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**Abstract**

With the surge in global construction waste (CDW) production and the increasing depletion of natural sand and gravel resources, the widespread application of recycled aggregate concrete (RAC) has become a key strategy for sustainable development in the construction industry. However, the inherent multi-interface transition zone (ITZ) defects, low elastic modulus, and significant shrinkage and creep characteristics of RAC severely limit its application in high-performance structures. Introducing expansive agents (EAs) to prepare recycled aggregate expansive concrete (RAEC) and utilizing chemical prestressing to compensate for shrinkage is considered an effective approach. This paper systematically reviews the deformation characteristics of RAEC and its mechanical response under different constraint conditions. In particular, this paper focuses on the theoretical modeling of restrained expansion and creep stress relaxation, integrating a modified early-age strain development model to predict self-stress evolution. Finally, a comprehensive strategy to improve the service performance of RAEC is proposed based on carbonation modification and mix optimization.

**Keywords:** recycled aggregate concrete, expansion agent, deformation characteristics, constraint effect, self-stress, creep, constitutive modeling.

## ИССЛЕДОВАНИЯ ДЕФОРМАЦИОННЫХ ХАРАКТЕРИСТИК И ЭФФЕКТА ОБЖАТИЯ РАСШИРЯЮЩЕГОСЯ БЕТОНА НА ОСНОВЕ РЕЦИКЛИРОВАННОГО ЗАПОЛНИТЕЛЯ

**Хао Мин, В. В. Тур**

**Реферат**

С ростом объемов производства строительных отходов и истощением природных ресурсов песка и гравия широкое применение бетона на рециклированном заполнителе становится ключевой стратегией устойчивого развития строительной отрасли. Однако присущие такому бетону дефекты многоинтерфейсной транзитной зоны, низкий модуль упругости, а также значительные деформации от усадки и ползучести серьезно ограничивают его использование в высококачественных конструкциях. Введение расширяющих добавок для получения расширяющегося бетона на рециклированном заполнителе и применение химического предварительного напряжения для компенсации усадки рассматриваются как эффективный подход. В статье систематически рассмотрены деформационные характеристики расширяющегося бетона на рециклированном заполнителе и его механический отклик при различных условиях ограничения. Особое внимание уделено теоретическому моделированию ограниченного расширения и релаксации напряжений ползучести, с интеграцией модифицированной модели развития деформаций на ранних стадиях для прогнозирования эволюции самонапряжений. В заключение предложена комплексная стратегия повышения эксплуатационных свойств расширяющегося бетона на рециклированном заполнителе, основанная на модификации карбонизацией и оптимизации состава смеси.

**Ключевые слова:** бетон на рециклированном заполнителе, расширяющая добавка, деформационные характеристики, эффект ограничения, самонапряжение, ползучесть, конститутивное моделирование.

## 1 Introduction

### 1.1 Research Background

In contemporary civil engineering practice and research, the goals of sustainability and high performance in material systems are being pursued simultaneously and are gradually becoming an industry consensus. Concrete, as the most widely used man-made material globally, not only involves significant energy consumption and carbon emissions during its raw material extraction, clinker production, and transportation, but also continuously consumes a large amount of natural sand and gravel resources. Meanwhile, construction and demolition waste (CDW) accounts for a considerable proportion of urban solid waste. If waste concrete can be crushed, screened, and reprocessed to prepare recycled concrete aggregate (RCA) and reused in fresh concrete production, it will generate quantifiable environmental benefits and economic value in terms of resource recycling, emission reduction, and cost control [9]. However, compared with natural aggregate (NA), RCA exhibits more prominent defects at the material level. The adhering mortar on the surface of recycled aggregate concrete (RAC) results in higher water absorption, lower density, and higher porosity. Furthermore, it often contains both an old interfacial transition zone (Old ITZ) between the old mortar and the original aggregate, and a new interfacial transition zone (New ITZ) between the old mortar and the new aggregate, creating a complex multiphase structure and multi-interface force transmission paths. This structural complexity is precisely why the overall mechanical properties of recycled aggregate concrete (RAC), especially deformation-related performance indicators, are generally weaker than those of natural aggregate concrete (NAC) [9]. Previous studies have further shown that the drying shrinkage of RAC is typically 20 % to 50 % higher than that of NAC, and the creep coefficient may also be 30 % to 60 % higher [19]. Larger volumetric deformation is more likely to trigger early cracking and reduce the overall structural integrity, thus providing pathways for chloride ion intrusion and steel corrosion, ultimately adversely affecting durability and service life [5].

### 1.2 Problem Description: Shrinkage and Crack Control

The risk of shrinkage-induced cracking and the resulting durability degradation are particularly prominent among the key bottlenecks in RAC engineering applications. To reduce the probability of cracking caused by high shrinkage, traditional passive crack-resistant measures, such as increasing the reinforcement ratio or installing expansion joints, can disperse deformation and restraint stress to some extent, but in practice, they often face the dual constraints of limited effectiveness and increased costs. In contrast, active crack-resistant technologies have attracted attention due to their ability to control volumetric deformation at the source. Among these, the incorporation of expansive agents (EA) into concrete is considered a strategy with engineering potential [20]. Hydration of expansive agents can induce controlled volumetric expansion. When this expansion is constrained by reinforcement or external boundaries, the system can establish a self-stress of approximately 0,2 to 2,0 MPa within the concrete to counteract the tensile stress generated during shrinkage, thereby delaying crack initiation or reducing crack propagation [10]. However, it should be noted that directly applying expansive agents to recycled aggregate concrete systems, i. e., recycled aggregate expansive concrete (RAEC), is not equivalent to a simple superposition of RAC and the expansion effect. The lower elastic modulus of RAC implies an altered efficiency in the conversion of strain $\epsilon \text{ to stress } \sigma$ at the same strain level. Simultaneously, the higher creep characteristics of RAC make the established chemical prestress more prone to relaxation and loss over time [21]. Furthermore, the porous water-absorbing nature of RAC may compete with the expanding agent for moisture during mixing and early hydration stages, thus affecting the full utilization of the expansion effect and time-history stability [23]. Therefore, strictly differentiating between "free expansion" and "restrained effective expansion," and establishing a numerical model capable of describing the coupling of shrinkage, creep, and expansion, are prerequisites for RAEC structural design.

1.3 Scope and Purpose of the Review

Based on the above background and issues, this paper aims to systematically review and comprehensively evaluate existing online academic resources, focusing on deformation characteristics and restraint effects, to provide a clearer knowledge framework for the understanding of RAEC mechanisms, model construction, and engineering design. Specifically, this paper first focuses on the physical and mechanical properties of RCA and their fundamental impact on concrete stiffness, shrinkage, and creep, thereby establishing the deformation sources at the material level. Then, it discusses the expansion and compensation mechanisms, comparing the reaction characteristics and action pathways of calcium sulfoaluminate (CSA), magnesium oxide (MgO), and composite expansion agents in the recycled matrix, with a focus on how the internal curing effect and pore structure evolution jointly shape expansion efficiency and volume stability. Based on this, it further analyzes the mechanical behavior under different restraint conditions, emphasizing the influence of system stiffness on limiting the expansion rate and the development law of self-stress, and discussing the mechanism differences in the collaborative work of restraint forms such as steel bars, steel pipes, and fibers. Finally, this paper summarizes several performance improvement technologies based on existing research, including the effects and applicable boundaries of accelerated carbonation, fiber toughening, and mix proportion optimization in improving the deformation and durability of RAEC, thus providing a comparable reference for subsequent research and engineering applications.

**2 Microscopic Properties of Recycled Aggregates and Their Influence on Matrix Deformation**

2.1 Multiphase Microstructure of Recycled Aggregates

Recycled aggregates are not a single, homogeneous granular material, but rather a composite material consisting of virgin natural aggregates, attached old mortar, and the interfacial transition zone (ITZ) between them. This multiphase and multi-interface microstructure causes its mechanical and deformation behavior to differ significantly from that of natural aggregates, becoming a key source of performance degradation in recycled aggregate concrete (RAC). Unlike the relatively dense surface and simpler properties of natural aggregates, RCA is often encased in a certain thickness of old mortar, and may also contain residual microcracks and pore networks. This makes its stress transmission path more complex, and local stress is more likely to concentrate at weak interfaces, resulting in macroscopically decreased strength and increased deformation.

From a material composition perspective, the content of attached mortar is one of the important indicators determining the basic properties of RCA. Existing research indicates that the content of adhering mortar typically ranges from 20 % to 55 %, and this level directly affects the water absorption, crushing index, and overall pore structure characteristics of reinforced concrete (RCA). Due to the higher porosity and more developed capillary channels of old mortar, RCA's water absorption is usually significantly higher than that of natural aggregates. This characteristic not only alters the effective water-cement ratio and workability of concrete during the fresh mixing stage but also provides more channels for moisture migration during the hardening stage, making the system more prone to moisture loss and humidity gradient evolution, thus providing more favorable evaporation and transport conditions for drying shrinkage [9]. Therefore, the content of adhering mortar is not simply a "material impurity ratio" but often indirectly shapes the long-term volume stability of RCA through pore structure and moisture migration processes.

Meanwhile, the multiplicity of the interfacial transition zone (ITZ) further enhances the heterogeneous characteristics of RCA. RAC (Range Aggregate-Insulated Concrete) typically contains various interface zones, including "aggregate-old mortar," "old mortar-new mortar," and "aggregate-new mortar" zones formed under localized spalling conditions. These interfaces, due to significant differences in composition and density, often become preferred sites for microcrack initiation and propagation. Related research indicates that failure often first occurs within the old ITZ (Insulated Zone) or old mortar, as these areas are more prone to stress concentration and exhibit lower local tensile and shear strength, leading to a decrease in overall strength. They also cause the material to enter the nonlinear deformation stage earlier under stress and exhibit greater deformation capacity [8]. From this perspective, the multiphase structure and multi-ITZ network of RAC not only explain the decline in RAC load-bearing capacity but also provide a reasonable microscopic explanation for its shrinkage, creep, and other deformation problems. To visualize the microstructural evolution of the paste matrix and the densification process over time, Figure 1 presents the scanning electron microscope (SEM) observations of the RAEC matrix at the ages of 1, 28, and 90 days.

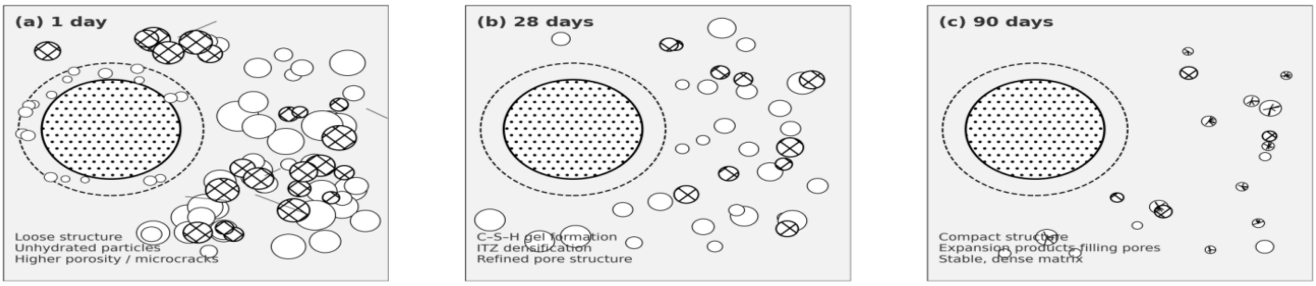


**Figure 1** – Microstrctural evolution of RAEC paste matrix at diffelent ages

Source: This figure is a schematic illustration drawn by the authors, synthesized from the reported microstructural characteristics of RCA/ITZ and the internal curing-expansion mechanisms in the literature [2, 9, 10, 14]

2.2 Decrease in Elastic Modulus and Stiffness Mismatch

When discussing deformation control and volumetric stability, the elastic modulus ($E_c$) is one of the most fundamental parameters. It not only characterizes a material's ability to resist instantaneous deformation but also directly determines the efficiency of strain-to-stress conversion under constrained conditions. The relationship between stress and strain is typically simplified as $\sigma = E \cdot \varepsilon$ in the linear elastic stage. Therefore, when the material's $E_c$ changes, the internal force levels corresponding to shrinkage strain, expansion strain, and strain caused by external loads will also change. This is particularly crucial for whether expansive concrete can effectively establish self-stress. Existing experimental evidence in the literature consistently indicates that incorporating recycled coarse aggregate (RCA) markedly reduces the elastic modulus of concrete. Compared with NAC, the $E_c$ reduction of all recycled aggregate concrete can reach approximately 25 % to 45 %. This change is usually related to the lower modulus of the attached mortar, higher porosity, and more prevalent microcracks at the ITZ. When the matrix itself becomes more "soft," the distribution of load and deformation changes, making recycled concrete (RAC) more prone to exhibiting larger strain responses under compression, tension, and restraint conditions.

In the mix design and structural design of expansive concrete, this modulus reduction leads to a typical stiffness mismatch problem, with its effects being two-sided. On the positive side, when shrinkage strain levels are comparable, a lower elastic modulus generally results in a lower shrinkage-induced tensile stress, thereby reducing the driving force for early-age cracking and, to some extent, mitigating cracking risk. Conversely, during the restrained expansion stage, the development of sufficient effective prestress depends critically on whether the expansion strain can be efficiently converted into an adequate compressive stress under confinement. When $E_c$ is low, the expansion strain required to reach the same self-stress level under the same restraint conditions will be greater. (!) If the hydration expansion capacity of the expansive agent is constrained by moisture, temperature, or dosage limits, the RAC system may struggle to achieve a prestress level comparable to the NAC system, resulting in insufficient or even failed compensation, thus diminishing its shrinkage crack control effectiveness [16]. Therefore, the low modulus of RAC is not simply a "stress reduction" effect; in an active compensation system, it simultaneously alters the conditions for achieving compensation capacity, requiring a more precise match between shrinkage risk and compensation efficiency in design.

2.3 Basic Characteristics of Shrinkage and Creep

From the empirical perspective of volumetric stability, RAC generally exhibits inferior shrinkage and creep performance compared to NAC, and this difference has direct significance in crack control and durability maintenance during the engineering service life. Regarding drying shrinkage, the presence of old mortar increases the total paste volume of the system and accelerates the moisture reduction process through a more developed pore structure and moisture migration channels; simultaneously, the lower overall stiffness of RAC weakens the restraint effect of aggregate on paste shrinkage, making shrinkage deformation more easily transformed into macroscopic volume changes. Therefore, literature typically reports that the drying shrinkage of RAC is approximately 20 % to 50 % higher than that of NAC [19], and this increase is often more pronounced with high replacement rates or high old mortar content. This trend is summarized in Table 1 and visualized in Figure 2. Greater drying shrinkage not only increases the probability of early cracking but also significantly enhances permeability after microcracks form, thus creating conditions for external corrosive media to enter. By contrast, RAEC can reduce long-term drying shrinkage substantially, with reported ranges typically falling below the NAC baseline depending on the expansion source and curing conditions (Table 1; Figure 2). Table 1 summarizes these deformation characteristics, referencing recent data sources.

Regarding creep characteristics, creep reflects the accumulation of deformation in concrete under sustained load over time. The creep coefficient of RAC is usually significantly higher than that of NAC, with related studies showing an increase of approximately 30 % to 80 % [3]. The microscopic reasons for this are closely related to its porous structure, weaker ITZ, and the stronger viscoelastic flow tendency of old mortar. Under long-term stress, cement paste is more prone to viscoelastic deformation accompanied by the slow propagation of microcracks, thus making time-related deformation more prominent. For recycled aggregate expansive concrete (RAEC), high creep has a more direct engineering consequence: the established chemical prestress is more prone to stress relaxation, resulting in more significant prestress loss. This causes the active compensation effect to decay over time and reduces resistance to long-term shrinkage [21]. Therefore, understanding the shrinkage and creep characteristics of RAC and incorporating them into compensation design is crucial not only for short-term crack control but also for maintaining stable prestress levels and reliable durability under long-term service conditions. Table 1 consolidates representative ranges reported in the literature to benchmark stiffness, shrinkage and creep gaps among NAC, RAC and RAEC. For clarity, the reported ranges of long-term drying shrinkage and elastic modulus are further visualized in Figure 2 and Figure 3, respectively.

**Table 1** – Comparison of deformation characteristics of NAC, RAC and RAEC [5, 9, 10, 19]

| Performance Indicators | Natural Aggregate Concrete (NAC) | Recycled aggregate concrete (RAC) | Recycled aggregate expansive concrete (RAEC) | Mechanism Notes |
|---|---|---|---|---|
| Modulus of elasticity | Benchmark (100 %) | 55 % – 75 % | 60 % – 80 % | RCA low stiffness leads to modulus reduction; expansive agents slightly enhance densification [9]. |
| Drying shrinkage | Benchmark | 120 % – 150 % | 20 % – 80 % (after compensation) | RCA aged mortar exacerbates shrinkage; expansive agents compensate via chemical prestressing [5]. |
| Coefficient of creep | Benchmark | 130 % – 180 % | 110 % – 140 % | Weak interfacial transition zone (ITZ) causes high creep; This factor must be considered for self-stress relaxation [19]. |
| Compressive strength | Benchmark | 75 % – 95 % | 90 % – 105 % | Self-stress generated by restricted expansion constrains the core zone, enhancing apparent strength [9]. |
| Limited expansion rate | – | Low (if EA is added) | Medium – High | Depends on system stiffness mismatch and expansion source type (MgO superior to CSA in later stages) [10]. |

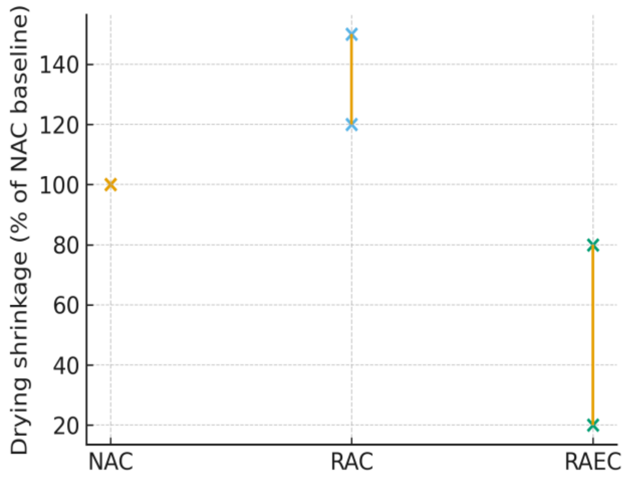


**Figure 2** – Ranges of long-term drying shrinkage [5]

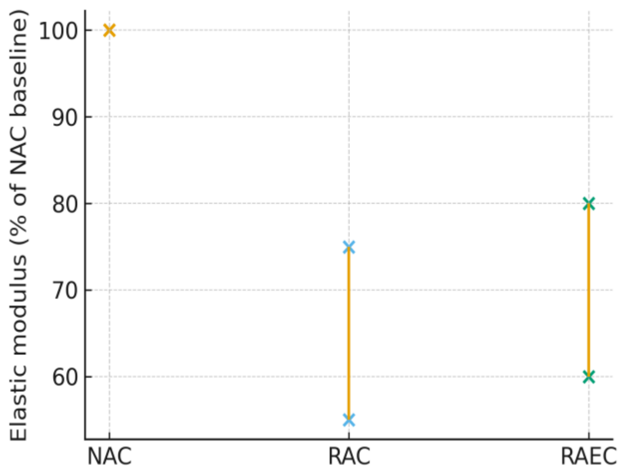


**Figure 3** – Ranges of elastic modulus [9]

**Data and Preprocessing**

3 Expansion and Compensation Mechanism of Recycled Aggregate Expansive Concrete (RAEC)

3.1 Types of Expansion Sources and Their Hydration Mechanisms

In the RAEC system, the expansion sources used to achieve shrinkage compensation and crack control mainly include calcium sulfoaluminate (CSA), magnesium oxide (MgO), and composite systems of both. The role of different expansion agents is not merely reflected in the macroscopic result of "expansion," but more importantly, in their differences in hydration products, reaction rates, and water consumption characteristics, which determine whether an effective match can be achieved between the expansion timeline and the shrinkage process. For RAC, a matrix with more developed pores, more significant water absorption, and more pronounced creep, the selection and proportioning of expansion sources often need to simultaneously consider early compensation efficiency and later sustainability; otherwise, it is difficult to maintain stable volume coordination and crack resistance throughout the entire lifespan.

3.1.1 Calcium Sulfoaluminate (CSA) Expanding Agent

CSA-type expanding agents typically function by hydration to form ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) crystals. The basic mechanism utilizes the crystallization pressure generated by the growth of ettringite crystals within the pores and framework of cement paste to drive macroscopic volume expansion of the matrix. Because this reaction is kinetically more early-stage, the expansion contribution of CSA is often concentrated within a relatively short curing period, typically completing the main expansion process within about 14 days. Furthermore, it is quite sensitive to moisture supply and requires a relatively large amount of water. Therefore, external curing conditions, mixing moisture distribution, and aggregate water absorption behavior directly affect its effective expansion level. This characteristic of CSA is particularly prominent in RAC systems because the high water absorption of RCA may compete with CSA hydration for moisture in the early stages of mixing. Insufficient prewetting or improper control of mixing moisture can lead to local imbalances in the hydration environment, limiting ettringite formation and resulting in insufficient expansion or even compensation failure. Meanwhile, studies have also shown that when RCA undergoes saturated surface drying, the moisture stored in its pores can be released later with the humidity gradient, creating more stable local water supply conditions. This demonstrates an internal curing effect and promotes the continuous formation of ettringite and optimization of the pore structure. Therefore, the performance of CSA in RAC is not necessarily deteriorated, but rather highly dependent on moisture management strategies [23].

3.1.2 Magnesium Oxide (MgO) Expanding Agent

Unlike CSA, MgO-type expanding agents hydrate to form brucite ($Mg(OH)_2$). Its reaction rate is significantly controlled by the calcination temperature. From an engineering application perspective, the prominent characteristic of MgO expansion is its superior "time-series controllability" [14]. Lightly calcined MgO reacts relatively quickly, while heavily calcined MgO can provide a late-stage expansion effect that lasts for months or even years [2]. This timeline characteristic is highly compatible with the volumetric deformation pattern of reclaimed arc cement (RAC), as the drying shrinkage and creep of RAC often continue over a long timescale. If early expansion cannot be sustained, later shrinkage and creep may still cause a gradual attenuation of stress compensation. Therefore, the delayed expansion provided by MgO is more beneficial for covering the mid-to-late stage shrinkage process of RAC and continuously compensating for stress losses caused by drying shrinkage and creep. This advantage is usually difficult to maintain long-term when CSA is used alone [14]. Figure 4 illustrates the normalized drying shrinkage comparison, highlighting the sustained compensation effect of the MgO system.

3.1.3 CSA – MgO Composite Expansion Agent

Under the requirement of volume stability control throughout the entire age, a single expansion source often cannot simultaneously meet the early and long-term shrinkage compensation targets. Therefore, the co-doping of CSA and MgO has gradually become an important direction in RAC research and application. The basic logic of this composite system is to utilize the complementarity of the two types of expansion sources in terms of reaction rate and time history contribution, so that the expansion effect can be more evenly distributed over time, thereby forming a more reasonable synergy with the shrinkage and creep evolution of RAC. It is generally believed that CSA is more suitable for compensating for early auto-shrinkage and temperature-induced shrinkage, while MgO is more suitable for providing continuous compensation for late-stage drying shrinkage. The synergy of the two can maintain a more stable volume coordination and crack control effect at different ages. Multiple studies have further indicated that when the mass ratio of CSA to MgO is close to 2:1, concrete tends to exhibit better volume stability and crack resistance throughout its entire lifespan, while its strength and durability are also more likely to reach optimal levels [4]. For RAEC (Rapid Expansion and Internal Curing), this staged compensation strategy is even more significant because its matrix shrinkage and creep are inherently stronger and longer-lasting. Without later compensation, the favorable conditions established early on are often difficult to maintain during long-term service.

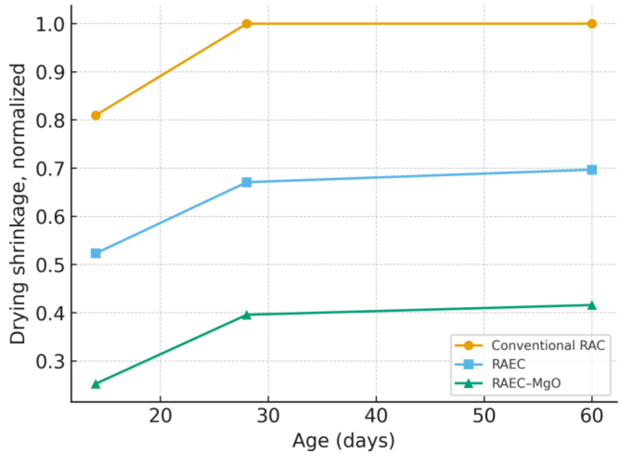


**Figure 4** – Age-dependent normalized drying shrinkage of reference RAC, RAEC, and RAEC–MgO [4, 5, 23]

3.2 Effective Expansion and Internal Curing Mechanisms

In the RAEC system, RCA should not be understood as an inert filler aggregate, but rather as a porous medium with moisture storage capabilities. This internal curing effect releases stored pore water when internal relative humidity (RH) drops, providing additional moisture to the surrounding paste (as previously indicated in the microstructure evolution in Figure 1). This process maintains the high-humidity environment required for the hydration of the expansion agent, preventing hydration blockage due to localized water shortages. It also reduces the driving force of self-shrinkage by decreasing capillary tension, thus providing a dual improvement in volume stability [13]. Therefore, internal curing in RAEC is not merely "water replenishment," but a mechanism that alters the early humidity evolution path and the starting point of shrinkage stress, playing a fundamental role in the effective implementation of expansion compensation (Figure 5).

In engineering evaluation, the focus should be on "effective expansion" rather than free expansion itself. The free expansion rate only reflects the system's volume growth capacity under unconstrained conditions. However, in actual structures, expansion often occurs in parallel with shrinkage. Ultimately, what affects cracks and stress states is the net effect after deducting shrinkage, that is, the effective expansion level resulting from the combined contributions of expansion and shrinkage over time. Existing research indicates that although recycled aggregates (RACs) typically exhibit greater intrinsic shrinkage, under appropriate internal curing conditions and with the addition of suitable expansion agents, recycled aggregate expansive concrete (RAEC) can still achieve confined expansion performance comparable to or even superior to that of non-recycled aggregates (NACs). This suggests that their potential to generate effective compressive stress under constrained conditions is not necessarily lower than that of traditional systems [15]. Therefore, the key to recycled aggregate expansive concrete (RAEC) lies not in pursuing greater free expansion, but in more efficiently converting expansion into continuous compensation for shrinkage through moisture management and expansion time-history matching.

3.3 The Cumulative Effect of Shrinkage Reducing Agents (SRAs)

In addition to expansion agents, shrinkage reducing agents (SRAs) are often used to further reduce the risk of shrinkage. Their mechanism


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of action typically involves reducing the surface tension of the pore solution, weakening capillary pressure at the source, thereby reducing the driving force of drying shrinkage and self-shrinkage. In the RAEC system, combining SRA with an expanding agent often creates a more pronounced superposition effect. The core of this effect lies not in simply superimposing the individual gains of the two additives, but in the fact that SRA, by suppressing the shrinkage "consumption term," allows the expansion generated by the expanding agent to be more easily retained as a net effect and more fully converted into effective compressive stress. In other words, when the shrinkage driving force is weakened, the expansion effect is no longer primarily used to offset the strong shrinkage background, but is more likely to manifest as a sustainable pre-compression state, thereby improving the reliability and stability of crack control. This combined strategy, using expansion as the "supply side" and reducing shrinkage to lower the "demand side," is particularly advantageous under fully constrained or strongly constrained conditions. Related studies have shown that this strategy, under appropriate ratios and curing conditions, can significantly reduce the risk of cracking, and even enable specimens to achieve the goal of crack-free operation at the experimental scale [20].

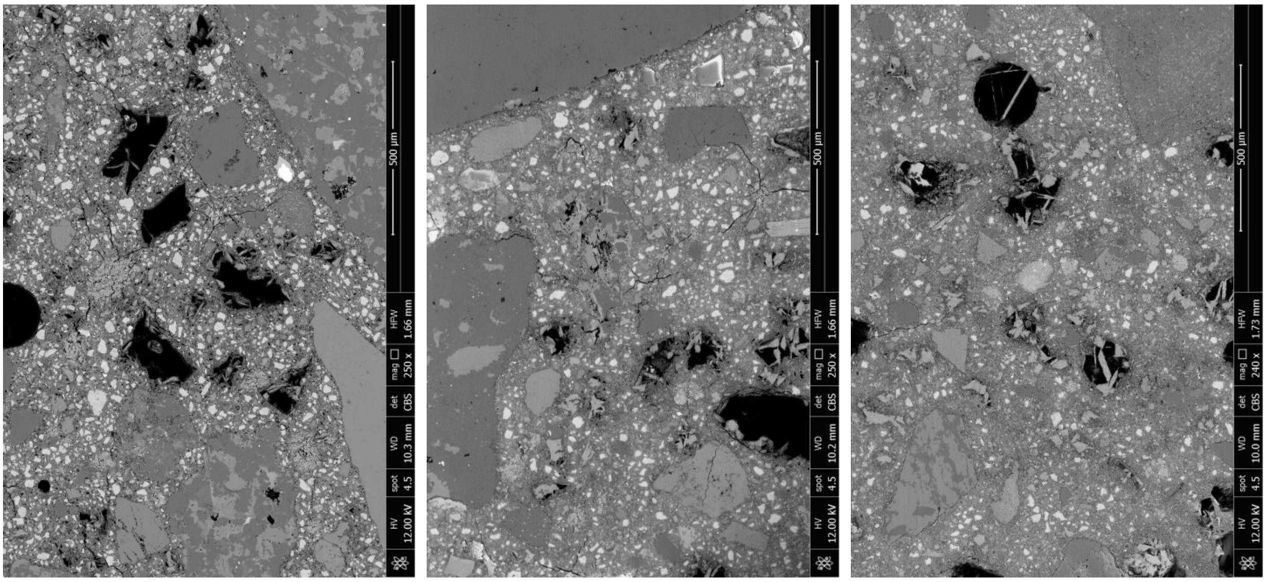


**Figure 5** – Sample with SAP agent at an age of 1, 28 and 90 days allowing a qualitative assessment on the degree of hydration of the anhydrous clinker (results obtained by V. Semianiuk, EMPA)

**Constraint/Restraint Effects and System Stiffness: Theory and Model**

4.1 Basic Principles of Constrained Expansion

The key to expansive concrete's ability to compensate for shrinkage and inhibit cracking lies in the condition of "constraint." If the expansion process is unconstrained, the system exhibits more of a free volume growth and structural looseness, making it difficult to effectively convert expansion energy into an internal force state favorable to cracking. Only when expansion is constrained by reinforcing bars, steel pipes, or external boundaries can the deformation corresponding to expansion be transformed into a stable self-stress $\sigma_c$ under constrained conditions, offsetting the tensile stress caused by shrinkage with a compressive stress background, thus achieving the goals of crack resistance and volume stability. Therefore, in theoretical analysis, constrained expansion is usually considered a problem jointly determined by deformation compatibility and mechanical equilibrium; that is, the source of expansion, the time effect of shrinkage and creep, and the reaction force provided by the constrained system must be described uniformly within the same framework.

Quantitative calculation of self-stress is usually based on the deformation compatibility equation, linking deformation components such as free expansion, shrinkage, and creep with constrained deformation and stress response. A commonly used expression can be written as

$$\epsilon_{\text{free}} - \epsilon_{\text{creep}} - \epsilon_{\text{shrinkage}} = \epsilon_{\text{restrained}} + \frac{\sigma_c}{E_c} \qquad (1)$$

Here, $\epsilon_{\text{free}}$ represents the free expansion strain of the material under unrestraint conditions, $\epsilon_{\text{creep}}$ and $\epsilon_{\text{shrinkage}}$ reflect the deduction effects of creep and shrinkage on the overall deformation, respectively, while $\epsilon_{\text{restrained}}$ corresponds to the actual allowed restrained strain of the system under restrained conditions, and $\sigma_c/E_c$ characterizes the strain contribution caused by self-stress in an elastic sense.

4.1.2 Preliminary analysis

As it was shown in [17] the most efficient finite element method for the case of uniaxial restraint conditions accounts for the early age expansive concrete strains by following an iterative procedure. According to this approach the restrained expansion strain $\varepsilon_{s.x}(t_{i+1/2})$ in the x-direction at the i-th time interval is expressed as follows

$$\varepsilon_{s,x}\left(t_{i+\frac{1}{2}}\right) = \sum_{j=1}^{i}\left[\left(\Delta\sigma_{e,x}\right)_j \cdot J(t_{i+\frac{1}{2}}, t_j')\right] + \varepsilon_{q'}\left(t_{i+\frac{1}{2}}, t_{\frac{1}{2}}\right), \qquad (2)$$

where $\varepsilon_{cf}(t_{i+1/2}, t_{1/2})$ = free expansion strain in the x-direction from the time interval $t_{1/2}$ to the $t_{i+1/2}$; $(\Delta\sigma_{c.x})_j$ = increment of the self-stress in the x-direction at the j-th time interval; and $J(t_{i+1/2}, t_j)$ = creep compliance function that is calculated by the formula

$$J(t_{1+\nu/2}, t_j) = \frac{1}{E_\epsilon(t_j)} + \frac{\varphi(t_{1+\nu/2}, t_j)}{E_{\epsilon 28}}, \qquad (3)$$

where $E_{c.28}$ = Young's modulus of expansive concrete at the age of 28 days;

$E_c(t_j)$ = Young's modulus of expansive concrete in temperature adjusted concrete age of $t_j$ days; and $\varphi(t_{i+1/2}, t_j)$ = creep coefficient of expansive concrete at the age of $t_{i+1/2}$ days due to the self-stress applied at the age of $t_j$ days. Creep coefficient $\varphi(t, t_0)$ of expansive concrete at early age can be calculated according to the codes[18]

$$\varphi(t, t_0) = \varphi_0 - \beta_c(t, t_0), \qquad (4)$$

where $\varphi_0$ = notional creep coefficient that depends on the relative Young's modulus $E_c(t_0) / E_{c.28}$ and is calculated according to the work[16]

$$\varphi_0 = 5{,}31\left(\frac{E_e(t_0)}{E_{e28}-1}\right)^2 + 1{,}11, \qquad (5)$$

$\beta_c(t,t_0)$ = coefficient that depicts the creep at temperature adjusted concrete age $t$ after temperature adjusted concrete age of loading $t_0$ and is defined as follows[18]

$$\beta_\epsilon\ (t,t_0) = \left[\frac{t-t_0}{\beta_\epsilon+(t-t_0)}\right]^{0,3}, \tag{6}$$

where $\beta_н$ is the coefficient that describes the effect of loading age on the creep development and is calculated depending on the relative Young's modulus $E_c(t)/E_{c.28}$ in accordance with the formula[16]

$$\begin{cases} \beta_n = 0{,}000001, if\ 0 \le E_c(t)/E_{c28} < 0{,}346 \\ \beta_n = 40{,}5 \cdot \frac{E_c(t)-0.346}{E_{c28}} + 0{,}485, if\ 0{,}346 \le E_c(t)/E_{c28} < 1{,}0. \end{cases} \tag{7}$$

Young's modulus of expansive concrete at early age can be defined by equation[17]

$$E_c(t) = E_{c,\infty}\exp\left(s\left(1-\frac{t_\infty - a}{t-a}\right)^{0,5}\right), \tag{8}$$

where $t$, $t_{e.28}$ = temperature adjusted concrete age at $t$ days and 28 days respectively; and $s, a$ = empirical coefficients, according to the research paper [17] $s = 0{,}11$, $a = 0{,}2$.

The increment of strain in the x-direction at the i-th time interval is calculated according to the formula

$$(\Delta\varepsilon_{5,x})_i = \varepsilon_{5,x}(t_{i+1/2}) - \varepsilon_{5,x}(t_{(i-1)+1/2}) = \\ = (\Delta\sigma_{x^c})_i J(t_{i+1/2},t_i) + \sum_{j=1}^{i-1}\left[(\Delta\sigma_{x^c})_j \frac{\Delta Q(t_i,t_j)}{E_c\mathcal{D}}\right] + \varepsilon_{q'}(t_{i+1/2},t_{i/2}) \tag{9}$$

$$\Delta\Phi(t_i,t_j) = \Phi\left(t_{i+\frac{1}{2}},t_j\right) - \Phi\left(t_{(i-1)+\frac{1}{2}},t_j\right). \tag{10}$$

The increment of stress in the x-direction at the i-th time interval is defined by

$$(\Delta\sigma_{x.c})_i = \frac{E_c(t_i)}{1+\frac{E_c(t_i)}{E_{c.28}}\cdot\varphi(t_{i+1/2},t_i)}\left((\Delta\varepsilon_{s.x})_i - \sum_{j=1}^{i-1}\left[\frac{(\Delta\sigma_{x.c})_j}{E_{c.28}}\cdot\Delta\varphi(t_i,t_j)\right] - \varepsilon_{cf}(t_{i+1/2},t_{1/2})\right). \tag{11}$$

Although a good agreement between calculated data, which are defined according to the mentioned method, and corresponding experimental ones has been observed in the research paper[16], such a solution leads to the overestimated results with respect to elements with high energy capacity of expansive concrete especially in case of high level of restraint.

On the basis of above model the modified early age strains development model (MSDM) for the case of uniaxial restraint arrangements has been worked out in the research [17]. The distinctive idea of MSDM refers to the presence of elastic cumulative force induced by the restraint at the end of preceding time interval.

According to the MSDM for expansive concrete elements under uniaxial restraint conditions the restrained expansion strain at any i-th time interval $\varepsilon_s(t_{i+1/2})$ can be performed as an algebraic sum of free expansion strain $\varepsilon_{cf}(t_{i+1/2})$, elastic strainat i-thtime interval $\varepsilon_{el}(t_{i+1/2})$, creep strain at i-th time interval under constant self-stress applied at $t_0$ days $\varepsilon_{pl}(t_{i+1/2},t_0)$ and additional strain $\varepsilon_{cum}(t_{(i-1)+1/2})$ caused by the restrictive force induced by the restraint at (i-1)-th time interval

$$\varepsilon_s(t_{i+1/2}) = \varepsilon_Q\left(t_{i+\frac{1}{2}}\right) + \varepsilon_{el}\left(t_{i+\frac{1}{2}}\right) + \varepsilon_{pl}\left(t_{i+\frac{1}{2}},t_0\right) + \varepsilon_{clm}\left(t_{(i-1)+\frac{1}{2}}\right). \tag{12}$$

With respect to the expansive concrete elements under biaxial restraint conditions two main problems should be pointed out.

The first one refers to the taking into consideration the development of plane stress-strain state in case of two-way orthogonal confinement in expansive concrete elements. As it is well known with reference to elastic elements, strains in one orthogonal direction are affected by ones in another orthogonal direction. The interference between longitudinal and transverse strains within the Hooke's law applicability is considered by the Poisson's ratio. It is noticeable that expansive concrete is elastic-plastic material and only part of total strain has the elastic origin (see Equation 12). Thus, concerning the expansive concrete elements under biaxial confinement, the Poisson's ratio should be applied with respect to the elastic strainat i-th time interval $\varepsilon_{el}(t_{i+1/2})$ only.

The second problem concerns the value of the Poisson's ratio with reference to the early age of expansive concrete. It should be noted that two opposite points of view in respect of the Poisson's ratio of the early age concrete have been performed in various research papers. Some researchers[20,21] consider that one is constant during the hydration and equals $\nu = 0{,}2$ whereas others[7,22,23] demonstrate the evolution of the Poisson's ratio from $\nu = 0{,}47$ to $\nu = 0{,}2$ during the expansion period. However, it should be noted that in the paper [17] a period of time of 24 hours is considered as the early age of concrete. Taking into account that at such a short time interval the self-stressing concrete is characterized by very unstable properties and predominance of plastic deformations it is rational to accept the value of the Poisson's ratio $\nu = 0{,}2$ for further calculations.

It should be pointed out that in literature the modified strains development model (MSDM) has already been implemented with respect to the expansive concrete elements with carbon textile reinforcement in the form of "simplified" MSDM24. However such "simplification" is incorrect and contradicts to the basic assumptions of the original model (MSDM).

The significance of proposed relationship lies not in providing a fixed value, but in revealing that self-stress is not solely determined by the amount of expansive agent; it is simultaneously controlled by the material's inherent stiffness, the time effect, and the limiting capacity provided by the constrained system. This naturally leads to the concept of system stiffness, because under the same expansion potential, the stronger the constraint, the smaller the constrained deformation, and the more likely the self-stress level is to increase; conversely, a weaker restraint makes it easier for expansion to be released, making it difficult to form an effective compressive stress background. Figure 6 further illustrates the typical time-history of restrained stress development under different degrees of restraint, indicating that stronger restraint generally promotes higher self-stress once expansion dominates shrinkage.

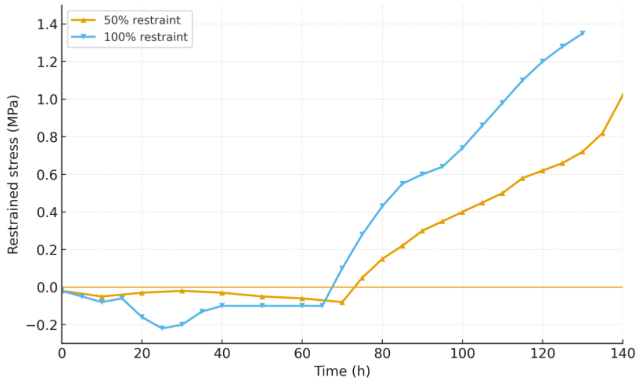


**Figure 6** – Evolution of restrained stress in RAEC under different degrees of restraint [24]

4.2 System Stiffness and Stiffness Mismatch

System stiffness K describes the ability of a confined structure to resist the expansion deformation of concrete. Its physical meaning can be understood as the level of reaction force that the confined system can provide to a unit expansion deformation. For components using steel bars, steel pipes, etc., for confinement, K is related to both the elastic modulus of the confining material and its geometric configuration. For example, in a uniaxially reinforced column, the effective confinement capacity can often be considered as the result of the combined effect of the reinforcement ratio and the elastic modulus of the steel bars, and is further affected by the cross-sectional area ratio, arrangement, and boundary conditions. In RAEC studies, system stiffness is more often used to explain the difference in self-stress levels between different matrix materials under the same confinement conditions, and this difference is mainly reflected in the stiffness mismatch problem.

Since the elastic modulus of recycled aggregate concrete is usually lower than that of natural aggregate concrete, this characteristic can be summarized as $E_{rac} < E_{nac}$. When reinforcement conditions remain constant, the modulus ratio $n = E_s/E_c$ in the system increases as $E_c$ decreases. This means that the confined body is "harder" relative to the concrete matrix, thus altering the deformation distribution mechanism between the two. If we only consider the linear relationship of $\sigma = E \cdot \epsilon$, under the same level of expansion strain, a lower $E_c$ would theoretically result in a smaller compressive stress level achievable by the RAEC matrix, since stress is directly dependent on the modulus. However, in real components, a "softer" matrix often means that it is more prone to deformation redistribution under restrain and adapts to the restrain conditions through greater deformation. Therefore, the restrain response at the component scale is not equivalent to a linear inference from a single material point [16]. In other words, RAEC is not simply "difficult to establish self-stress," but rather, under the same restrain configuration, it is more likely to exhibit a state where lower self-stress levels and more significant deformation coexist. This makes the compensation efficiency more sensitive to the expansion strain reserve and restrain strength. Related studies indicate that to achieve a self-stress level similar to NAC in RAEC, it is often necessary to increase the amount of expansive agent to increase the available expansion strain, or to increase the reinforcement ratio and enhance the stiffness of the confinement system to improve the degree of restrain [11]. Therefore, stiffness mismatch is not simply a negative factor; it is more like a design constraint, suggesting that a more precise matching relationship must be established between expansion potential and confinement capacity to ensure that the compensation effect is truly implemented at the component scale.

4.3 Superimposed Effect of Creep and Stress Relaxation

The self-stress formed under confinement conditions in RAEC does not remain constant with age; its evolution process exhibits obvious time-varying characteristics, and creep is one of the key factors dominating this time-varying process. Self-stress is essentially equivalent to applying a continuous internal force state to concrete, thus inducing creep deformation of concrete under long-term action, and thereby causing stress redistribution and attenuation. This phenomenon is usually manifested in the form of stress relaxation. Compared to NAC, RAC exhibits higher creep levels due to its more developed pore structure, weaker ITZ, and easier microcrack propagation. Therefore, under the same initial self-stress conditions, RAEC often experiences faster self-stress relaxation. Literature reports indicate that stress relaxation in RAC can lead to approximately 40 % to 60 % prestress loss [21]. This means that even if a considerable self-stress level is established early on, without consideration for long-term relaxation, the later compensation effect may still significantly diminish, affecting durability and the sustainability of crack control.

In long-term deformation analysis, the treatment of time-related effects often requires the introduction of superposition principles. The Time-Temperature Superposition (TTS) principle is commonly used for polymer materials, but similar superposition ideas are also employed in a more general form in the field of concrete creep prediction. For example, the superposition principle combines the strain contributions from different time periods into a total strain response. For RAEC, a system with significant material heterogeneity, using overly idealized creep descriptions for ordinary concrete often fails to accurately predict the retention level of long-term self-stress. Therefore, modified creep models are needed for correction, such as introducing coefficients that consider aging effects into the effective modulus method to more reasonably reflect the viscoelastic characteristics of the material as it ages [1]. Meanwhile, the relationship between expansion, contraction, and creep in the early stages is not simply linearly additive. During rapid hydration and continuous microstructure evolution, damage accumulation and microcrack propagation alter the material's rheological path, causing RAC to exhibit more pronounced nonlinear rheological behavior. Based on this understanding, some studies have proposed introducing damage factors or correction coefficients into the model to characterize the amplification effect of microcrack evolution on creep and relaxation, thereby improving the predictive ability of early-age and long-term coupled deformation of RAEC [22].

## 5 Performance Enhancement Strategies: Carbonization Modification and Optimized Design

5.1 Accelerated Carbonization Treatment of Recycled Aggregates

To address the common problems of low stiffness, high water absorption, and well-developed pore structure in recycled aggregates (RCA), accelerated carbonization is widely regarded as one of the most effective and relatively engineerable aggregate modification pathways. Its core advantage lies in its ability to directly act on the old mortar and interfacial region, simultaneously improving the density of recycled aggregates through chemical reactions and pore structure reshaping, thereby enhancing the mechanical and deformation properties of RAC and RAEC from the material source. Mechanistically, the accelerated carbonization process mainly relies on the diffusion and reaction of $CO_2$ into the pore system of the old mortar. $CO_2$ reacts with $Ca(OH)_2$ and some C-S-H gel in the old mortar to form harder and denser $CaCO_2$. These calcium carbonate products can deposit and fill micropores and fine cracks, transforming the relatively loose porous structure of old mortar into a denser skeletal structure, thereby improving the density, strength, and overall integrity of recycled aggregates [12]. During this process, microscopic defects in the interfacial region are often passivated and repaired to some extent, preventing the structural shortcomings of recycled aggregates from being concentrated in the superposition effect of "high porosity and weak interfaces."

Carbonation modification typically improves deformation properties through multiple pathways and is directly coupled with the compensation mechanism of RAEC (Reinforced Expansion Coefficient). First, carbonation can restore or enhance the elastic modulus of RCA (Reinforced Compressive Acid) to a certain extent, making its overall stiffness closer to that of natural aggregates. This change is particularly crucial for constrained expansion systems because, under the same expansion strain conditions, a higher material modulus is more conducive to converting deformation into self-stress, thus making it easier for RAEC to form a higher level of effective compressive stress background under constrained conditions [6]. Secondly, carbonation reduces the porosity and water absorption of RCA, weakening the rapid migration channels of water between aggregate and paste, thus mitigating drying shrinkage caused by moisture loss and humidity gradients at the source. Simultaneously, densification of old mortar and ITZ strengthening reduce the space for long-term viscoelastic deformation, causing the creep coefficient of RAEC to tend to decrease, thereby slowing down the relaxation process of self-stress under long-term action, reducing prestress loss and improving the durability of the compensation effect [7]. The comprehensive benefits of this modification can also be seen from experimental results. For example, a research report indicates that after using carbonized fine aggregate, the compressive strength of fully recycled aggregate concrete can increase by approximately 19,8 %, the water absorption decreases by approximately 14,6 %, and there is a significant improvement in durability-related indicators [7]. These data suggest that accelerated carbonation not only improves individual performance indicators but may also provide a more stable material basis for the deformation control and crack resistance of RAEC through the combined effects of "pore structure densification, interface strengthening, and stiffness restoration."

5.2 Mix Proportioning and Curing Optimization

Beyond material-level modification, mix design and curing regime also determine whether RAEC can effectively convert its expansion potential into a usable compensation effect. Regarding the dosage of expansive agents, RAEC, due to its higher intrinsic shrinkage and creep levels, often has a stronger compensation requirement than NAC systems; therefore, the recommended dosages proposed in engineering and research are usually relatively higher. Taking CSA-type expansive agents as an example, the commonly recommended dosage range is approximately 8 % to 12 %, aiming to establish sufficient effective expansion reserves even under high shrinkage conditions. If CSA and MgO are co-admixed, a combination with a mass ratio of approximately 2:1 is often used to cover the early and late shrinkage compensation needs, achieving more balanced volumetric stability throughout the entire age [18]. It is important to emphasize that a higher expansive agent dosage is not always better. Excessive addition may lead to adverse internal damage risks under insufficient constraints or unstable moisture supply. Therefore, a reasonable dosage should be matched with the constraints, aggregate moisture content, and target compensation level.

Another key variable closely related to the dosage of the expanding agent is the water-cement ratio and curing conditions. A lower water-cement ratio generally benefits strength and reduces permeability, but it may also limit the hydration reaction and expansion development of the expanding agent, as the expansion process is more sensitive to available moisture and humidity. The RAEC system has certain unique characteristics in this regard, namely, the pore water content of RCA can provide continuous replenishment for hydration and expansion through the internal curing effect, but this replenishment capacity cannot completely replace the humidity stability brought about by external curing. Therefore, after the mix proportion is determined, maintaining a high humidity environment in the early stage through sufficient external wet curing remains a key measure to ensure expansion efficiency. Related studies usually recommend wet curing for no less than 14 days to reduce the inhibitory effect of early self-drying and insufficient moisture on the expansion reaction [23]. In engineering implementation, this also means that mix proportion optimization and curing optimization need to be considered as a whole and simultaneously. Only when the moisture supply, expansion time, and restrain conditions are matched can the compensation mechanism of RAEC function stably and achieve a more reliable comprehensive balance between strength, volume stability, and durability.

**Conclusions and Outlook**

A review of existing literature shows that a relatively clear consensus has been reached regarding the mechanism and engineering application of recycled aggregate expansive concrete (RAEC). Overall, although RAC inherently suffers from drawbacks such as high shrinkage, significant creep, and low elastic modulus, stable shrinkage compensation can still be achieved by appropriately introducing expansive agents, especially a composite expansive system of CSA and MgO. Under suitable constraints, considerable levels of chemical prestress can also be established. Existing studies generally indicate that RAEC can generate approximately 0,5 to 1,5 MPa of chemical prestress within a controllable engineering range, effectively offsetting the tensile stress caused by shrinkage and significantly improving crack resistance. This means that "expansion compensating for shrinkage" is not only feasible in recycled systems but also possesses a clear performance gain path. Meanwhile, the design logic of RAEC cannot simply follow the empirical framework of natural aggregate concrete (NAC). This is because the stiffness mismatch caused by low modulus alters the conversion efficiency of expansion strain into self-stress, often requiring a higher level of restricted expansion rate to achieve the same self-stress. Furthermore, a higher creep level accelerates self-stress relaxation and amplifies prestress loss, making the favorable state established early on more prone to decay during long-term service. Based on this characteristic, employing expansion sources covering the entire age range, such as MgO that can provide delayed expansion, and incorporating relaxation loss considerations into structural design are generally considered necessary conditions for improving the durability and predictability of the compensation effect.

Regarding performance enhancement technologies, the importance of aggregate modification has been repeatedly emphasized. Among these, accelerated carbonation is considered one of the most targeted key means to improve the overall performance of RAEC. The densification effect formed by the carbonation reaction can not only restore the stiffness of recycled aggregate to a certain extent but also reduce porosity and water absorption, weakening drying shrinkage caused by moisture migration at the source. It also reduces creep levels through interface strengthening and microstructure densification, thereby enabling the expansion efficiency to be more fully and stably converted into an effective self-stress background. Meanwhile, the synergistic effect of multiple restrain systems provides more structurally significant support for improving the brittleness and compensation efficiency of RAEC. Fiber-based materials such as steel fibers and basalt fibers can reduce strain concentration through crack bridging and dispersed constraints, making the expansion energy more likely to form a uniform internal restrain force distribution and suppressing the propagation of microcracks that may be induced during the expansion process. The steel tube restrain system provides continuous confining pressure at the component level and helps solve the interfacial voiding problem caused by core concrete shrinkage, thereby improving overall ductility and load-bearing stability. The above evidence collectively demonstrates that the advantages of RAEC do not stem from a single material measure, but rather rely more on the systematic matching between the expansion source time history, restrain conditions, aggregate modification, and crack control methods.

Looking to the future, RAEC research still needs to be further deepened along three main lines: long-term service mechanism, environmental durability, and engineering standardization. Firstly, regarding long-term performance, it is necessary to establish long-term constitutive and creep relaxation models that can reflect the coupling effect of RCA damage evolution and the hydration process of the expansion agent, thereby quantifying the influence boundary of stress relaxation on the self-stress retention level and structural safety, enabling design to move from short-term performance to traceable life-scale evaluation. Secondly, regarding durability, a more in-depth discussion is needed on the stability of expansion products under corrosive environments such as chloride and sulfate, especially ettringite. The long-term correlation between ettringite and the evolution of microcrack networks, changes in permeability, and the risk of steel reinforcement corrosion needs to be clarified, thereby establishing a durability evaluation path that more closely reflects actual service environments. Finally, to promote large-scale engineering applications, developing standardized design methods and mix design specifications for RAEC remains essential. In particular, the optimal type and reasonable dosage range of expansion agents corresponding to different quality grades of recycled aggregates should be clearly defined, and moisture management, curing requirements, and constraints should be incorporated into operable engineering clauses to improve the replicability and reliability of RAEC in different engineering scenarios.

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# RESEARCH PROGRESS ON MECHANICAL MECHANISM AND CONSTITUTIVE MODEL OF CFRP STRIP ACTIVELY CONSTRAINED RECYCLED AGGREGATE EXPANSIVE CONCRETE

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**Abstract**

Recycled aggregate (RA) concrete has attracted much attention due to its environmental benefits, but its low mechanical properties and high brittleness limit its application in structures. Fiber-reinforced polymer (FRP) confinement is an effective means to improve its performance. Among them, the "active confinement" achieved by combining expansive concrete (EC) with CFRP strips is a promising new technology. This technology generates pre-tension stress in the CFRP strips through chemical expansion, placing the core concrete in a triaxial pre-compression state, thereby optimizing concrete performance before loading. However, the interaction between the porosity of recycled aggregate, the effectiveness of the expansive agent, and the discontinuous confinement effect of the CFRP strips is very complex, and its mechanical mechanism is not yet clear, nor is a mature constitutive model available. This paper aims to systematically review the current research status of the mechanical mechanism and constitutive model of CFRP strip-confined recycled aggregate expansive concrete. First, the multiple physical and mechanical coupling mechanisms among the expansive agent, recycled aggregate, and CFRP strips were explored. Second, the influence of key factors such as the replacement rate of recycled aggregate, the type of expansive agent, and the spacing of CFRP strips on the mechanical properties of the composite structure was reviewed. Finally, the limitations of existing constitutive models were analyzed in detail, pointing out that existing models cannot accurately describe the full stress-strain curve of this novel composite material. This paper aims to clarify the research gaps in this field and provide direction for the future development of high-precision constitutive models.

**Keywords:** CFRP strips, active constraint, recycled aggregate, expansive concrete, constitutive model.

## ИССЛЕДОВАНИЯ МЕХАНИЗМА РАБОТЫ И КОНСТИТУТИВНОЙ МОДЕЛИ РАСШИРЯЮЩЕГОСЯ БЕТОНА НА РЕЦИКЛИРОВАННОМ ЗАПОЛНИТЕЛЕ С АКТИВНЫМ ОГРАНИЧЕНИЕМ ПОЛОСАМИ ИЗ CFRP

**Лю Мин, В. В. Тур**

**Реферат**

Бетон на переработанных заполнителях (RA) привлек большое внимание из-за его экологических преимуществ, но его низкие механические свойства и высокая хрупкость ограничивают его применение в конструкциях. Одним из эффективных путей применения рециклингового заполнителя является его использование совместно с напрягающим цементом в условиях активного ограничения в виде пластиковых труб с навивкой полосового армирования из CFRP. Эта технология позволяет сгенерировать предварительные напряжения в полосах из CFRP посредством физико-химического расширения, создавая в бетонном ядре в условия трехосного ограничения предварительное сжатие, тем самым оптимизируя характеристики бетона до нагружения. Однако взаимодействие между пористостью переработанного заполнителя, эффективностью расширяющегося агента и непрерывным эффектом ограничения полос CFRP очень сложно описать т. к. механизм не ясен до конца, и апробированная конституционная модель отсутствует. Настоящая статья направлена на систематический обзор текущего состояния исследований механизма и конституционной модели напрягающего бетона на переработанном заполнителе в условиях ограничения CFRP полосами. В статье подробно проанализированы существующие конститутивные модели расширения напрягающего бетона на рециклинговых заполнителях в условиях трехосного ограничения, отмечая, что существующие модели не могут точно описать полную кривую развития самонапряжения во времени для этого нового композитного материала. Целью настоящей статьи является выяснение пробелов в исследованиях в этой области и формулирования направления для будущей разработки высокоточных конститутивных моделей.

**Ключевые слова:** полосы из CFRP (углепластика), активное ограничение, рециклинговый заполнитель, расширяющийся бетон, конституционная модель.

### 1 Introduction

With the ongoing advancement of global infrastructure development and the accelerating pace of urbanisation, the construction industry's demand for concrete raw materials has grown exponentially. This has simultaneously generated vast quantities of construction and demolition waste (CDW). Addressing the dual crises of resource scarcity and environmental pollution while meeting structural performance requirements has become a pressing core issue within the civil engineering sector. Recycled Aggregate Concrete (RAC) technology achieves this by crushing and screening waste concrete to replace natural aggregates, significantly reducing carbon emissions while enabling closed-loop recycling of construction resources [1, 5]. However, the surface-adhered aged mortar and micro-fractures generated during crushing impart inherent physical and mechanical deficiencies to recycled concrete aggregate (RCA), such as elevated porosity, high water absorption, and low crushing value [7]. These inherent limitations result in recycled aggregate concrete typically exhibiting lower compressive strength, elastic modulus, and durability compared to natural aggregate concrete (NAC) of equivalent grades, thereby restricting its widespread application in high-performance structural components [7].

To enhance the mechanical properties of recycled aggregate concrete and broaden its application scope, fibre-reinforced polymer (FRP) confinement technology has been introduced into the field of recycled aggregate concrete structural reinforcement [25]. FRP materials offer advantages such as lightweight high strength, corrosion resistance, and ease of construction. They can significantly enhance the strength and ductility of the concrete core by providing lateral confinement forces. Carbon fibre reinforced polymer (CFRP), in particular, is widely adopted due to its exceptional mechanical properties. However, traditional FRP wrapping techniques primarily provide passive confinement. Under passive confinement, the restraining force of FRP relies on lateral expansion of the core concrete. This implies that the restraining effect can only be fully realised after the concrete has undergone significant axial deformation and sustained a certain degree of damage [18]. For recycled aggregate concrete, which inherently possesses low stiffness and is prone to cracking, this delayed confinement mechanism often fails to effectively suppress early crack initiation. Consequently, the stiffness enhancement of the member during the elastic stage remains limited.

To overcome the limitations of passive confinement, the concept of active confinement emerged. By introducing expansive agents (EA) to prepare expansive concrete, the interaction between the volume expansion during concrete hardening and the external FRP materials enables the establishment of chemical prestressing within the core concrete prior to loading, thereby achieving 'active confinement' [2]. This chemical prestressing not only compensates for concrete shrinkage deformation but also enhances the cracking load and initial stiffness of the member, fundamentally improving the load-bearing performance of RAC. Furthermore, considering the potential issues of poor breathability and high cost associated with full-wrap FRP, the partial confinement technique using CFRP strips offers an alternative solution that balances economy and functionality [17]. CFRP strips permit moisture and heat exchange between concrete and the external environment, benefiting the hydration of expansive agents and the long-term performance of concrete. However, this also introduces more complex non-uniform constrained stress fields and arching action issues [13].

It is noteworthy that the confinement mechanics governed by a surrounding jacket has been well established in concrete-filled steel tube (CFST) members and FRP-tube encased concrete, where equilibrium and strain-compatibility allow the core's free strains (e. g., shrinkage, thermal strain, or expansion) to be converted into interface pressure in a closed-form manner.

Such a tube-based formulation provides a rigorous baseline for explaining how expansive concrete can mobilize "active" confinement in the jacket, rather than treating confinement efficiency purely as an empirical modification.Therefore, in addition to summarizing CFRP-strip confinement and expansive concrete, this review also introduces a tube-mechanics perspective (Section 3.4) to bridge CFRP-strip active confinement with the mature CFST/continuous-tube analytical framework [5, 22, 23].

The integration of CFRP strip partial confinement technology with recycled aggregate expansive concrete establishes a novel composite structural system combining green, low-carbon, active reinforcement, and cost-effectiveness. This system involves the microporous structure of recycled aggregates, the chemical reaction kinetics of expansive agents, the non-uniform physical confinement of CFRP strips, and the complex mechanical coupling between these three elements. This paper aims to systematically review the mechanical mechanisms and constitutive model research progress concerning CFRP strip-actively constrained recycled aggregate expansive concrete. The paper will delve into the synergistic 'internal curing-expansion' mechanism between recycled aggregates and expansive agents, examine stress path effects under active confinement alongside the non-uniform characteristics of strip confinement, and critically evaluate and compare existing constitutive models. This endeavour seeks to provide robust theoretical underpinnings for the engineering design and application of such novel composite structures.

## 2 Material Properties and Microscopic Synergistic Mechanisms of Recycled Aggregate Expansive Concrete

2.1 Multi-interface Defect Characteristics of Recycled Aggregates and Their Potential for Internal Curing Effect

The most critical difference between recycled aggregates and natural aggregates lies in their more complex and heterogeneous interfacial structures. Recycled aggregates are typically composed of virgin natural aggregates and old cement mortar adhering to their surfaces. This "two-phase" structure inevitably leads to multiple interfacial transition zones (ITZs) within recycled aggregate concrete (RAC). These include interfaces between new and old mortar, interfaces between old mortar and virgin aggregates, and interfaces where new mortar directly contacts virgin aggregates, especially when old mortar partially peels off during the crushing process [10]. Due to the diverse interface types, poor structural continuity, and significant gradients in material properties, microstructural analysis generally indicates that the interphase zone (ITZ) of reclaimed concrete (RAC) is often more porous. Pores and microcracks are more easily enriched and interconnected in this region, a characteristic considered a significant microscopic cause of the reduced macroscopic mechanical properties of RAC. Further research data reveals the porosity characteristics of recycled aggregates at the material parameter level; their porosity is typically more than 30 % higher than that of natural aggregates, while their water absorption can reach 5 % to 10 % [21]. Therefore, in conventional concrete, recycled aggregates often introduce a stronger mixing water adsorption effect and exacerbate the interfacial weakness problem, thus adversely affecting workability and strength development.

However, in expansive concrete systems, the aforementioned high porosity and high water absorption do not necessarily imply performance degradation. On the contrary, they provide a structural basis for the system to induce an "internal curing" effect. Traditional expansive concrete often faces the risk of insufficient moisture supply in engineering applications. This is because the hydration reaction of the expansive agent continuously consumes water. If external curing is insufficient, the decrease in relative humidity inside the system will induce self-drying shrinkage, thereby weakening the compensatory role that expansion should play [11]. The porous structure of recycled aggregates allows them to quickly absorb and store a certain amount of free water in the early stages of concrete mixing. As the cement hydration and hardening process progresses, the relative humidity inside the matrix gradually decreases, forming a capillary pressure difference. This pressure difference further drives the release of water from the pores of the recycled aggregates into the surrounding paste, thus replenishing the water required for cement hydration and the reaction of the expansive agent in a more continuous manner [11]. When internal curing water is stably supplied at the microscale, its effect is not only to promote a more complete reaction of the expansive agent and increase the restricted expansion rate, but also to change the microscopic evolution path of the ITZ by improving the hydration environment of the interface zone. The C-S-H gel and hydrated aluminate generated near the interface can more effectively fill pores and bridge microcracks, making the ITZ structure more compact, thus achieving a certain degree of repair and weakening of microscopic defects in RAC [8].

2.2 Expansive Agent Reaction Kinetics and the Formation Mechanism of Chemical Prestress under Constrained Conditions

The volume increase of expansive concrete is usually achieved by incorporating calcium-based (CaO), magnesium-based (MgO), or calcium sulfoaluminate-based expansive agents. However, different expansive agents have significant differences in reaction mechanism, reaction rate, and expansion history, which directly determines the temporal characteristics of the expansion effect and its adaptability to shrinkage compensation. Calcium sulfoaluminate-based expansive agents primarily generate crystalline growth pressure within the cement paste skeleton by producing needle-like ettringite crystals (AFt), thereby driving volume expansion. This type of expansion typically occurs in the early stages of hydration and exhibits a relatively rapid development rate [4]. In contrast, MgO expansive agents generate magnesium hydroxide crystals ($Mg(OH)_2$) through hydration. Their reaction process is slower and more significantly affected by temperature, thus potentially providing a longer-lasting delayed expansion effect. This has more direct engineering significance for compensating for the later-stage shrinkage of large-volume concrete [19]. Since the expansion effect essentially originates from the generation and growth of hydration products, the system's moisture supply, temperature conditions, and pore structure all influence the reaction mechanism and final expansion contribution of the expansive agent to varying degrees, resulting in expansive concrete exhibiting a clear material-environment coupling characteristic.

When expansive concrete is within a CFRP strip-constrained system, the free expansion of the core concrete is restricted by the external FRP material. This restriction does not eliminate expansion but rather transforms it into a characterizable stress state. According to Newton's third law, the reaction of external constraints forces compressive stress $\sigma_{\mathrm{pre}}$ within the concrete, while simultaneously inducing corresponding tensile stress $\sigma_{\mathrm{frp,0}}$in the FRP strips. This state, driven by a chemical reaction and ultimately manifesting as mechanical stress, can be defined as "chemical prestressing." Previous studies have indicated that the level of chemical prestressing depends on key factors such as the type and dosage of the expansive agent, the water-cement ratio, curing conditions, and the stiffness of the external constraints [2]. When chemical prestressing is within a moderate range, the concrete more closely approximates a triaxial compressive working state, and its crack resistance and initial elastic modulus are often significantly improved. However, stronger expansion is not always more beneficial. When the expansive agent dosage is excessive or the expansion pressure exceeds the tensile strength of the concrete matrix in the unconstrained direction, new microcracks may form internally, compromising material integrity and thus negating the expected gains or even converting them into performance damage [2]. Therefore, the mix design and constraint system design of recycled aggregate expansive concrete need to simultaneously consider the regulatory effects of the water absorption and release behavior of recycled aggregate on the hydration environment, as well as the influence of the water consumption of the expansive agent during hydration and the growth of its products on the evolution of internal stress. Only by precisely matching the water supply capacity with the reaction requirements can a more stable and repeatable synergistic effect be achieved between microstructural densification and macroscopic mechanical property improvement.

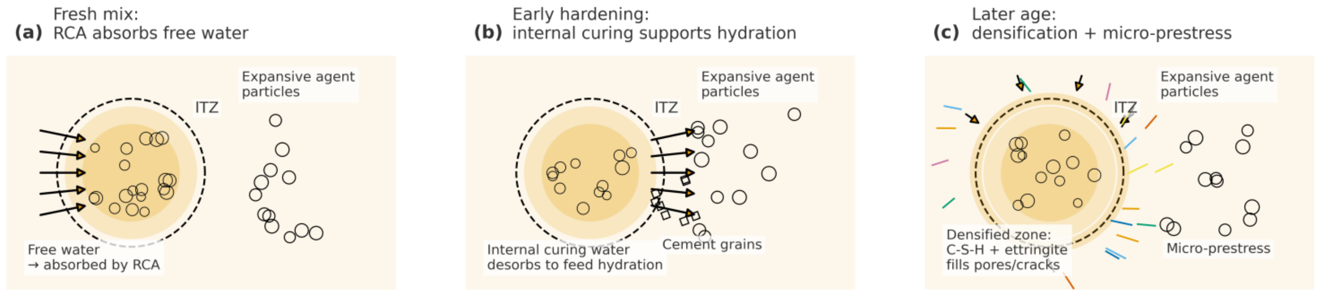


**Figure 1** – Schematic diagram of the microscopic synergistic mechanism between recycled aggregate and expansion agent [2, 10, 11]

Figure 1 aims to visually present the microscopic path and structural results of the synergistic effect between recycled aggregate and expansive agent during hydration. This schematic diagram illustrates the key stages of water migration and interface evolution in a time-progressive manner. The left side of the figure corresponds to the fresh mixing stage. In the initial stage of mixing, porous recycled aggregate (RCA) adsorbs and stores a large amount of free water, and the old mortar layer attached to its surface is in a high-saturation state. The expansive agent particles are relatively uniformly dispersed in the new cement paste, providing a spatially diffusible basis for subsequent reactions. The middle part of the figure depicts the water redistribution process in the early stages of hardening. As cement hydration continues to consume external moisture, the internal humidity of the matrix gradually decreases, forming capillary tension. Under this driving force, the internal curing water stored inside the recycled aggregate undergoes desorption and migrates outward. The released water is preferentially transported to adjacent expansion agent particles and unhydrated cement particles, thereby maintaining the local water environment required for the reaction at the microscale. The right side of the figure corresponds to the structural strengthening results in the later stages of hardening. Near the interface transition zone (ITZ) between RCA and the new paste, due to continuous water replenishment, more abundant ettringite crystals and dense C-S-H gel are generated. These hydration products fill and seal the previously loose pores and microcracks, forming a identifiable "densified zone" around the interface. At the same time, the growth of expansion products is restricted by the external skeleton and constraints, inducing a prestressed state at the microscale, making the overall matrix structure more compact and possessing stronger crack resistance potential. This schematic process provides a clearer understanding of how internal curing, in conjunction with micro-expansion, affects the evolution of interfacial defects and pore structure in RAC, thereby promoting simultaneous improvement of material properties at both the micro and macro levels [10].

### 3 Mechanical Mechanism of CFRP Strip Active Constraint Systems

3.1 Differences in Stress Initiation Points and Path-Dependent Responses Between Active and Passive Constraint

The core prerequisite for understanding CFRP strip active constraint systems lies in clarifying the fundamental differences between ‘active constraint’ and ‘passive constraint’ in terms of constraint initiation mechanisms and stress onset points. Furthermore, it is essential to recognise how these differences influence material damage evolution and ultimate load-bearing performance through stress pathways. Traditional FRP-constrained concrete typically constitutes a passive constraint system. During the initial loading phase, the FRP jacket bears negligible effective stress. Only when the core concrete undergoes longitudinal compression under axial pressure, accompanied by lateral expansion, does the FRP develop circumferential tensile forces through passive stretching. This subsequently imposes lateral constraint pressure $\sigma_l$ upon the core concrete. Within this framework, the magnitude of the confinement pressure is governed by the lateral strain $\varepsilon_l$, i. e., $\sigma_l = f(\varepsilon_l)$. Consequently, the establishment of confinement exhibits pronounced hysteresis. This hysteresis implies that the confinement effect is often only gradually activated after the concrete has already developed a certain degree of microcrack initiation and damage accumulation. For recycled aggregate concrete, which exhibits greater brittleness, more initial defects, and lower overall stiffness, the material is more sensitive to damage during the early loading stages. Irreversible micro-deterioration may occur before the confinement effect is fully developed, thereby inherently limiting the subsequent enhancement of strength and ductility through confinement [18].

Upon introducing expansive agents, the confinement mechanism undergoes a fundamental transformation. Concrete can generate initial lateral compressive stress $\sigma_{l,ini}$ internally through volumetric expansion before external axial working loads are applied. Concurrently, CFRP strips are prestressed due to the induced tensile strain. The presence of confining pressure alters the material's failure criteria. From the perspective of the Mohr-Coulomb failure criterion, the initial confining pressure effectively extends the elastic range of the concrete at the onset of loading and raises the crack initiation threshold. This results in earlier and more effective suppression of microcrack nucleation and propagation. More significantly, active confinement not only provides a non-zero initial confining pressure value but also fundamentally alters the stress path of the concrete: under passive confinement, confining pressure typically increases monotonically from zero as axial load increases; whereas under active confinement, confining pressure commences from a non-zero level, with its subsequent growth rate jointly governed by FRP stiffness and concrete shear-expansion characteristics. Consequently, the evolution of confining pressure exhibits distinct temporal characteristics compared to passive confinement. Extensive research indicates that concrete's mechanical response exhibits pronounced path-dependency. Even when ultimately reaching identical confining pressure levels, specimens subjected to active confinement pathways frequently demonstrate higher ultimate strengths and superior ductility [9]. This disparity does not stem from a simple comparison of ‘final confining pressure values,’ but rather relates more profoundly to whether damage is suppressed in the early stages. Active confinement imposes restrictions on microcrack evolution from the onset of loading, enabling the material to maintain higher structural integrity throughout the loading process. This provides a more stable microstructural foundation for subsequent strength development and deformation capacity.

3.2 Arch Effect of Partially Constrained Strips and Evolution of Effective Constraint Induced by Expansion

Compared to continuous FRP tubes or fully wrapped configurations, CFRP strip confinement introduces a pronounced non-uniform stress field alongside lateral restraint. This non-uniformity manifests not only in the cross-sectional direction but more markedly in discontinuous distribution characteristics along the component height. Within the strip coverage zones, concrete experiences strong confinement, whereas in the inter-strip gaps, it remains weakly confined or even unconstrained. Consequently, confinement stresses do not propagate uniformly along the height. The classical 'arching action' theory is commonly employed to explain this phenomenon. Its fundamental principle posits that confinement stress does not propagate linearly between adjacent strips but traverses the gap regions via arched stress paths, enabling transfer from one confinement ring to the next. During this process, only the concrete within the arched region forms an effective confined core and receives effective confining pressure, whereas the concrete outside the arch, closer to the free surface, is more prone to spalling or brittle failure [13]. Consequently, the load-bearing contribution of strip confinement largely depends on the adequate formation of the arch effect and the actual extent of the effective confined core under geometric and material conditions.

When the confined material transitions from ordinary concrete to expansive concrete, the mechanism of arch effect formation and confinement effectiveness exhibit heightened dynamism. This arises because expansion constitutes a volumetric deformation process, wherein the core concrete exhibits an outward expansion tendency even within the strip gaps. This tendency may manifest prior to the application of external axial loading. Should the spacing between CFRP strips be excessively large, the concrete within the gaps may crack under expansive forces, potentially leading to localised failure even before axial loading. This creates a persistent 'pre-damage' effect, prematurely diminishing the potential for strength and ductility enhancement during subsequent compression stages. Precisely because expansion introduces pre-loading deformation and internal stress evolution, the determinants of the effective confinement coefficient $k_e$ are no longer confined to geometric parameters alone. Instead, they must simultaneously account for the expansion energy generated by the admixture reaction and the resulting stress redistribution process. The classical expression proposed by Mander et al. is typically written as $k_e = (1 - s'/2d_c)^2$, where $s'$ denotes the net spacing between strips and $d_c$ represents the core diameter [27]. This formulation essentially characterises the reduction in the effective core size through geometric relationships. However, for expansive concrete systems, direct application of this geometric coefficient often fails to reflect the actual deviations caused by expansion-induced stress increases in the interstitial zone or pre-damage effects. Consequently, $k_e$ requires modification to incorporate the influence of stress redistribution induced by expansion [6]. Further research indicates that when the ratio of net strip spacing to member dimensions exceeds a certain threshold, arching effects struggle to stabilise, leading to a sudden drop in confinement efficiency. The failure mode may shift from confinement-dominated behaviour to shear failure of the interstitial concrete. This threshold is frequently reported in multiple studies to be close to 0,5 [17]. Consequently, in the strip confinement design for expansive concrete, strip spacing does not merely determine the 'strength of confinement'. It more directly influences whether the expansion phase will induce premature damage in the gap zone, thereby affecting the effectiveness and stability of the entire confinement system throughout the entire compression process.

3.3 Stress Concentration and Constraint Efficiency Modulation Induced by Cross-Section Geometric Effects

When the cross-section of a component is rectangular or square, the non-uniformity encountered by CFRP strip confinement exhibits a superposition effect, typically exhibiting significantly greater complexity than circular cross-sections. On the one hand, the strip spacing in the height direction still causes discrete distribution of confinement pressure along the height due to the arch effect. On the other hand, the corner effect in the cross-sectional direction further leads to significant in-plane non-uniformity of confinement pressure. For rectangular cross-sections, lateral confinement pressure tends to concentrate in corner regions, while confinement at the mid-sections of straight edges is relatively weaker. This occurs because FRP, as a flexible membrane material, tends to provide membrane tensile response rather than directly forming stable confining pressure in straight segments. Consequently, the mid-sections of straight edges struggle to achieve lateral compressive stress levels comparable to those at corners [14]. When the material is replaced with recycled aggregate concrete, its internal defect distribution exhibits greater randomness and heterogeneity. The non-uniform constraint stress field is more likely to trigger damage propagation at local defects and weak interfaces, manifesting as localised failure initiating and rapidly evolving into global failure. Concurrently, the high stiffness of CFRP strips provides strong confinement to localised regions but may also induce stress concentration at strip edges or locations of stress discontinuity. This generates significant shear effects within the concrete at these points, potentially triggering localised shear failure. Consequently, the overall utilisation rate and ductility contribution of the confinement system are diminished. Consequently, corner rounding of rectangular columns is widely regarded as a crucial method for enhancing confinement efficiency. Increasing the radius of curvature improves the continuity of FRP strain development and confining pressure distribution at corners, resulting in more uniform lateral confinement and enhancing the effective utilisation of CFRP material [16].

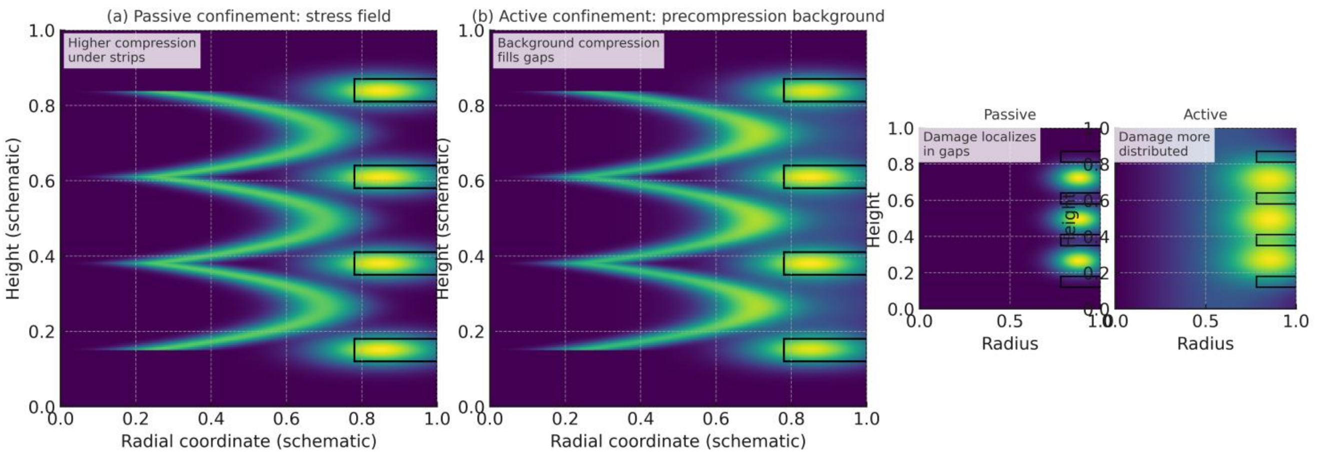


**Figure 2** – Comparison of internal stress fields within CFRP-constrained concrete under active and passive constraint conditions [2, 5, 18, 24]

To elucidate the coupling relationship between active confinement and the partial confinement effect of the strips, a comparative analysis of the two states can be conducted using stress contour plots derived from finite element numerical simulations. Figure 2a corresponds to the passive confinement state, displaying the distribution of minimum principal stresses along the longitudinal section of the CFRP strip-confined concrete cylinder during the initial stage of axial loading. Where compressive stresses predominantly concentrate directly beneath the CFRP strips. Darker hues indicate higher local confining pressure levels. Distinct arched stress transfer pathways emerge between the strips: the inner arch region exhibits elevated compressive stresses forming an effective confinement core, while the outer arch area near the concrete surface shows markedly lighter colours, even exhibiting near-zero stress zones. This reflects a low-confinement blind zone where effective confining pressure is scarcely established during the early loading stage. Figure 2b corresponds to the active confinement state, illustrating the stress distribution characteristics prior to axial loading after introducing the expansive agent. Compared to Figure 2a, a background compressive stress field is observed throughout the entire cross-section, including the inter-strip void regions. While the highest compressive stress levels persist beneath the strips, stresses in the void regions are significantly elevated, and the original low-stress blind zones tend to disappear. This indicates that the initial confining pressure introduced by chemical prestressing spatially compensates for the inherent weak zones in the discontinuous confinement provided by the strips. Consequently, a continuous compressive stress field is established earlier within the component. Figure 2c further presents a comparative damage contour plot during the failure stage. The passively constrained specimen exhibits greater susceptibility to damage concentration at the strip gaps, forming distinct shear zones. Conversely, the actively constrained specimen typically displays more uniform damage distribution, with crack morphology tending towards finer and more dispersed patterns. This disparity numerically corroborates the mechanism by which active confinement mitigates stress concentration and suppresses localised failure [6].

3.4 Tube-based mechanical model and analogy with CFST members

From a mechanics viewpoint, the actively confined RAC–EC with CFRP strips can be regarded as a discontinuous approximation of a full tube surrounding the concrete core. This configuration is conceptually close to classical concrete-filled steel tube (CFST) and FRP-tube encased concrete members, in which the tube and the core concrete share compatible deformations and interact through radial interface pressure. Tube-based analytical models developed for CFST and FRP tubes therefore provide a useful reference framework for interpreting the stress transfer mechanism in the present system [5, 22, 23].

For a thin-walled circular tube with thickness ttt and mean radius rrr, made of an isotropic linear-elastic material with elastic modulus EsE_sEs and Poisson's ratio μs\mu_sμs, the hoop and axial stresses can be expressed in terms of the corresponding strains as

$$\sigma_{s,\theta} = \frac{E_s}{1-\mu_s^2}\left(\epsilon_{s,\theta} + \mu_s\epsilon_{s,z}\right), \quad \sigma_{s,z} = \frac{E_s}{1-\mu_s^2}\left(\epsilon_{s,z} + \mu_s\epsilon_{s,\theta}\right). \quad (1)$$

Assuming perfect bond at the tube–concrete interface and uniform internal pressure, radial equilibrium of a closed tube leads to the classical thin-walled relations

$$q = \frac{t}{r}\sigma_{s,\theta}, \quad \sigma_{s,z} = \frac{qr}{2t}, \quad (2)$$

where q is the confining pressure acting on the concrete core. Equations (1), (2) show that the active confining pressure generated by expansion or differential deformation in the core can be directly related to the hoop and axial strains in the surrounding tube (see Figure 3).

The concrete core is simultaneously subjected to axial stress and lateral confinement. Neglecting radial stress gradients within the core and adopting an effective time-dependent modulus $E_{cm}(t)$ and Poisson's ratio $\mu_c$, the tangential and axial concrete stresses associated with the elastic part of the strains can be written in a form analogous to generalized Hooke's law

$$\sigma_{c,\theta\theta} = \frac{E_{cm}(t)}{(1+\mu_c)(1-2\mu_c)}\left[(1-\mu_c)\epsilon_{c,\theta\theta} + \mu_c\epsilon_{c,zz}\right],$$
$$\sigma_{c,zz} = \frac{E_{cm}(t)}{(1+\mu_c)(1-2\mu_c)}\left[(1-\mu_c)\epsilon_{c,zz} + \mu_c\epsilon_{c,\theta\theta}\right], \quad (3)$$

with radial equilibrium at the interface requiring $\sigma_{c,rr}(r_i) = -q$. Together with the strain-compatibility conditions $\varepsilon_{s,\theta} = \varepsilon_{c,\theta\theta}$ and $\varepsilon_{s,z} = \varepsilon_{c,zz}$ at the interface, Equations (1)–(3) form a closed "tube model" that links the free expansive strain of RAC-EC, the tensile response of the CFRP (or steel) tube, and the resulting three-dimensional stress state in the core. In CFST members, similar formulations are widely used to quantify how temperature rise, shrinkage and creep of the concrete core generate active confinement in the steel tube; here the same approach can be used to interpret the chemical prestressing produced by expansive agents in RAC-EC.

When time-dependent effects are included, the total strains in both tube and concrete can be decomposed into instantaneous elastic parts and creep components. For the concrete core, the circumferential and axial strain increments at a generic time step $t_i$ may be expressed as

$$\Delta\epsilon_{c,\theta\theta}^{(i)} = \Delta\epsilon_{c,\theta\theta}^{E(i)} + \sum_{j=1}^{i}\Delta\sigma_{c,\theta\theta}^{(j)}\frac{\Delta\varphi(t_i,t_j)}{E_{cm,28}} + \sum_{j=1}^{i}\Delta\sigma_{c,zz}^{(j)}\frac{\Delta\psi(t_i,t_j)}{E_{cm,28}},$$
$$\Delta\epsilon_{c,zz}^{(i)} = \Delta\epsilon_{c,zz}^{E(i)} + \sum_{j=1}^{i}\Delta\sigma_{c,zz}^{(j)}\frac{\Delta\varphi(t_i,t_j)}{E_{cm,28}} + \sum_{j=1}^{i}\Delta\sigma_{c,\theta\theta}^{(j)}\frac{\Delta\psi(t_i,t_j)}{E_{cm,28}}, \quad (4)$$

where $\Delta\varphi(t_i, t_j)$ and $\Delta\psi(t_i, t_j)$ are discrete creep functions associated with the history of tangential and axial stresses, respectively, and $E_{cm}$ is a reference modulus at 28 days. The corresponding stress increments in the tube, $\Delta\sigma_{s,\theta}^{(i)}$ and $\Delta\sigma_{s,z}^{(i)}$, are obtained from Equation (1) using the compatible strain increments in the tube. Substituting these stress increments into Equation (2) provides the evolution of the confining pressure q(t) and thus the time-varying active confinement level in the core.

For RAC-EC members confined by CFRP strips rather than a continuous tube, the above tube model can still be used in an "equivalent-tube" sense. An effective tube thickness teq may be introduced by distributing the total strip area uniformly around the perimeter, while the non-uniformity of strip confinement is accounted for through the effective confinement coefficient ke discussed in Sections 3.2 and 4.3. In this way, the active confining pressure derived from Equations (1)–(4) can be interpreted as the mean confining pressure in the effectively confined core, and the influence of strip spacing, strip width and expansion level can be translated into modifications of teq and ke. This tube-based analytical framework provides a direct theoretical bridge between the well-established mechanics of CFST/FRP-tube systems and the more complex behaviour of CFRP-strip-actively confined RAC-EC members.

**4 Axial Compression Performance, Failure Modes and Key Parameter Analysis**

4.1 Failure Patterns and Their Evolutionary Mechanisms

The failure patterns exhibited by CFRP-strip-actively-constrained recycled aggregate expansive concrete under axial compression fundamentally result from the competitive and mutually reinforcing interplay of multiple mechanisms across different stages. The dominant mechanism is typically governed by the combined effects of constraint stiffness, recycled aggregate replacement rate, and expansive agent dosage. Constraint stiffness is determined not only by the number of CFRP layers but also closely relates to strip spacing, strip width, and their mode of shaping the effective constraint core. The recycled aggregate replacement rate influences crack initiation locations and propagation pathways by altering the matrix's initial defect level, interfacial weakness, and shear-expansion response; the expansive agent dosage further modifies the pre-loading initial stress state and early-loading crack initiation threshold through the magnitude and distribution of chemical prestress. Based on experimental phenomena and the temporal characteristics of failure processes, common failures can be categorised into several representative types. However, these are not mutually exclusive; they often occur sequentially or concurrently within the same specimen, differing only in their dominant features.

When confinement is strong – that is, when strip spacing is small, the number of layers is high, and the effective confinement core area is large – the specimen is more likely to exhibit a failure mode dominated by CFRP tensile rupture. This failure typically commences when tensile strain in one or several strips near the mid-column rapidly approaches its limit, accompanied by a distinct audible crack. Subsequently, due to the instantaneous loss of lateral confinement locally, the core concrete rapidly transitions to crushing failure under high axial compression, producing significant fragmentation and spalling. It is important to note that within active confinement systems, the expansion phase already induces initial tensile strain in the CFRP strips. This effectively consumes part of the strain reserve before axial loading commences. Consequently, the 'additional available fracture strain' that CFRP can provide during loading is often less than the material limit values measured in uniaxial tensile tests. Concurrently, the volume deformation and shear expansion characteristics of recycled aggregate systems are more pronounced. Under intermittent confinement conditions, the strips may exhibit greater strain inhomogeneity, causing the strain efficiency coefficient to vary across different structural parameters and material combinations [24]. This affects the actual location and sequence of reaching the limit state defined by 'reaching $\epsilon_f$'.


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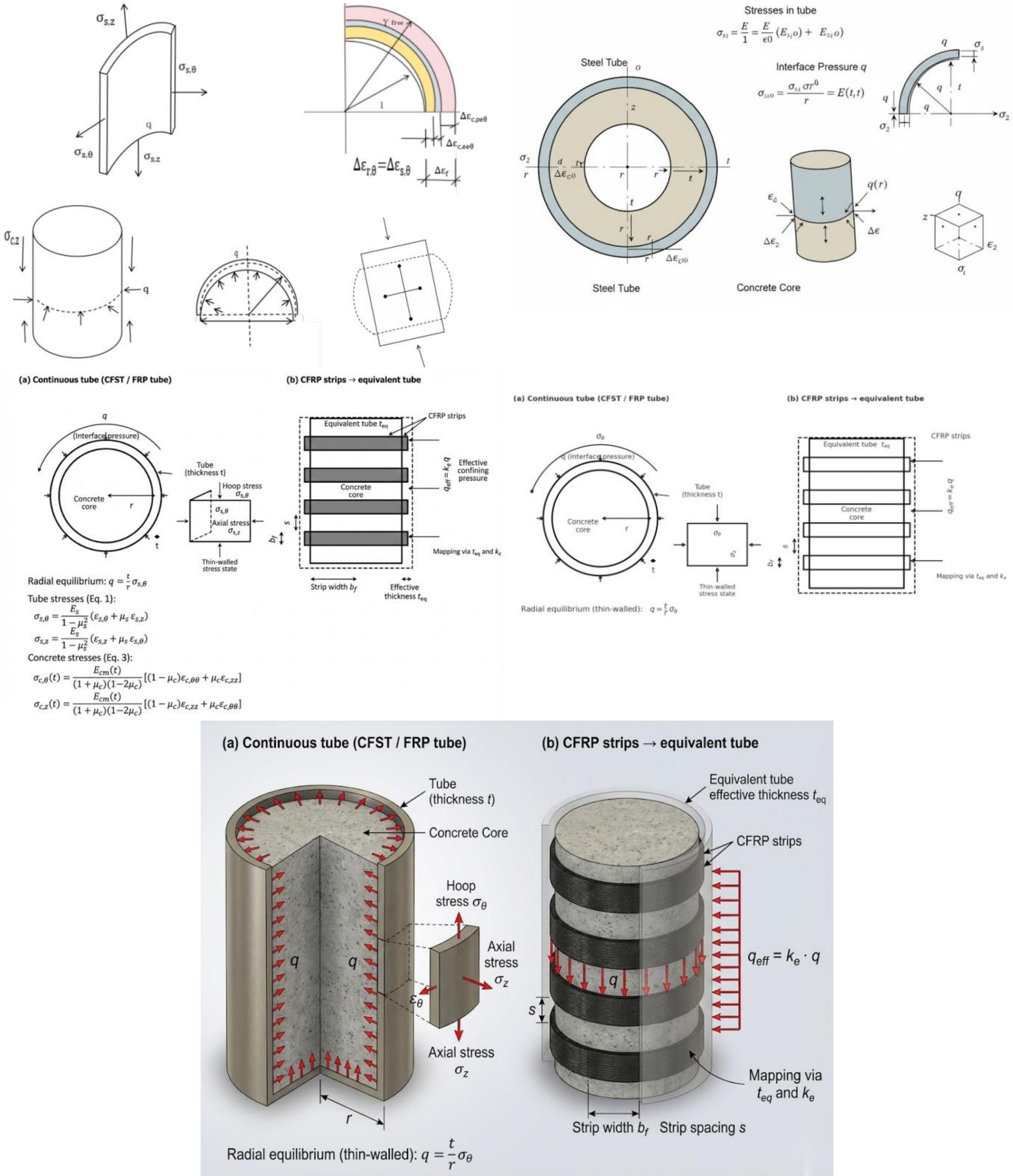


**Figure 3** – Tube-based mechanical model and its analogy with CFST/FRP-tube members

When constraints are weaker – that is, when strip spacing is large and arching effects struggle to form a continuous, effective core in the height direction – failure often initiates earlier in the concrete at strip gaps. Due to insufficient confining pressure in these gap regions, the concrete is more prone to bulging outward under axial compression. The combined action of tensile strain induced by bulging and shear strain then leads to longitudinal cracks, diagonal cracks, and even local spalling. The aged mortar interface and multiple inter-tension zones (ITZ) in recycled aggregate concrete readily compromise its shear and tensile load-bearing pathways. resulting in more pronounced shear slip zones and distinct brittle behaviour. Even when CFRP strips have not reached ultimate strength or ultimate strain $\epsilon_f$, members may prematurely lose overall load-carrying capacity due to localised core concrete instability and failure of the load-transfer chain [17]. Under such circumstances, the strips function more as ‘restricting crack propagation and delaying delamination’ rather than providing full-height confinement pressure. Consequently, their contribution to peak strength and ultimate deformation is markedly capped.

Mixed failure is more likely to occur under combinations of moderate confinement stiffness or high expansive agent dosage, often manifesting as a composite outcome of 'pre-loading state' and 'loading evolution'. Should the chemical prestress induced by expansion be substantial, CFRP strips may approach their tensile strength limit early in axial loading, thereby limiting subsequent strain development. Concurrently, excessive strip spacing or uneven local release may permit micro-precracks to form in the gap zone concrete during the free expansion phase. These may rapidly evolve into shear zones upon axial loading application. At this juncture, CFRP failure and shear crushing of concrete at the gap may occur in close temporal proximity. Macro-scopically, this manifests as FRP failure and localised concrete failure occurring almost simultaneously, resulting in a more abrupt and discrete failure process. Consequently, the residual load-bearing capacity and failure warning characteristics of the specimen become relatively weaker.

4.2 Full-Cycle Axial Stress–Strain Response

Under axial compression, the axial stress–strain curve of CFRP-strip-constrained RAC generally exhibits typical bilinear characteristics. However, its curve morphology, key inflection point locations, and late-stage evolution patterns demonstrate more pronounced differences compared to the constraint responses of conventional passive-constrained or ordinary natural aggregate concrete [2]. This divergence stems from the active confinement system introducing non-zero confining pressure and prestressing conditions from the onset of loading. This places the material under stronger triaxial compression and crack closure from the initial stage. while the strip-like partial confinement significantly influences the spatial distribution and load-dependent uniformity of confining pressure through geometric constraints. Consequently, each segment of the curve bears the combined imprint of both 'chemical prestressing' and 'arch effect confinement'.

During the initial response phase, the curve typically exhibits a steeper ascent, reflecting higher initial stiffness and a lower early damage growth rate. This primarily stems from expansion-induced chemical prestressing, which promotes closure of existing microcracks and elevates crack initiation stress levels. Consequently, RACs under macroscopic compression exhibit deformation patterns closer to those of continuous media. Simultaneously, the confining pressure background suppresses shear expansion, favouring the conversion of axial compression into volumetric compaction and skeletal co-loading. This enhances the equivalent elastic modulus during the curve's initial segment. When incorporating prestress as an initial condition, the curve's origin typically deviates from the absolute starting point, exhibiting rapid stress growth within the low-strain range. This 'origin offset' does not indicate measurement anomalies but reflects pre-existing stress reserves and crack closure effects within the system prior to loading.

As axial stress further increases, the region where the curve transitions from the initial near-linear segment to the second stage typically corresponds to the 'knee point'. This point may be regarded as the critical location where the core concrete shifts from predominantly elastic deformation to predominantly plastic damage participation. Active confinement generally significantly elevates the stress level corresponding to the knee point, delaying the onset of the pronounced damage accumulation phase. This enables the material to maintain more stable stiffness and more controllable deformation development within the service load range. This is particularly crucial for recycled aggregate concrete, as its interfacial transition zone (ITZ) defects are more readily activated at lower stress levels. Active confining pressure suppresses crack initiation, raising the threshold for micro-to-macro crack transition and promoting finer, more dispersed damage development.

Upon entering the strengthening phase, the secondary stiffness curve is primarily governed by CFRP strip stiffness and confinement efficiency. However, under strip confinement, secondary stiffness often exhibits more pronounced specimen variability. This arises because the arching effect dynamically adjusts with increasing load and shear expansion evolution, while confining pressure levels in the void zone and strip-covered zone do not increase synchronously. For RAC, owing to its stronger constitutive softening tendency, a rising strengthening segment may still form under sufficient confinement, though its slope may be slightly lower than that of natural aggregate concrete, manifesting as a slower load capacity increase. When confinement is insufficient or significant prior damage occurs in the void zone, the curve may exhibit premature softening trends, or even enter a descending branch after the peak. At this stage, the magnitude of load capacity enhancement is constrained, and the development of ultimate strain becomes more dependent on the deformation space released by local spalling and shear zone expansion.

Near the ultimate state, the influence of recycled aggregate replacement rate often presents a combined characteristic of 'decreased strength but potentially increased deformation capacity'. As the replacement ratio increases, the peak stress of the core concrete typically decreases, consistent with the fundamental principle of reduced material strength and interface quality. However, under triaxial compression and confining pressure constraints, the porous structure of RAC actually endows it with greater compaction potential. This allows it to accommodate more compaction deformation and shear-expansion-constrained deformation before overall crushing occurs, potentially increasing ultimate strain and exhibiting more pronounced ductile characteristics [20]. It should be noted that this enhanced ductility does not equate to reduced damage; rather, it manifests as 'more dispersed damage and a more gradual evolution'. Whether this translates into reliable engineering toughness ultimately depends on whether the strip spacing, number of layers, and expansion prestress collectively maintain the stability of the effectively constrained core, thereby preventing premature localised instability in the interstitial zones from dominating failure.

4.3 Key Parameter Sensitivity and Design Implications

For actively restrained RAC expansive concrete, the parameters influencing axial compression performance typically interact through three pathways: geometric constraints, chemical prestressing levels, and matrix material variations. Certain parameters exhibit high sensitivity to restraint efficiency, where slight deviations from optimal ranges may induce qualitative changes in failure modes and stress-strain responses. Regarding geometric configuration, the net spacing between strips and strip width constitute the most direct combination of parameters determining effective confinement. The net spacing exhibits particular sensitivity in influencing the effective confinement coefficient. Existing research indicates that as net spacing increases, the effective confinement coefficient follows an approximate quadratic decay pattern. This implies that increased spacing not only linearly reduces the confining pressure level but also significantly amplifies adverse effects by diminishing the effective confinement core area. When $s'/d$ is small, the specimen's overall response more closely resembles the hardening behaviour of fully wrapped confinement, with a more pronounced curve-strengthening segment and a more significant increase in peak load-bearing capacity. When $s'/d$ exceeds a critical threshold – commonly reported around 0,5 – the arching effect struggles to stabilise vertically. Bulging in the gap zone and expansion of shear bands begin to dominate failure, making stress–strain curves more prone to softening segments and causing load-bearing gains to plummet sharply [17]. Under such conditions, the strips primarily inhibit crack width and local spalling rather than sustainably providing adequate confining pressure. Consequently, even increasing the strip strength grade may not linearly translate to higher peak strength.

The influence of expansive agent dosage on active confinement exhibits a characteristic non-monotonic behaviour, fundamentally stemming from a significant trade-off between 'beneficial prestressing' and 'self-damage or depletion of strength reserves'. An appropriate expansion agent dosage establishes a reasonable chemical prestressing background prior to loading, enhancing initial stiffness and elevating the stress level at the knee point. This stabilises the material within the service stress range while also reducing the activation of early microcracks, thereby providing a more complete microstructural foundation for subsequent strengthening phase development. However, excessive dosage may yield adverse consequences through two pathways: firstly, during the free expansion phase, insufficient confinement may induce expansion cracks in the matrix, creating irreversible self-damage that compromises integrity at the onset of subsequent compression loading; Secondly, excessive expansion may cause CFRP strips to consume excessive strength and strain reserves prior to loading, effectively increasing the initial tensile level and reducing the subsequent available $\epsilon_f$ space. This diminishes deformation potential and load-bearing reserves at ultimate limit states [2]. Consequently, the optimal range for expansive agent dosage typically aligns with the constraint stiffness and RAC strength grade. Within this range, the establishment of chemical prestress significantly amplifies the effectiveness of strip confinement. Deviations from this range may lead to two distinct issues: 'ineffective prestress conversion' or 'reverse prestress damage'.

The replacement rate of recycled aggregates primarily influences the overall performance of the active confinement system by altering the fundamental mechanical properties, lateral deformation capacity, and time effects of the core concrete. As the replacement ratio increases, the elastic modulus of the RAC typically decreases, enhancing its tendency for lateral deformation and consequently increasing its lateral deformation coefficient. Within passive restraint systems, this characteristic may prompt FRP to enter tension earlier and become 'activated' sooner. However, in active restraint systems, confining pressure is already present prior to loading. Therefore, variations in replacement ratio more prominently manifest as the 'level of restraint required' to compensate for the loss in matrix strength and achieve the target performance level. In other words, when RAC strength diminishes and defects proliferate, insufficient constraint strength or an inadequate effective core zone may lead to failure being dominated by localised failure in the gap zone, thereby undermining the advantages of active confinement. Furthermore, the relatively high creep and pronounced long-term deformation characteristics of RAC may lead to more significant loss of chemical prestressing over time, resulting in an actual $\sigma_{l,ini}$ during loading that falls below design expectations. This time-dependent prestressing decay warrants particular consideration within design and evaluation frameworks under long-term service conditions [7]. Consequently, the replacement ratio not only determines the 'level of strength' but also alters the actual working state of the restraint system through lateral deformation and time effects. This, in turn, influences the overall shape of the stress – strain curve and the final failure mode classification.

To quantify the impact of the above parameters, we use a comprehensive data table to compare typical experimental results. Table 1 clearly shows that introducing active constraints (A) can further improve the strength compared to passive constraints (P); although the gain of strip constraints is lower than that of full constraints, the performance of active strip constraints (RAC-A-Strip) is close to or even exceeds that of ordinary full-enclosed passive constraints, proving the efficiency of this technical approach.

**Table 1** – Typical influence of expansive agent dosage on active confinement effectiveness [2]

| Specimen Type | Restraint Method | Expansion agent dosage (%) | Aggregate Type | Peak stress gain (%) | Maximum Strain Gain (%) | Failure Modes |
|---|---|---|---|---|---|---|
| RAC-Ctrl | Unrestrained | 0 | 100 % RCA | – | – | Shear Failure |
| RAC-P-Full | Fully Enclosed Passive | 0 | 100 % RCA | +120 % | +350 % | FRP Fracture |
| RAC-P-Strip | Strip Passive | 0 | 100 % RCA | +65 % | +180 % | Gap Crushing |
| RAC-A-Full | Fully Enclosed Active | 10 | 100 % RCA | +145 % | +320 % | FRP Fracture |
| RAC-A-Strip | Strip Active | 10 | 100 % RCA | +95 % | +210 % | Mixed Mode |
| RAC-A-HighExp | Strip Active | 20 | 100 % RCA | +85 % | +150 % | Pre-cracking/FRP Fracture |

Note – Although the source data comes from GFRP specimens, the non-monotonic trend of strength gain regarding expansion dosage is representative and applicable to CFRP systems discussed in this review.

**5 Progress and Evaluation of Constitutive Model Research**

Establishing constitutive models with sufficient accuracy and transferability is a prerequisite for structural design, load-bearing capacity verification, and nonlinear finite element analysis. For CFRP strip-constrained recycled aggregate expansive concrete, both the material and constraint system exhibit characteristics such as a multi-defect matrix caused by recycled aggregates, an initial stress state introduced by expansive agents, and a non-uniform constraint stress field resulting from the strip configuration. These features render the stress-strain relationship no longer a simple response explainable by a single mechanism. Consequently, existing research typically advances along two main lines: on the one hand, targeted modifications to classical FRP-constrained concrete models to enable their application in predicting limit states for engineering design; on the other hand, a greater emphasis on constructing incremental analysis models based on physical mechanisms to generate full curves and reproduce path-dependent responses under active confinement conditions. Within this framework, a model's universality is often demonstrated by its compatibility with diverse constraint configurations, aggregate systems, and expansion levels. Its usability, meanwhile, manifests as a balance between parameter identifiability, computational stability, and engineering expressiveness.

5.1 Design-Oriented Ultimate State Models

Design-oriented models prioritise direct prediction of ultimate state indicators, typically employing peak stress $f_{cc}'$ and ultimate strain $\epsilon_{cu}$ as core outputs. They provide engineering convenience through explicitly formulated equations that are as concise as practicable. The advantage of such models lies in their compatibility with structural verification and standardised applications, enabling rapid establishment of quantitative relationships between 'constraint strength and load-bearing capacity gains'. However, their limitations are also evident: they offer relatively limited capability to characterise stiffness evolution, inflection point locations, and softening behaviour throughout the loading process. Consequently, they are often regarded as result-oriented ultimate state estimation tools rather than complete constitutive expressions directly driving full-process numerical analysis.

5.2 Modifications to Classical Models

Among numerous ultimate limit state models, the Lam and Teng model is widely adopted due to its clear formulation and readily obtainable parameters. Its fundamental expression can be written as

$$\frac{f'_{cc}}{f'_{co}} = 1 + 3.3\frac{f_l}{f'_{co}}, \qquad \frac{\epsilon_{cu}}{\epsilon_{co}} = 1.75 + 12\frac{f_l}{f'_{co}}\left(\frac{\epsilon_{h,rup}}{\epsilon_{co}}\right)^{0.45}. \qquad (5)$$

Among these, $f_{co}'$ and $\epsilon_{co}$ typically correspond to the peak stress and peak strain of unconstrained concrete, $f_l$ denotes the nominal lateral confinement pressure, while $\epsilon_{h,rup}$ relates to FRP rupture. For the CFRP strip-enhanced active confinement (RAC) system, direct application of the aforementioned model often introduces systematic biases concerning confinement effectiveness and initial stress state. Consequently, researchers typically extend and modify the model across three dimensions: confinement non-uniformity, material variations within RAC, and the contribution of active confining pressure [9]. Firstly, to account for height-direction non-uniformity in confinement caused by strip spacing, the concept of effective confinement pressure should be introduced. This replaces $f_l$ with $f_{l,eff} = k_e \cdot f_l$, where $k_e$ is typically determined using arch effect-related formulas. When the cross-section is rectangular or corner effects are present, $k_e$ often requires consideration alongside shape coefficients to account for non-uniformity in both height and cross-sectional directions. Secondly, recognising that the matrix strength and deformation characteristics of RAC differ from those of natural aggregate concrete, some models further incorporate reduction factors related to the replacement ratio $r$. These factors characterise the weakening effect of inherent defects and multiple interfacial transition zones (ITZs) on strength gain. For instance, the strength gain term may be expressed as $(1 - \alpha \cdot r)$ to reflect RAC's material properties. More significantly, under expansive concrete conditions, the confinement system already possesses an initial confining pressure $f_{l,ini}$ induced by expansion prior to external loading application. Consequently, it is essential to explicitly incorporate the active confinement contribution within the limit state expression. Some studies favour a superposition approach, decomposing the total strength gain into the sum of passive confinement gain and active prestressing gain, expressed as $f_{cc}'' = f_{co}'' + \Delta f_{passive} + \Delta f_{active}$, where $\Delta f_{active}$ is treated as a term proportional to the level of chemical prestressing [3]. This approach maintains relative engineering simplicity while enabling the model to establish a more direct mapping relationship between two key mechanisms: strip non-uniform confinement and expansion-induced active confining pressure.

5.3 Incremental constitutive models for analysis

Models designed for analysis place greater emphasis on the generation and evolution mechanisms of the full stress-strain curve. Their objective is not merely to provide $f_{cc}'$ and $\epsilon_{cu}$, but to reconstruct the entire response process – from the elastic stage through the strengthening stage to post-peak softening or failure – via an incremental iterative procedure. Such models typically reference a family of stress–strain curves under active constraint conditions. By progressively updating confining pressure, lateral strain, and damage variables, they solve the equilibrium relationship between axial stress and constraint reaction forces at each strain increment. As strip constraints induce simultaneous spatial and temporal variations in confining pressure, incremental models offer distinct advantages in handling 'evolutionary rather than constant confining pressure'. Consequently, they are frequently employed for numerical calibration, parameter sensitivity analysis, and explaining complex constraint mechanisms.

5.4 Correction of Lateral Dilation Relationship

In analytical models, the relationship between axial strain $\epsilon_c$ and lateral strain $\epsilon_l$ is usually given by the dilation model, which is a key factor determining the evolution of confining pressure and the rate of constraint activation. For RAC, due to differences in Poisson's ratio, dilatation angle, and pore compaction behavior compared to ordinary concrete, its lateral dilation is more likely to enter nonlinear growth at lower stress levels, and the volumetric dilation point appears earlier than in natural aggregate concrete. This phenomenon suggests that RAC may activate passive constraints earlier, and also indicates that it is more prone to localized damage and premature weakening of constraint efficiency when constraints are insufficient. Including expansive concrete further complicates the problem because the system may initially possess non-zero transverse strain as an expansive strain background. This means the evolution of transverse strain no longer starts from zero, but requires the introduction of an initial strain term $\epsilon_{l,0}$ into the model to correct the superposition of the expansion path and subsequent Poisson effect [9]. From a computational perspective, the introduction of $\epsilon_{l,0}$ not only affects the starting point of the confining pressure but also alters the mapping slope in subsequent incremental iterations where "the current confining pressure is determined by the current transverse strain." Therefore, its influence on the overall curve morphology often extends throughout the entire process, not just to the initial stage.

5.5 Path-Dependent Constitutive Models

A common approach in traditional analytical models is to assume that the stress state of FRP-confined concrete passes through a series of active constraint curves under constant confining pressure, and to construct the overall response based on this. However, in actively constrained systems, this assumption faces two real-world differences: firstly, the starting point of active constraint is not at zero confining pressure; the initial confining pressure and initial transverse strain alter the damage initiation conditions; secondly, during loading, the confining pressure continuously adjusts with expansion, Poisson's effect, and shear dilatation, and strip constraints give this adjustment a distinctly non-uniform characteristic. Based on these understandings, recent research has proposed model frameworks that emphasize path dependence, clearly distinguishing the different effects of passive and active constraint paths on damage accumulation rate, yield evolution, and strength degradation behavior [9]. In terms of implementation, these models often utilize plasticity theory, introducing kinematic hardening criteria into the constitutive relation to describe the effect of expansion prestress on the position and shape of the yield surface, thus mathematically reflecting the path dependence phenomenon that "the same final confining pressure but different loading histories lead to different strengths and ductility." Compared to simply superimposing active prestress into a constant confining pressure term, path-dependent models emphasize the continuous influence of prestress on the internal state variables of the material, thus demonstrating greater mechanistic consistency in explaining the differences between early damage suppression and later strengthening.

5.6 Unified Constitutive Framework

To describe the differences between fully enclosed and strip-enclosed concrete, natural aggregate concrete and RAC, and ordinary concrete and expansive concrete within the same theoretical framework, some scholars have attempted to establish a unified constitutive framework, merging geometric nonhomogeneity and material nonhomogeneity through higher-level parameters or energy indices. The model proposed by Shayanfar et al. is representative, its core idea being to construct a unified expression based on energy balance and combined with effective constraint coefficients [16]. This framework introduces the concept of energy integral, assuming that the total energy density corresponding to the FRP reaching the fracture state can be considered approximately constant, thereby uniformly converting the height nonhomogeneity caused by strip spacing and the horizontal nonhomogeneity caused by cross-sectional shape to the same scale through energy dissipation coefficients. Because energy methods can simultaneously incorporate information from both strength and deformation dimensions, these frameworks often exhibit good universality in predicting limit states under complex constraints, and are also more convenient for comparing and calibrating different experimental databases under a unified benchmark.

5.7 Machine Learning Modeling Methods

Given the numerous parameters involved in CFRP strip active constraint RAC, and the significant nonlinear coupling relationships between variables such as strip spacing, strip width, number of layers, FRP elastic modulus, RAC replacement rate, and expansion level, traditional regression-based mechanical models often struggle to simultaneously achieve simplicity and high accuracy. In recent years, data-driven methods have gradually become an important supplement. Algorithms such as Artificial Neural Networks (ANN), Genetic Expression Programming (GEP), and Support Vector Machines (SVM) have been used to construct high-precision predictive models. Their basic strategy is to use large-scale experimental databases for training and capture implicit higher-order coupling patterns through statistical learning. Compared to explicit mechanical models, which require clearly defining the contribution of each mechanism, machine learning models excel at identifying relationships that are difficult to model directly, such as the nonlinear mapping between microstructural differences in recycled aggregates and the hydration process of the expansive agent. Therefore, in predicting key indicators such as $f_{cc}'$ and $\epsilon_{cu}$, well-trained ANN models often achieve higher fits, with their coefficient of determination $R^2$ outperforming traditional mechanical models in some studies [12]. However, from an engineering application perspective, the interpretability, extrapolation boundaries, and data quality sensitivity of these models still require further cross-database validation. Therefore, a more reasonable approach is often to use them as a supplement to mechanistic models, employing them for parameter selection, sensitivity identification, and model error correction.

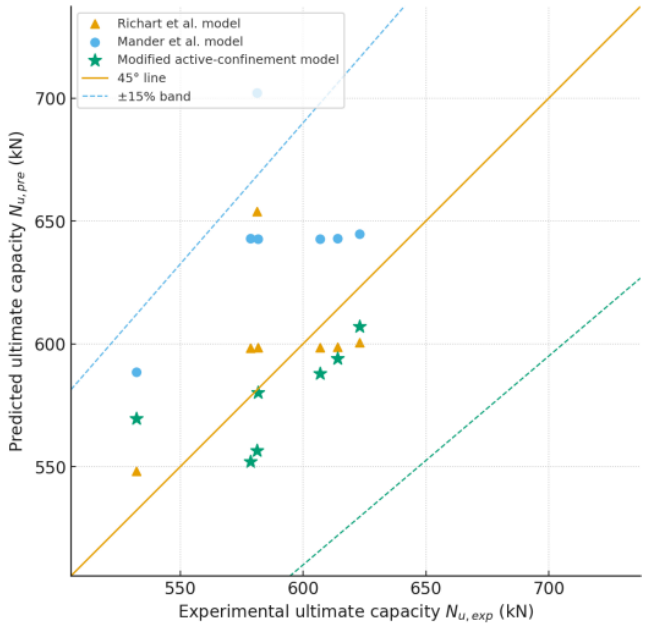


**Figure 4** – Schematic illustration of the comparison between model predictions and experimental data [26, 27]

To evaluate the applicability of different models in this complex system, a scatter plot comparing model predictions and experimental measurements can be used for intuitive verification. This graph uses the experimentally measured ultimate compressive strength as the horizontal axis and the model-predicted ultimate compressive strength as the vertical axis, with a 45-degree diagonal as the baseline for "prediction equals measurement." The position and dispersion of the scatter points relative to the diagonal reflect the model's bias and stability. If the results of the uncorrected Lam & Teng model are plotted, the scatter points tend to be more concentrated below the diagonal, exhibiting a systematic underestimation trend. This is because the model does not explicitly consider the contribution of initial confining pressure caused by expansion, resulting in insufficient characterization of active constraint gains. If a Mander-type model considering RAC correction is used, the scatter point distribution may be even more discrete [25]. Although the model introduces material-level reduction to reflect the strength differences of RAC, the Mander model is initially based on the assumption of steel hoop constraint, and the constraint pressure is closer to the confining pressure expression under constant yield stress. Therefore, it is difficult to stably describe the global law when facing the variable confining pressure mechanism corresponding to FRP linear elastic constraints. In contrast, when the model explicitly introduces the effective constraint coefficient $\mathrm{k_e}$ and incorporates the active confining pressure term $\mathrm{f_{l,ini}}$, the predicted scatter points tend to be more closely distributed around the 45-degree diagonal, and the error band is more convergent. This indicates that simultaneously incorporating the geometric effect of the strip non-uniform constraint and the initial state of the expansion active constraint into the model is a key approach to improving prediction accuracy and reducing system bias.

**Durability and Long-Term Performance Considerations**

While CFRP strip active restraint systems can significantly improve the load-bearing capacity and deformation performance of recycled aggregate expansive concrete (RAC), from an engineering application perspective, the time effects and environmental impacts experienced by structures during their service life are often more complex. Therefore, their long-term performance and durability also need to be systematically incorporated into the evaluation and design framework. Especially under active restraint conditions, the chemical prestress and confining pressure established in the initial stage of the system do not remain permanently unchanged. The evolution of the material's volumetric deformation, the attenuation of interfacial bonding, and the cumulative effects of environmental erosion can all gradually alter the actual working state of the restraint system, thus affecting long-term safety and performance stability.

First, the coupled effects of creep and shrinkage need to be considered. Because recycled aggregates contain old mortar and have a more developed pore structure, the creep coefficient and shrinkage rate of RAC are usually significantly higher than those of natural aggregate concrete (NAC), making it more prone to additional deformation over time during long-term service. In FRP active confinement systems, concrete shrinkage, especially drying shrinkage, macroscopically offsets some of the chemical prestress established by the expansive agent, resulting in a "prestress loss" as the initial prestress level decreases over time. This loss is not merely a numerical attenuation; it also signifies a decrease in the confining pressure initiation point, a weakening of the crack closure effect, and a lowering of the threshold for entering the damage accumulation stage, thus having a cascading effect on subsequent load-bearing capacity and crack control capabilities. Simultaneously, under long-term high stress levels or repeated loading, concrete creep causes a redistribution of stress between the concrete and the CFRP strips. Tensile stress in the strips may relax or shift, and this stress redistribution alters local confinement strength and further amplifies the spatial non-uniformity of confinement efficiency. For strip systems, the concrete in the gap zone is more directly exposed to the external environment, resulting in more thorough moisture exchange and often more severe drying shrinkage. Therefore, the resulting confinement attenuation is more likely to first appear near the strip gaps, thus affecting the continued establishment of the arch effect and the long-term stability of the effective confinement core [15]. From a design perspective, this means that peak strength or ultimate strain obtained from short-term tests cannot be used as the sole basis for assessment. Instead, long-term prestress loss should be predicted and verified as a key parameter, and a reasonable safety margin should be reserved for it in material selection, strip construction, and curing and protection strategies.

Secondly, the degradation of interfacial properties under environmental erosion conditions is also a crucial factor determining the durability of the system. In complex environments such as freeze-thaw cycles, sulfate attack, chloride exposure, or alternating wet and hot conditions, the interfacial bond performance between CFRP and concrete may decline over time. Changes in bond-slip behavior directly affect the efficiency of strip constraint force transfer to concrete. Because strip structures are more prone to desquamation-sensitive zones at the ends and edges, and these areas are often accompanied by stress concentration and increased strain gradients, once interfacial properties degrade, desquamation failure is more likely to be triggered prematurely at the ends, making it difficult to maintain the confining pressure that was originally established by strip tension. For expansive concrete, environmental effects can further influence internal damage evolution by altering the stability of hydration products. For example, ettringite generated by the reaction of the expansive agent may decompose under high temperature or sulfate attack conditions, or induce delayed ettringite formation (DEF) under specific temperature and humidity conditions. This can lead to the propagation of internal microcracks and disrupt the existing constraint equilibrium, causing the confining pressure background and damage state to evolve unfavorably over time [4]. It is worth noting that CFRP materials themselves have good resistance to corrosion and chemical media. Their presence can, to some extent, act as an external coating barrier, slowing down the penetration and diffusion of corrosive media into the core concrete, thereby delaying the deterioration of internal materials. However, this protective effect does not mean that the durability requirements of the interface and end details can be ignored. Especially at critical locations such as strip edges, bonded ends, and the concrete surface of gap areas, it is necessary to reduce the impact of long-term degradation on the overall performance of the system through reasonable interface treatment, end anchoring, and surface protection measures.

**Conclusion**

Based on existing research, it can be concluded that introducing an expansive agent into recycled aggregate concrete and coupling it with CFRP strip confinement to form an active confinement system can establish chemical prestress before loading, making the core concrete closer to a triaxial compression state, thereby delaying microcrack development and improving elastic limit and bearing capacity [2]. Simultaneously, the high water absorption and release capacity of recycled aggregates can manifest as an internal curing effect in the expansive system; continuous water supply is beneficial for the expansion reaction and densification of the interfacial transition zone, and mitigates the adverse effects of self-drying shrinkage [11]. Strip confinement relies on the arch effect to provide effective confining pressure. If the net spacing of the strips is controlled within approximately $0.5$ times the column diameter, and the active compensation brought about by expansion is utilized, the disadvantages of non-uniform strip confinement can be compensated to some extent, achieving a near-fully encapsulated mechanical effect while balancing economy and permeability.

At the model level, constitutive research is moving from empirical regression to a unified analytical framework that can simultaneously consider path dependence, damage evolution, and geometric non-uniformity. Explicitly introducing the effective constraint coefficient $k_e$ and the active confining pressure term is often key to improving prediction accuracy. Further work needs to supplement evidence on both service life and environmental effects, focusing on clarifying the prestress loss mechanism caused by the coupling of long-term effects of CFRP creep, RAC shrinkage, and expansion, and revealing the impact of FRP-concrete interfacial bond degradation on constraint efficiency under freeze-thaw cycles, corrosion, and fire. Simultaneously, developing mesoscopic numerical models that can characterize the random aggregate distribution, non-uniform expansion nucleation, and interfacial slip in RAC, and combining these with machine learning to extract implicit patterns from large-scale databases, will contribute to achieving more accurate performance-based design [6].

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# THE BEHAVIOR OF REINFORCED CONCRETE SLABS ON BASES SUBJECTED TO SHRINKAGE AND CONSTRUCTED WITH COMPLEX HOLE GEOMETRIES

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**Abstract**

This paper presents a comprehensive study on shrinkage cracking in large-scale concrete slabs with complex openings, a critical concern for industrial and civil structures like nuclear plant foundations and industrial floors. The research systematically quantifies the influence of key geometric parameters – hole shape (circular, elliptical, hexagonal) and spatial distribution (centrally symmetric, eccentric, random multi-hole patterns) – on the shrinkage interaction between the slab and its foundation. An integrated methodology combining full-scale experimental testing on 4 × 4 × 0,25 m slabs, theoretical modeling using an enhanced Pasternak – Vlasov foundation model, and detailed finite element analysis (FEA) in Abaqus was employed. Results demonstrate that elliptical holes induce the most severe stress concentration, increasing shrinkage stress by approximately 33 % compared to circular holes, while random multi-hole configurations raise corner stresses by 42 % due to global stiffness reduction. Eccentricity was found to linearly shift the zero-shear stress location (Δx = 0,75 e). A novel predictive model for the stress concentration factor (Kt), incorporating shape aspect ratio (λ), relative eccentricity (e/l), and number of holes (n), was developed with high accuracy ($R^2$ = 0,92). The study provides essential parameters and robust theoretical support, leading to practical design recommendations for reinforcement detailing and hole geometry optimization to enhance crack resistance in perforated slabs, thereby enabling more reliable and economical engineering solutions.

**Keywords:** concrete large slabs, complex holes, geometric parameters, shrinkage stress, interaction.

## ПОВЕДЕНИЕ ЖЕЛЕЗОБЕТОННЫХ ПЛИТ НА ОСНОВАНИИ ПОДВЕРЖЕННЫХ УСАДКЕ И ВЫПОЛНЕННЫХ СО СЛОЖНОЙ ГЕОМЕТРИЕЙ ОТВЕРСТИЙ

**Нань Моу, А. Е. Желткович**

**Реферат**

В данной статье представлено всестороннее исследование усадочных трещин в крупногабаритных бетонных плитах со сложными отверстиями, что является критически важной проблемой для промышленных и гражданских сооружений, таких как фундаменты атомных электростанций и промышленные полы. В ходе исследования систематически количественно оценивается влияние ключевых геометрических параметров – формы отверстий (круглая, эллиптическая, шестиугольная) и пространственного распределения (центрально-симметричное, эксцентричное, случайное расположение нескольких отверстий) – на усадочное взаимодействие между плитой и ее фундаментом. Была использована интегрированная методология, сочетающая полномасштабные экспериментальные испытания плит размером 4 × 4 × 0,25 м, теоретическое моделирование с использованием усовершенствованной модели фундамента Пастернака – Власова и детальный анализ методом конечных элементов (FEA) в Abaqus. Результаты показывают, что эллиптические отверстия вызывают наиболее сильную концентрацию напряжений, увеличивая усадочные напряжения примерно на 33 % по сравнению с круглыми отверстиями, в то время как случайные конфигурации с несколькими отверстиями повышают угловые напряжения на 42 % из-за общего снижения жесткости. Было обнаружено, что эксцентриситет линейно смещает местоположение нулевого сдвигового напряжения (Δx = 0,75 e). Была разработана новая модель прогнозирования коэффициента концентрации напряжений (Kt), включающая в себя соотношение сторон формы (λ), относительную эксцентриситет (e/l) и количество отверстий (n), с высокой точностью ($R^2$ = 0,92). Исследование предоставляет важные параметры и надежную теоретическую поддержку, что позволяет сформулировать практические рекомендации по проектированию арматуры и оптимизации геометрии отверстий для повышения сопротивления растрескиванию перфорированных плит, что в свою очередь обеспечивает более надежные и экономичные инженерные решения.

**Ключевые слова:** большие бетонные плиты, сложные отверстия, геометрические параметры, усадочное напряжение, взаимодействие.

### Introduction

Large-scale concrete slabs, such as those employed in nuclear power plant containment foundations and expansive industrial floors, invariably require the incorporation of openings to accommodate essential equipment and service conduits. The introduction of these geometrically complex perforations disrupts the structural continuity and alters the stiffness distribution of the slab. Consequently, under the restraining action of the foundation, shrinkage-induced tensile stresses are not uniformly distributed but instead concentrate at the peripherals of the openings and the corners of the slab. This stress concentration phenomenon significantly elevates the propensity for cracking [9].

Prevailing structural design codes, including GB50010 and ACI318, primarily provide guidance for reinforcement detailing around singular, centrally located circular openings [4, 20]. However, these specifications lack comprehensive provisions for non-circular hole geometries or asymmetric distribution patterns. This regulatory shortfall often leads to inadequate crack control in practical engineering scenarios, as the influence of critical geometric parameters – such as shape, eccentricity, and proximity of multiple holes – is not sufficiently accounted for in the design phase [10]. Consequently, improper consideration of these dimensional attributes is a frequent contributor to cracking failures in actual structures [2].

The phenomenon of shrinkage stress in perforated plates has been the subject of considerable research efforts domestically and internationally [12, 18]. For instance, Kumar et al. determined stress concentration factors for square openings via photoelastic experimentation, reporting values approximately 20 % greater than those for circular holes [11]. A limitation of this work, however, is its omission of other geometrically complex hole profiles commonly encountered in engineering practice, such as elliptical and hexagonal openings [8]. Subsequent investigations by Zhang et al., utilizing finite element analysis, demonstrated that the presence of eccentric holes alters the distribution of shear stresses, shifting the location of minimum shear within the slab [15]. Notwithstanding this insight, their model did not incorporate the critical parameter of foundation constraint stiffness, which fundamentally governs the slab-foundation interaction [5]. A prevalent gap in the existing literature is the predominant focus on isolated hole typologies, resulting in a lack of systematic comparative analysis across a spectrum of sizes, shapes, and spatial arrangements. Consequently, a significant discrepancy remains between prevailing theoretical models and the complex, multi-variate conditions characteristic of actual engineering applications [16].

To address these research gaps, the present study employs a full-scale experimental approach utilizing large concrete slabs measuring 4 × 4 × 0,25 m. The experimental matrix is designed to systematically investigate three distinct hole shapes – circular, elliptical, and hexagonal – under three distribution patterns: centrally symmetric, eccentric, and random multi-hole configurations. By integrating full-scale testing with theoretical modeling and finite element simulation, this research elucidates the mechanistic influence of complex hole geometric parameters on the shrinkage interaction behavior between the slab and foundation [3]. The ultimate objectives are to establish a practical predictive model for shrinkage stress applicable to engineering design and to provide a robust theoretical basis for the crack-resistant design of perforated slabs.

**Materials and Methods**

The geometric configuration of openings within a slab is defined by a set of distinct parameters, which are systematically classified in this study into three primary categories: shape, distribution, and quantity.

● The category of Shape Parameters characterizes the cross-sectional geometry of the opening. The investigated shapes:

– are Circular – Defined by its radius, *R*;

– Elliptical – Defined by its major semi-axis *a*, minor semi-axis *b*, and the aspect ratio *λ* = *a*/*b*;

– Regular Hexagonal – Defined by its side length *c*, with an equivalent diameter calculated as *D* = 1,1547*c* for comparative analysis.

● The category of Distribution Parameters describes the spatial arrangement of the hole(s) relative to the slab's centroid:

– Centrally Symmetric: Holes positioned with an eccentricity *e* = 0;

– Eccentric – Holes with a defined offset from the center, within a range of *e* = 0,5–1,5 m;

– Randomly Distributed: Configurations of 3 to 5 holes, whose coordinates (*xi*, *yi*) satisfy the conditions |*xi*|, |*yi*| ≤ 1,8 m and maintain non-overlapping boundaries.

● The category of Quantity Parameters specifies the number of openings present:

– Single hole;

– Double holes, with a center-to-center spacing in the range *s* = 1,0–2,0 m;

– Multiple holes, where the number of holes *n* = 3–5.

A schematic representation illustrating the classification of these complex hole geometric models is provided in Figure 1.

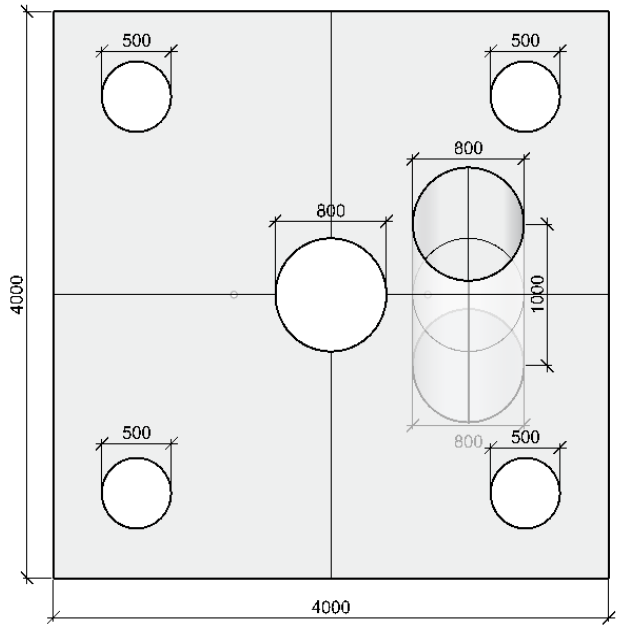


**Figure 1** – Schematic diagram of the classification of complex hole geometric parameters

The classical Winkler foundation model, which assumes independent linear springs, is insufficient to capture the shear interaction at the plate-foundation interface, especially when considering the effects of shrinkage and potential shear keys. To account for this, a two-parameter Pasternak – Vlasov model is adopted, which incorporates a shear layer over the Winkler springs. Within the framework of this model, the governing differential equation for the plate with holes, considering shrinkage effects, takes the following form

$$D\nabla^4\omega + K_p\omega = -\alpha T D\nabla^2\omega.$$

Where $= \frac{Eh^3}{12(1-\nu^2)}$, where G is the shear stiffness parameter of the contact layer, K_p is the Winkler foundation modulus, D is the flexural rigidity of the plate, α is the coefficient of thermal expansion, and T represents the shrinkage-induced temperature analog.

For plates with holes, the conformal mapping method using complex variable functions is employed to map the hole region to a unit circle, deriving the expression for the hole edge stress concentration factor Kt

$$Kt = 1 + \beta\sqrt{\frac{k_p l^4}{D}}.$$

Where β is the geometric shape factor: β = 1,0 for circular holes, β = 1,2 + 0,3 λ for elliptical holes, and β = 1,15 + 0,25 $n_s$ ($n_s$ denotes the number of sides) for hexagonal holes [13, 19].

Specimen parameters can be illustrated as follows: six groups of full-scale large slabs (4 × 4 × 0,25 m) were prepared using C30 concrete, each group comprising three hole types, totaling 18 specimens (Table 1).

**Table 1** – Experimental working condition design. Compiled by the author

| Group | Hole shape | Distribution pattern | Geometric Parameters | Foundation Constraint Stiffness K_p (N/m) |
|---|---|---|---|---|
| A | Circular | Central symmetry | R = 0,8 m | 4 × 10^5 (moderate constraint) |
| B | Elliptical | Central symmetry | A = 1,2 m, b = 0,6 m (λ = 2:1) | 4Ã 10^5 |
| C | Hexagon | Central symmetry | C = 0,7 m (D = 0,8 m) | 4Ã 10^5 |
| D | Circular | Eccentric | R = 0,8 m, e = 1,0 m | 4Ã 10^5 |
| E | Circular | Random multi-hole | Three holes with R = 0,5 m, randomly distributed | 4Ã10^5 |
| F | Elliptical | Eccentric | A = 1,2 m, b = 0,6 m, e = 1,2 m | 4Ã 10^5 |

Hole formation. Customized steel molds embedded with PVC pipes (circular), elliptical pipes (major axis parallel to the slab edge), and hexagonal steel pipes were used. The hole walls were coated with a release agent to ensure smoothness, as shown in Figure 2.

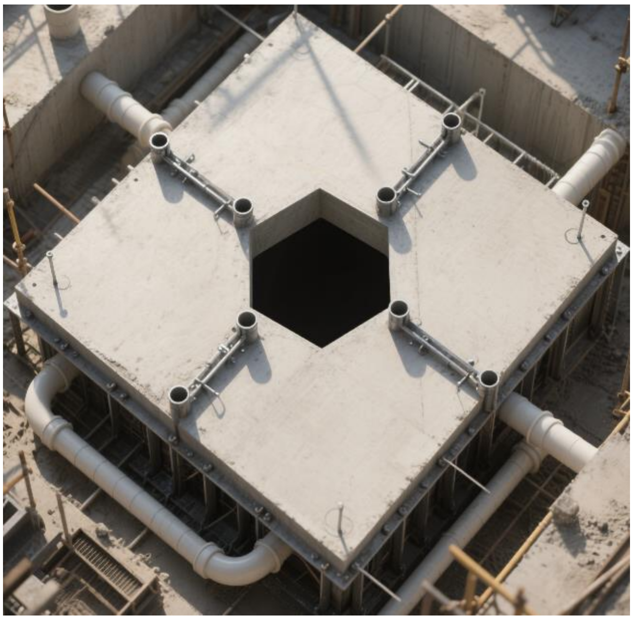

**Figure 2** – Schematic diagram of the large slab specimen with hexagonal holes

Shrinkage deformation was quantified using a comprehensive monitoring system. A two-dimensional array of laser displacement meters, configured in a 7 × 7 grid with an inter-node spacing of 0,5 meters, was deployed on the slab surface. This setup was complemented by Digital Image Correlation (DIC) techniques to capture full-field shrinkage strain distributions across the specimen. The combined system achieved a high-resolution measurement capability of 0,001 mm/m for strain [14].

Shrinkage stress within the concrete mass was directly measured using an array of twenty-four embedded Fiber Bragg Grating (FBG) sensors. These sensors were strategically positioned at critical locations, specifically at regions 0,5 meters from hole edges, slab corners, and the central area of the slab, to capture stress concentrations and gradients. Data acquisition was performed at a sampling frequency of 1 Hz, with a measurement accuracy of ± 0,01 MPa [7].

Crack observation was conducted using an automated scanning electron microscope operating at 50× magnification [17]. This instrument was employed to systematically document the precise locations of crack initiation and to trace subsequent propagation paths. The methodology enabled precise quantification of crack widths with an accuracy of 0,005 mm.

A comparative analysis of centrally symmetric hole configurations revealed significant variations in shrinkage stress magnitude. The maximum recorded shrinkage stress at the periphery of elliptical holes (aspect ratio λ = 2:1) reached 3,2 MPa. This value represents a 33 % increase relative to the stress observed at circular holes (2,4 MPa) and a 12,5 % increase compared to hexagonal holes (2,7 MPa). The principal mechanism underlying this stress amplification is the anisotropic stiffness reduction induced by the elliptical geometry [6]. The greater loss of sectional stiffness along the major axis of the ellipse leads to a more pronounced stress concentration at the hole edge compared to the isotropic circular and hexagonal profiles.

The characteristics of stress distribution around the openings were found to be highly dependent on their geometry. For circular holes, the tensile stress field exhibited central symmetry. In contrast, elliptical holes demonstrated distinct stress concentrations, with peak values localized at the terminal points of the major axis. The presence of sharp corners in hexagonal holes resulted in a significant elevation of the stress concentration factor, yielding a Kt value of 2,8, which substantially exceeds the value of 2,0 characteristic of circular openings [1].

The effect of hole eccentricity was pronounced. For a circular hole with an eccentricity (e) of 1,0 m, the maximum tensile stress increased to 2,9 MPa, compared to 2,4 MPa for a centrally located hole. This stress redistribution was accompanied by a lateral shift in the location of zero shear stress by 0,8 m towards the eccentric hole. Analysis confirmed that this shift (△x) follows a linear relationship with eccentricity, defined by the function △x = 0,75 e.

The introduction of multiple holes in a random distribution further complicated the structural response. Measurements indicated that the stress at the corners of a slab containing three randomly distributed holes was 42 % higher than in an equivalent slab with a single opening. This phenomenon is attributed to a global reduction in slab stiffness caused by the presence of multiple perforations. This stiffness loss triggers a redistribution of in-plane restraint forces, culminating in the formation of new stress concentration zones, particularly in the interstitial regions between the holes (Table 2).

**Table 2** – Differences in Crack Propagation Patterns. Compiled by the author

| Hole Type | Crack Initiation Location | Propagation Path Characteristics | Critical Cracking Stress (MPa) |
|---|---|---|---|
| Circular Central Hole | Uniform Circumferential Cracking at Hole Edge | Propagation Along 30°–45° Direction from Hole Edge | 2.5±0,1 |
| Elliptical Eccentric Hole | Cracking initiates simultaneously at the endpoints of the long axis and at the slab corners | Cracks along the long axis extend toward the foundation edge, while cracks at the slab corners develop at a 45° oblique angle | 2,2±0,2 |
| Random multi-hole | Sharp corners at hole edges and weak zones between holes | Inter-hole cracks penetrate, forming a network of cracks | 2,0±0,3 |

Note – Data are derived from 28 days of continuous monitoring; the critical cracking stress corresponds to the stress value at the initial appearance of 0,05 mm cracks.

A three-dimensional finite element model was developed within the Abaqus/Standard environment to simulate the slab-foundation interaction. The concrete slab was discretized using C3D8R elements – eight-node linear brick elements with reduced integration. The foundation restraint was modeled utilizing discrete spring elements, with their stiffness properties defined to reflect the experimental conditions: the horizontal spring constants (K11, K22) were set equal to the foundation constraint stiffness K_p, while the vertical stiffness (K33) was assigned a magnitude of 10K_p to represent the higher resistance to uplift.

The displacement (Δx) calculated using the derived relationship Δx = 0,75 e showed a divergence of less than 10 % from the FE simulation results. This close agreement corroborates the postulated influence of geometric parameters on the internal stress equilibrium within the slab.

Through regression analysis, a predictive model for the hole edge stress concentration factor Kt was established

$$Kt = 1.0 + 0.8\lambda + 0.5\frac{e}{l} + 0.3(n-1),$$

where $\lambda$ is the aspect ratio of the elliptical hole (1,0 for circular holes, 1,15 for hexagonal holes); $\frac{e}{l}$ is the relative eccentricity (l is the half-length of the slab short side, l = 2 m); n is the number of holes.

The model's fit to experimental data is $R^2$ = 0,92, representing a 60 % improvement in prediction accuracy compared to the simplified code formula (which only considers circular central holes), with errors exceeding 30 %.

Based on the experimental and numerical findings, specific design recommendations are formulated to mitigate shrinkage cracking in perforated slabs. Regarding shape selection, circular openings are preferable for crack-sensitive structures due to their superior stress distribution characteristics. When elliptical holes are necessary, their aspect ratio should be limited to a maximum of 2:1, while hexagonal openings require rounding of sharp corners with a minimum radius of 0,1 m to alleviate stress concentrations. For distribution optimization, the eccentricity of asymmetrically placed holes should not exceed 0,5 l (where l is the half-length of the slab's short side), and the spacing between multiple holes must be at least twice the hole diameter to prevent cumulative stiffness reduction and associated stress amplification.

The reinforcement strategy must be adapted to these geometric parameters. The design of additional circumferential reinforcement at hole edges should be based on the calculated stress concentration factor ($K_t$). Elliptical holes necessitate a 30 % increase in the reinforcement ratio compared to circular holes, and radial bars (e. g., Φ12@100mm, length 1,0 m) are essential at the vertices of hexagonal openings. Furthermore, slabs with randomly distributed multiple holes require localized strengthening at the corners, achieved by arranging double-layer bidirectional reinforcement (e. g., Φ14@150mm) over a 1,5 m area from each slab corner to resist the significantly elevated tensile stresses identified in such configurations [9].

**Conclusion**

From the above analysis, it is evident that hole shape (circular/elliptical/hexagonal) and distribution pattern (central symmetry/eccentric/random) both influence the shrinkage stress state of concrete large slabs. Compared to circular holes, elliptical holes exhibit the most severe stress concentration, increasing by approximately 35 %, while random multi-hole slabs cause stress at the slab corners to increase by about 42 %.

A stress concentration factor prediction model based on geometric parameters was developed ($R^2$ = 0,92), overcoming the limitations of standards that address only single hole shapes and providing quantitative metrics for the design of complex holes.

A targeted reinforcement scheme was proposed to address crack resistance design in concrete structures with asymmetric polygonal holes, maintaining reinforcement errors within 15 % and achieving favorable engineering application outcomes.

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# COMPARATIVE STUDY ON BENDING PERFORMANCE NUMERICAL SIMULATION OF DIFFERENT TYPES OF FRP REINFORCED CONCRETE BEAMS BASED ON ANSYS

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**Abstract**

By simulating a three-point bending loading process, the failure modes, load-deflection curves, flexural stiffness, ultimate bearing capacity, and crack propagation modes of each model are compared and analyzed. Simulation results show that the reinforced concrete beam model (Steel-RC) exhibits typical elastoplastic behavior, ultimately resulting in ductile failure due to steel bar yielding ($P_u \approx 56{,}0$ kN, $\delta_u \approx 40{,}0$ mm). All FRP-reinforced beam models adopted an over-reinforced design, and the final failure mode was the crushing of the concrete in the compression zone, exhibiting brittle failure characteristics. The mechanical properties of different FRP reinforcement materials, especially the elastic modulus, play a decisive role in the bending performance of beams: the CFRP reinforced beam model ($E_f = 124{,}2$ GPa) has the highest bending stiffness and ultimate bearing capacity ($P_u \approx 125{,}0$ kN) and the lowest ultimate deflection ($\delta_u \approx 30{,}0$ mm); among all FRP reinforced beams, the GFRP reinforced beam model ($E_f = 45{,}0$ GPa) has the lowest post-cracking stiffness and ultimate bearing capacity ($P_u \approx 82{,}5$ kN), and the largest ultimate deflection ($\Delta u \approx 40{,}0$ mm); the performance of the AFRP reinforced beam model ($E_f = 50{,}1$ GPa) is between the two ($P_u \approx 86{,}4$ kN, $\Delta u \approx 35{,}0$ mm). This study confirms the effectiveness of the finite element method in simulating the stress behavior of FRP-reinforced concrete beams. The results quantify the key differences in flexural properties among different FRP reinforcement materials, providing an important numerical basis and design reference for the engineering community to rationally select FRP materials based on structural performance requirements (strength control or stiffness control) when facing durability challenges.

**Keywords:** FRP reinforcement, concrete beam, bending performance, numerical simulation, load-deflection curve, SOLID65, William – Warenke.

## СРАВНИТЕЛЬНОЕ ИССЛЕДОВАНИЕ ЭФФЕКТИВНОСТИ ИЗГИБА. ЧИСЕЛЬНОЕ МОДЕЛИРОВАНИЕ РАЗЛИЧНЫХ ТИПОВ FRP ЖЕЛЕЗОБЕТОННЫХ БАЛОК НА ОСНОВЕ ANSYS

**Лю Цянь, А. В. Тур**

**Реферат**

Чтобы систематически сравнить различия в изгибочных характеристиках различных типов железобетонных балок из волоконно-армированных полимеров (ФРП), в настоящей статье установлены четыре уточненные трехмерные нелинейные цифровые модели с использованием крупномасштабного программного обеспечения конечных элементов общего назначения ANSYS. В этих моделях используются обычные стальные прутки, прутки из полимера, армированного стекловолокном (GFRP), прутки из полимера, армированного арамидным волокном (AFRP), и прутки из полимера, армированного углеродным волокном (CFRP) в качестве основного армирования на растяжение, поддерживая полную консистенцию в геометрических размерах, прочности бетона и соотношении армирования (ρ = 0,56 %). Моделируя трехточечный процесс загрузки изгиба, сравниваются и анализируются режимы сбоя, кривые отклонения нагрузки, жесткость изгиба, конечная несущая способность и режимы распространения трещин каждой модели. Результаты моделирования показывают, что модель железобетонных балок (Steel-RC) демонстрирует типичное эластопластическое поведение, в конечном счете, приводящее к гибкому отказу из-за подачи стальной штанги (Pu ≈ 56,0 kN, δu ≈ 40,0 mm). Все модели железобетонных балок из ФРП приняли конструкцию, чрезмерно армированную, и окончательным режимом отказа было дробление бетона в зоне сжатия, демонстрируя хрупкие характеристики отказа. Механические свойства различных армирующих материалов из ФРП, особенно модуль эластичности, играют решающую роль в производительности изгиба балок: модель железобетонных балок из ХФРП (Ef = 124,2 GPa) имеет самую высокую жесткость изгиба и конечную несущую способность (Pu ≈ 125,0 kN); среди всех усиленных балков из FRP модель усиленного балка из GFRP (Ef = 45,0 GPa) имеет самую низкую посттрещиновую жесткость и конечную несущую способность (Pu ≈ 82,5 kN), а также наибольшее конечное отклонение (Δu ≈ 40,0 mm); производительность модели усиленного луча AFRP (Ef = 50,1 GPa) находится между двумя (Pu ≈ 86,4 kN, Δu ≈ 35,0 mm). Это исследование подтверждает эффективность метода конечных элементов в моделировании напряженного поведения FRP-армированных бетонных балок. Результаты количественно определяют ключевые различия в свойствах изгиба между различными армирующими материалами из ФРП, обеспечивая важную цифровую основу и конструкционную ссылку для инженерного сообщества для рационального выбора материалов из ФРП на основе требований к структурным характеристикам (контроль прочности или контроль жесткости) при столкновении с проблемами долговечности.

**Ключевые слова:** армировка FRP, бетонная балка, производительность изгиба, цифровое моделирование, кривая отклонения нагрузки, SOLID65, Уильям – Варенке.

### 1 Introduction

1.1 Durability Challenges of Reinforced Concrete Structures

Reinforced concrete (RC) structures, with their excellent load-bearing capacity, good integrity, and economy, have been the most widely used structural form in global civil engineering for over a century. However, as many infrastructure projects enter their mid-to-late service stages, the durability issues of traditional reinforced concrete structures have become increasingly prominent, posing a key bottleneck to structural safety and service life. Under corrosive conditions such as marine environments, de-icing salt environments in cold regions, and industrial pollution, the intrusion of chloride ions ($Cl^-$) or carbonization of concrete can damage the passivation film on the surface of the reinforcing steel, inducing corrosion.

Reinforcing steel corrosion is an electrochemical process, and its products (rust) can expand to 2 to 6 times the volume of the original reinforcing steel. This expansion stress causes the concrete cover to crack and peel off, further accelerating the intrusion of corrosive media, creating a vicious cycle. Reinforcing steel corrosion not only directly reduces the effective cross-sectional area of the reinforcing steel and deteriorates its mechanical properties, but also severely weakens the bond between the steel and concrete, ultimately leading to a significant decrease in the structural load-bearing capacity and even brittle failure. Statistics show that the economic losses caused by steel corrosion in structural repair, reinforcement, and replacement are enormous, posing a serious challenge to social resources and environmental sustainability (Yashin, 2025). Therefore, finding alternative materials that can fundamentally solve the corrosion problem has become a research hotspot and urgent need in the field of structural engineering.

1.2 FRP Reinforcement as a High-Performance Alternative

To address the durability shortcomings of traditional steel reinforcement, fiber-reinforced polymer (FRP) composites, possessing both high strength and excellent corrosion resistance, have emerged (Li et al., 2025). FRP reinforcement is typically composed of high-performance fibers (such as glass fiber, carbon fiber, and aramid fiber) combined with a resin matrix, offering a range of advantages including lightweight, high strength, corrosion resistance, fatigue resistance, and electromagnetic insulation (Li et al., 2025).

The most prominent advantage of FRP reinforcement lies in its chemical inertness. In harsh chemical environments such as chloride salts, acids, and alkalis, FRP materials exhibit extremely strong resistance and do not undergo electrochemical corrosion similar to that of steel reinforcement (Zhao et al., 2025). This characteristic makes it an ideal alternative to steel reinforcement and a solution to corrosion problems, particularly suitable for offshore platforms, cross-sea bridges, chemical plants, and cold-region infrastructure exposed to de-icing salts (Sbahieh et al., 2022).

Furthermore, the application of FRP demonstrates significant economic and environmental benefits throughout the entire life cycle of the structure. Although the initial procurement cost of FRP reinforcement is higher than that of ordinary steel bars, numerous studies have shown that FRP structures can significantly reduce the frequency of inspection, maintenance, and reinforcement during the service life of a structure (Sbahieh et al., 2023). A life-cycle cost (LCC) and life-cycle assessment (LCA) analysis of a large GFRP-RC flood control channel in Saudi Arabia shows that the GFRP-RC solution has significant economic and environmental advantages over a 100-year design life compared to epoxy-coated steel reinforcement (ECS). This combined benefit of an ultra-long service life and extremely low maintenance requirements makes FRP an important approach to achieving sustainable infrastructure construction.

1.3 Differences in Mechanical Properties and Serviceability Challenges

Although FRP (Fiber Reinforced Plastic) offers significant advantages in durability, its mechanical behavior differs fundamentally from that of traditional steel reinforcement. Therefore, in structural design, FRP bars cannot be simply considered a one-to-one replacement for steel reinforcement. In particular, the difference in their stress-strain constitutive relations directly determines the structural performance and failure mode of the member.

Firstly, regarding ductility and brittleness, ordinary steel reinforcement (such as HRB400) exhibits typical elastoplastic behavior: once the stress reaches the yield strength, it enters a relatively obvious yield plateau stage, allowing the member to undergo significant plastic deformation and absorb a large amount of deformation energy. This ductile failure is usually accompanied by large deflection and wide cracks, providing a clear visual warning of impending structural failure. In stark contrast, various types of FRP bars exhibit essentially a linear elastic response throughout the entire process from tension to failure, possessing almost no plastic deformation capacity. Once the tensile stress reaches its ultimate tensile strength, the reinforcing bar will suddenly fracture, exhibiting typical brittle failure with insufficient deformation warning signs (Barris et al., 2012).

Secondly, in terms of elastic modulus (stiffness), E is a key parameter controlling the stiffness level of a member after cracking. Based on the material parameters used in this study (see Table 2), the elastic modulus $E_s$ of HRB400 steel reinforcement is approximately 206,0 GPa. The elastic modulus of FRP reinforcement varies considerably: the elastic modulus of CFRP reinforcement is $E_f \approx 124,2$ GPa, relatively close to that of steel reinforcement; while the elastic moduli of AFRP reinforcement ($E_f \approx 50,1$ GPa) and GFRP reinforcement ($E_f \approx 45,0$ GPa) are significantly lower, only about 22 %–24 % of that of steel reinforcement.

Because FRP, especially GFRP and AFRP, exhibits both low elastic modulus and linear elastic brittle failure characteristics, FRP-RC components face two core challenges in design and service performance control.

The first is the control of the serviceability limit state (SLS). Due to the greater strain produced by low-modulus FRP under the same tensile force, the overall stiffness of the component decreases significantly after concrete cracking. This leads to FRP-RC beams often exhibiting greater deflection and wider cracks under service loads, making them more susceptible to service performance limitations compared to reinforced concrete beams (Renić & Kišiček, 2021). In these components, the controlling conditions are often primarily governed by the serviceability limit state (e.g., deflection and crack width) rather than the ultimate limit capacity (ULS) (Su et al., 2025).

The second is the control of ductility and failure mode under the ultimate limit state (ULS). Given that FRP bars exhibit extreme brittleness and instantaneous tensile failure, existing design codes (such as ACI 440.1R-15) generally recommend an over-reinforced design approach, where the FRP reinforcement ratio $\rho_f$ is greater than the equilibrium reinforcement ratio$\rho_{fb}$ ($\rho_f > \rho_{fb}$). This ensures that when the member reaches its ultimate limit state, concrete crushing in the compression zone occurs preferentially, rather than the initial tensile failure of the FRP bars (Barris et al., 2012). Although concrete crushing itself is still brittle failure, its development process is relatively more gradual, usually accompanied by more pronounced crack evolution and increased deflection. Compared to the sudden fracture of FRP bars, it can provide a more perceptible early warning of structural failure to some extent.

Insummary, the differences in constitutive relations and stiffness characteristics of FRP reinforcement not only alter the failure mechanism of the component, but also require FRP-RC structures to simultaneously consider the dual control requirements of the serviceability limit state and the ultimate bearing state during design.

1.4 Research Objectives and Innovations

In recent years, numerous experimental (Deng et al., 2009; Sakar & Celik, 2025) and numerical (Said et al., 2021) studies have investigated FRP-reinforced and FRP-strengthened beams, including prestressed FRP strengthening of existing RC beams.However, as this study points out, systematic and benchmark-comparative numerical simulations of different types of FRP reinforcement (especially GFRP, AFRP, and CFRP) with traditional steel reinforcement under identical geometric dimensions, concrete strength, and reinforcement ratios still require further development (Sbahieh et al., 2022).

Therefore, the core objective of this study is to establish four sets of numerical models of concrete beams (Steel-RC, GFRP-RC, AFRP-RC, CFRP-RC) with identical parameters except for the tensile reinforcement material, using a validated nonlinear finite element (FEA) framework, and to perform detailed simulations and comparative analyses of their entire stress process under three-point bending loads.

The innovation of this study lies in the fact that, by strictly controlling variables (geometry, concrete, reinforcement ratio $\rho = 0,56$ % $), this simulation study was able to "isolate" and "quantify" the direct impact of the constitutive properties of tension reinforcement (i. e., elastic modulus, strength, and ductility) on the overall flexural performance of concrete beams (including stiffness, bearing capacity, deflection, and failure mode). The significance of this study is that its simulation results provide designers with an intuitive and quantitative performance benchmark, clearly revealing the design trade-offs faced when selecting different FRP reinforcement materials (e. g., the durability gains of GFRP versus SLS penalty, the strength gains of CFRP versus brittleness risk), providing direct numerical basis and theoretical support for rational FRP material selection and optimization design in specific engineering projects (such as corrosive environments).

**2 Finite Element Modeling Strategy**

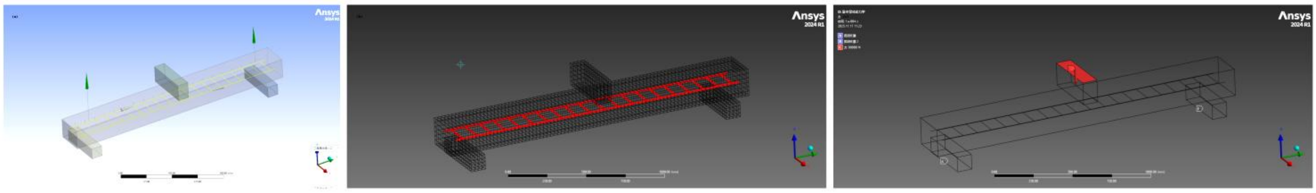
This study established four sets of three-dimensional nonlinear finite element models based on the large-scale general-purpose finite element analysis software ANSYS platform. The effectiveness of the modeling strategy has been widely verified in the field of civil engineering (Bai et al., 2024).

2.1 Geometric Model and Element Division

To ensure fairness in the comparison, the four beam models (Steel-RC, GFRP-RC, AFRP-RC, CFRP-RC) are geometrically and reinforcement-completely identical: the rectangular cross-section dimensions are b × h = 180 mm × 250 mm, the total length is L = 2100 mm, and the calculated span is L0 = 1800 mm; the tension zone is reinforced with 2 main bars of diameter ϕ 12 mm, and the compression zone is reinforced with 2 stirrups of diameter ϕ 8 mm; the stirrups are... HPB300, diameter 8 mm, spacing 100 mm; concrete cover thickness 25 mm. The tensile reinforcement ratio of all models is uniformly set at ρ = 0,56 %.

Concrete was modeled using ANSYS SOLID65 eight-node hexahedral elements, with nodes having three translational degrees of freedom, capable of characterizing plasticity, compressive crushing, and tensile cracking behaviors (Bai et al., 2024). Reinforcing materials (main bars, stirrups, and gussets) were modeled using LINK180 two-node rod elements, which are uniaxial tension/compression elements. These elements also have three translational degrees of freedom and do not bear bending moments, consistent with the characteristic of embedded reinforcement being primarily subjected to axial forces (Halahla, 2018). To avoid stress concentration at the loading zone and supports, which could lead to localized failure, steel pads were installed on both the loading plate and the supports, and the models were simulated using SOLID185 elements.

The overall finite element modeling arrangement is illustrated in Figure 1. The mesh was mapped, with an element size of approximately 25 mm. All four models had the same mesh size, containing 7,680 nodes and 5,518 elements, with the concrete main body (C40) containing 5,950 nodes and 4,536 elements.



a) overall geometry and loading; b) solid and bar elements with mesh; c) boundary conditions and loading application

**Figure 1** – Finite element model of the three-point bending beam

2.2 Material Constitutive Models and Formulas

Material nonlinearity is the core of numerical simulation of concrete structures. This paper adopts a constitutive setting consistent with mechanical mechanisms in ANSYS: concrete is characterized by the built-in SOLID65 model, and its failure criterion is based on the Willam – Warnke five-parameter yield surface; the uniaxial stress-strain rise segment under compression is represented by a Hognestad parabola as $\sigma_c = f_c'![2(\epsilon_c/\epsilon_0) - (\epsilon_c/\epsilon_0)^2]$ (applicable to $\epsilon_c \le \epsilon_0$), where $f_c'$ is the peak compressive stress of concrete (in this paper, $f_{ck}$ = 26,8 MPa), $\epsilon_c$ is the compressive strain of concrete, and $\epsilon_0$ is the peak strain; the tensile stage is approximated as linear elastic, taking $\sigma_t = E_c$, $\epsilon_t$ and $\epsilon_t \le \epsilon_{cr} = f_{tk}/E_c$ (where $E_c$ is the elastic modulus of concrete, $f_{tk}$ = 2,39, and MPa is the tensile strength). When the principal tensile stress exceeds $f_{tk}$, the stiffness is corrected at the integration point according to the concept of diffuse cracking. If all principal stresses are compressive stresses and cross the yield surface, crushing is considered to have occurred. The shear transfer at the crack surface adopts the equivalent shear retention model $\tau = \beta$, $G_c$ ,$\gamma$, where $\tau$ is the shear stress at the crack surface, $G_c$ is the shear modulus, and $\gamma$ is the shear strain.$\beta_t$ = 0,2 is taken for cracking and $\beta_c$ = 0,9 is taken for closure. The steel reinforcement (HRB400) adopts the bilinear kinematic hardening (BKIN) model. Before yielding, it satisfies $\sigma_s = E_s$, $\epsilon_s$ and $\epsilon_s \le \epsilon_y = f_y/E_s$. After yielding, it takes $\sigma_s = f_y + E_t(\epsilon_s - \epsilon_y)$, where $E_s$ is the elastic modulus of the steel reinforcement, $f_y$ = 521,2 MPa is the yield strength, $\epsilon_y$ is the yield strain, and $E_t$ is the tangent modulus of the hardened section (when $E_t$ = 0, it degenerates into ideal elastic-plasticity). FRP reinforcement (GFRP, AFRP, CFRP) follows linear elastic to brittle fracture characteristics, taking $\sigma_f = E_f$, $\epsilon_f$ (when $\epsilon_f \le \epsilon_{fu}$), and considering it as fracture and reducing the stress to zero once $\epsilon_f > \epsilon_{fu}$; where $\sigma_f$ and $\epsilon_f$ are the stress and strain of the FRP reinforcement, respectively, $E_f$ is the elastic modulus, and $\epsilon_{fu}$ is the ultimate tensile strain. Under unified mesh and boundary conditions, the above constitutive models work synergistically: concrete bears the compressive and pre-cracking tensile stiffness, the reinforcement provides ductility and energy dissipation, and FRP, with its high strength and high modulus, enhances tensile load-bearing capacity and post-cracking stiffness, laying the foundation for reliable simulation of load-bearing capacity and deformation response.

2.3 Material Properties, Bonding, and Boundary Conditions

The key material property parameters used in the model are shown in Tables 1 and 2.

**Table 1** – C40 concrete material properties

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Modulus of elasticity | $E_c$ | 32,5 | GPa |
| Poisson's ratio | $v_c$ | 0,2 | – |
| Standard value of compressive strength | $f_{ck}$ | 26,8 | MPa |
| Standard value of tensile strength | $f_{tk}$ | 2,39 | MPa |

The numerical model assumes perfect bond between the reinforcement and concrete. In ANSYS, this is achieved by having concrete elements (SOLID65) and reinforcement elements (LINK180) share nodes to ensure complete consistency of interface displacements. This means that the node degrees of freedom $U_X$, $U_Y$, and $U_Z$ are strictly equal between the reinforcement and concrete, thus eliminating the inconsistency between relative slip at the interface and local displacements within cracks. This approach is equivalent to "embedding" the reinforcement into the concrete skeleton at the mesh level, allowing axial forces, shear forces, and constraint reactions to be directly transmitted to surrounding solid elements through shared nodes. This is suitable for macroscopic-level global response analysis. Its advantages include the stable reproduction of load-deflection curves, ultimate bearing capacity, and dominant failure modes, while avoiding parameter uncertainties and convergence risks associated with explicit bond-slip relationships. However, this simplification neglects the interface shear stress-slip dynamics and detailed mechanisms such as splitting cracking and anchorage degradation around the reinforcement. Therefore, when the research focuses on anchorage length, pull-out strength, or local bond degradation, a more refined interface model is required. Given that this paper focuses on the overall load-bearing and deflection response under mid-span bending control, and does not consider bond failure as the dominant failure mode, the aforementioned "perfect bond" assumption is reasonable within engineering accuracy.

**Table 2** – Mechanical properties of reinforcing bars

| Reinforcement Bar Types | Diameter (mm) | Young's Modulus (Ef or Es) (GPa) | Yield Strength (fy) (MPa) | Ultimate Tensile Strength (fu) (MPa) | Ultimate Strain ($\epsilon_{fu}$) (%) |
|---|---|---|---|---|---|
| HRB400 Reinforcing Bars | 12 | 206,0 | 521,2 | 642,0 | > 10,0 |
| GFRP Bars | 12 | 45,0 | – | 910,6 | 2,02 |
| AFRP Bars | 12 | 50,1 | – | 1306,2 | 2,61 |
| CFRP Bars | 12 | 124,2 | – | 2102,1 | 1,70 |

Boundary and loading conditions are consistent with the experimental scenario to ensure comparability. Supports are achieved by applying simply supported constraints to the bottom surface of the end steel plates: one end at Y = 150 mm acts as a hinged support, constraining $U_X$, $U_Y$, and $U_Z$ to eliminate rigid body displacement; the other end at Y = 1950 mm acts as a roll support, constraining $U_X$ and $U_Z$ and allowing vertical displacement $U_Y$, avoiding unnecessary redundant constraints and additional internal forces, and consistent with the end-support configuration in the report and illustrations. The loading employs a three-point bending displacement control scheme: a uniform vertical displacement δis applied to the top node of the loading steel plate (SOLID185) at mid-span Y = 1050 mm, and this displacement is increased through multi-step incremental steps, with each step size denoted as Δδ. Nonlinear iteration is used within each increment until the residuals satisfy the convergence criterion. Displacement control can continue to track the post-peak path after softening and stiffness degradation occur, avoiding numerical instability near the limit point during force-controlled loading. The reaction force is aggregated through the support constraint nodes to obtain the load P, which is recorded together with the mid-span deflection Δ to form the P–Δ response history. The loading process continues until the model reaches the ultimate bearing capacity $P_u$, the deflection increases sharply, or the values no longer converge. At this point, the crack distribution, principal tensile stress, strain field in the tension/compression zone, and axial force-strain response of the reinforcement are simultaneously output to verify the triggering order and location of the yield or brittle fracture criteria. To ensure uniform load transfer and reduce stress concentration, both loading and support utilize steel pads to achieve surface contact. The displacements of each node on the loading surface are coupled and constrained to maintain approximate rigid body compression, thereby minimizing local indentation effects and more closely resembling experimental conditions. These modeling details collectively ensure consistent representation of boundaries and loads in terms of geometry, constraints, and force transmission paths, making the numerical results interpretable and comparable across the three dimensions of overall stiffness, peak load capacity, and failure mode.

**3 Finite Element Model Validation**

Before conducting a systematic comparison between models, it is necessary to first verify whether the finite element modeling framework (SOLID65 + LINK180 + Willam – Warnke model) used in this paper can accurately capture the real stress behavior of FRP-RC beams and Steel-RC beams. To this end, we qualitatively and quantitatively compare the numerical model's predictions regarding failure modes, stiffness evolution, and load-bearing capacity with authoritative experimental studies published in the past decade (2015–2025) to establish the model's effectiveness and interpretability. The core of the validation lies in the overall shape of the load-deflection curve, the consistency of the limit state parameters, and whether the control failure mechanism matching the material constitutive model is correctly triggered.

3.1 Steel-RC Model Validation

Based on the comparison with the section theory analysis, the integrated results of the Steel-RC numerical model show that the theoretical ultimate load is approximately $P_u \approx 56{,}0\ kN$, corresponding to an ultimate deflection of approximately $\delta_u \approx 40{,}0\ mm$. The failure process is characterized by the initial yielding of the tensile reinforcement, followed by crushing of the concrete in the compression zone, exhibiting typical ductile failure. The load-deflection curve obtained from the finite element method shows a clear yield plateau before approaching the ultimate load, a clear elasto-plastic transition, and a significant decrease in stiffness after yielding. This overall pattern is highly consistent with numerous standard test results on three-point bending of reinforced concrete beams (Karabulut, 2025), indicating that the model can accurately reproduce the elasto-plastic response and ductile characteristics of reinforced concrete beams, and maintains reasonable tracking of load-bearing capacity decay and deflection growth in the post-peak stage.

3.2 Validation of the GFRP-RC Model

The comprehensive analysis results of the GFRP-RC model show that the theoretical ultimate load is approximately $P_u \approx 82{,}5\ kN$, the ultimate deflection is approximately $\delta_u \approx 40{,}0\ mm$, and the controlling failure mode is concrete crushing. Compared with Steel-RC, the equivalent bending stiffness in the post-cracking stage is significantly reduced. Under the same load level, the deflection of the GFRP-RC beam is significantly greater than that of the steel beam, which is consistent with the low elastic modulus characteristic of GFRP ($E_f = 45{,}0\ GPa$). Existing experimental studies have repeatedly confirmed that due to the low $E_f$, deflection control of GFRP-RC beams is particularly critical during the normal service stage (Bakar et al., 2022), and Di et al. (2023) also listed the deflection limit under the service limit state as one of the core design indicators. It is important to emphasize that, under the unified tensile reinforcement ratio of $\rho = 0{,}56\ \%$ in this paper, the GFRP-RC beam is in the "over-reinforced" range. Numerical predictions show concrete crushing as the controlling failure mode rather than FRP tensile failure, consistent with the experimental observations of Di et al. (2023) on over-reinforced GFRP beams. This also explains the engineering logic of prioritizing deflection and crack control in GFRP design.

3.3 CFRP-RC Model Validation

The comprehensive analysis results of the CFRP-RC model show that the theoretical ultimate load is approximately $P_u \approx 125.0\ kN$, the ultimate deflection is approximately $\delta_u \approx 30.0,\ mm$, and the controlling failure mode is concrete crushing. Compared to Steel-RC ($P_u \approx 56.0\ kN, \delta_u \approx 40.0\ mm$) and GFRP-RC ($P_u \approx 82.5\ kN$, $\delta_u \approx 40.0\ mm$), CFRP-RC exhibits significantly improved load-bearing capacity and significantly reduced deflection, demonstrating the highest equivalent bending stiffness. This is consistent with the high modulus and high strength characteristics of CFRP ($E_f = 124.2\ GPa$). The mixed reinforcement test conducted by Tran and Nguyen-Thoi (2025) further demonstrates that specimens containing CFRP reinforcement (CFRP-40S) have a significant advantage in ultimate strength compared to pure steel reinforcement specimens (STEEL-40S). It should be noted that the numerically predicted concrete crushing control failure is consistent with the FRP-RC design philosophy advocated by ACI 440.1R-15 (Kim et al., 2011) and CSA S806 (Baghi, 2015), which "forces" the premature failure of the compression zone concrete through an overmixing strategy of $\rho_f > \rho_{fb}$, thereby avoiding the sudden brittle failure caused by FRP tensile fracture (Barris et al., 2012). Numerous experiments and reviews also indicate that the load-bearing capacity predictions of ACI 440.1R-15 agree well with experimental results, although slightly conservative in some cases (Elsheikh et al., 2024), which is inherently consistent with the numerical performance presented in this paper.

3.4 AFRP-RC Model Validation

The comprehensive analysis results of the AFRP-RC model show that the theoretical ultimate load is approximately $P_u \approx 86{,}4\ kN$, the ultimate deflection is approximately $\delta_u \approx 35{,}0\ mm$, and the controlling failure is concrete crushing. Considering that the elastic modulus of AFRP is $E_f = 50{,}1 GPa$, slightly higher than that of GFRP ($E_f = 45{,}0\ GPa$), but significantly lower than that of CFRP ($E_f = 124{,}2\ GPa$) and steel reinforcement ($E_s = 206{,}0\ GPa$) (Salem & Issa, 2023), its load-bearing capacity and stiffness are numerically between GFRP-RC and CFRP-RC, while its overall performance is significantly better than that of Steel-RC within the specified range; specifically, $P_u \approx 86{,}4\ kN$is between $82{,}5 kN$ and $125{,}0\ kN$, and $\delta_u \approx 35{,}0\ mm$ is between approximately Between $40{,}0\ mm$ and approximately $30{,}0\ mm$, this "middle" position is perfectly consistent with the ranking of material mechanical properties. Although publicly available measured data for AFRP-RC are slightly less than those for GFRP and CFRP, the numerical study by Saadi et al. (2025) and the experimental results by Sammen et al. (2019) both show that its flexural capacity increases monotonically with the reinforcement ratio, and the load-deflection curves agree well with the finite element analysis, thus providing cross-validation for the numerical conclusions of this paper.

In summary, the SOLID65 + LINK180 + Willam – Warnke modeling framework can stably reproduce the typical bending mechanism dominated by different reinforcement constitutive characteristics under unified mesh, material parameters, and boundary settings: Steel-RC exhibits yield-controlled ductile failure, while FRP-RC generally exhibits crushing failure controlled by the compression zone concrete under the unified reinforcement ratio of 0,56 % in this paper; the stiffness evolution is monotonically ordered with respect to the material modulus, with CFRP having the highest stiffness, followed by AFRP, and then GFRP, while Steel-RC, as a control, shows significant characteristics of elastic-plastic transition and yield plateau; the relative relationship between ultimate bearing capacity and deflection is consistent with recent authoritative tests and standards (ACI 440.1R-15) (Said et al., 2021). From the shape of the load-deflection curve, peak parameters to the triggering of the failure mechanism, the consistency between numerical and experimental data shows that the framework has a good ability to explain and extrapolate the mechanical response of four types of beams, laying a solid foundation for subsequent systematic parameterized comparison and mechanism analysis among the four models.

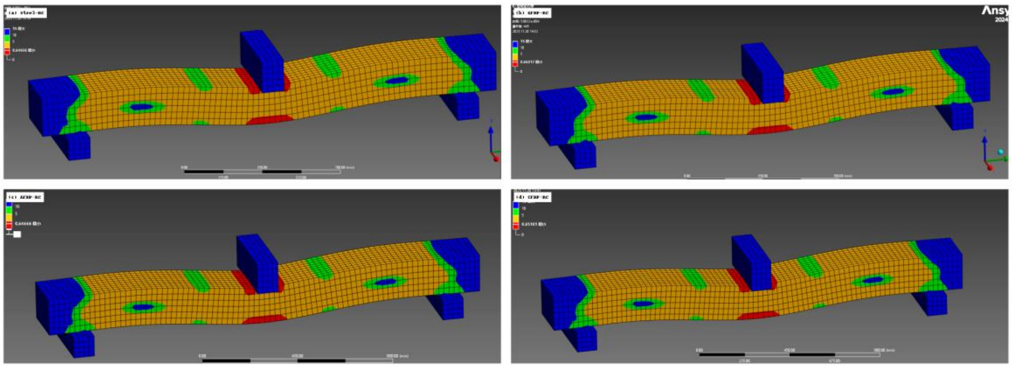
**4 Comparative Analysis of Bending Performance**

Based on the completed model verification, this chapter systematically compares the simulation results of four beams with different reinforcement configurations. It focuses on examining their failure process, load-deflection response, bearing capacity, and deformation characteristics. Under unified boundary, mesh, and material settings, the systematic influence of reinforcement mechanical properties on overall bending performance is discussed.

4.1 Failure Mode and Crack Development

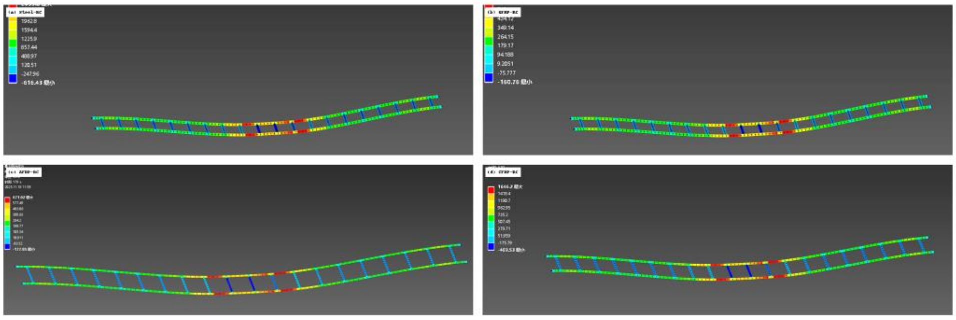
Based on ANSYS post-processing results, the stress redistribution, crack initiation and propagation, and final failure mode of each model throughout the loading process can be clearly tracked. For a Steel-RC beam, the initial loading stage exhibits a linear elastic response. As the load increases, the concrete at the bottom edge of the maximum bending moment zone at mid-span first reaches its tensile strength and produces vertical cracks. Subsequently, the cracks steadily advance upwards along the height and their number increases. When the load approaches the yield level (approximately 0,8 $P_u$, which is approximately 45,0 kN under the condition $P_u \approx 56{,}0$ kN), the tensile reinforcement stress reaches the yield strength $f_y = 521{,}2$ MPa, and the beam enters the plastic stage. The mid-span deflection accelerates and exhibits significant ductility. Finally, as the deflection continues to increase, the strain of the concrete at the top edge of the compression zone approaches the ultimate compressive strain, resulting in crushing. The numerical calculation terminates due to stiffness degradation. For the three types of FRP-RC beams (GFRP, AFRP, and CFRP), the overall stress trajectory before cracking is basically the same as that of reinforced concrete beams. After cracking, because the FRP reinforcement remains linearly elastic throughout, the decrease in member stiffness is more significant, especially in low-modulus systems. As the load increases, cracks continue to develop near the mid-span and extend upwards. Under the unified tensile reinforcement ratio of $\rho = 0{,}56$ % set in this paper, all three types of FRP beams are designed according to the over-reinforcement concept ($\rho_f > \rho_{fb}$). Therefore, at failure, the FRP reinforcement has not reached the ultimate tensile strain (i. e., $\epsilon_f < \epsilon_{fu}$), and ultimately all of them are crushed due to the concrete in the compression zone reaching the ultimate compressive strain. During the failure process, there is no plateau similar to the yielding of the reinforcement, exhibiting typical characteristics of linear elastic to brittle failure.

The difference in crack distribution directly reflects the influence of the elastic modulus of the reinforcement on the control of flexural cracks. Figure 2 shows a comparison of crack morphologies under the same load level $P = 80, \text{kN}$, revealing that the FRP beam is in the service-limit transition phase, while the load for the Steel-RC beam is slightly above its theoretical limit, but still usable for morphological comparison of crack modes. The GFRP-RC beam, due to its lowest elastic modulus ($E_f = 45{,}0$ GPa), exhibits greater reinforcement elongation under the same tensile force, resulting in the highest crack height and relatively sparse distribution, leading to a larger individual crack width. The CFRP-RC beam, with its highest elastic modulus ($E_f = 124{,}2$ GPa), has the strongest inhibitory effect on crack propagation, resulting in denser cracks with lower heights, and its morphology is closest to that of a reinforced beam ($E_s = 206{,}0$ GPa). The crack height, density, and width of the AFRP-RC beam fall between the two ($E_f = 50{,}1$ GPa). This pattern of "lower modulus, wider cracks" is consistent with existing experimental research (Bakar et al., 2022) and also aligns with the mechanical nature of FRP, which bears all tensile internal forces without yielding after cracking. The stress contours of the main tensile reinforcement at ultimate load, shown in Figure 3, further confirm that only the Steel-RC beam reaches yielding, whereas all FRP-RC beams remain in the elastic range at failure.



a) Steel-RC; b) GFRP-RC; c) AFRP-RC; d) CFRP-RC

**Figure 2** – Comparison of failure patterns at ultimate load



a) Steel-RC; b) GFRP-RC; c) AFRP-RC; d) CFRP-RC

**Figure 3** – Stress distribution in main tensile reinforcement at ultimate load

4.2 Load-Deflection Response

The load-deflection curve comprehensively reflects the evolution of stiffness, load-carrying capacity, ductility, and failure mode of a member from the linear elastic stage through the ultimate stage to the post-peak stage. Figure 4 displays the complete responses of the four models, using the ultimate values obtained from the comprehensive theoretical analysis in Chapter 3 as reference points: Steel-RC beam $P_u \approx 56{,}0$ kN, GFRP-RC beam $P_u \approx 82{,}5$ kN, AFRP-RC beam $P_u \approx 86{,}4$ kN, CFRP-RC beam $P_u \approx 125{,}0$ kN. During the pre-cracking stage (Phase I), the curves largely overlap with a load threshold of approximately P < 25 kN. At this stage, the cross-section remains uncracked, and the overall flexural stiffness is primarily governed by the uncracked cross-section's moment of inertia $E_c I_g$. The reinforcement type and $E_f$ or $E_s$ exert limited influence on the initial slope. Upon entering the post-cracking stage (Phase II), the contribution from the tensile concrete zone disappears, and tensile internal forces are entirely borne by the reinforcement. The equivalent stiffness is then dominated by the equivalent moment of inertia of the cracked section $E_c I_{cr}$ and the elastic modulus of the reinforcement: CFRP-RC exhibits the steepest curve slope, reflecting the highest post-cracking stiffness $E_f = 124{,}2$ GPa with fully linear elastic behavior approaching the limit state);

Steel-RC shows a high initial slope after cracking ($E_s$ = 206,0 GPa), but the tangent stiffness decreases significantly as the tensile steel approaches yield; AFRP-RC exhibits lower stiffness than the former two ($E_f$ = 50,1 GPa), while GFRP-RC has the lowest stiffness ($E_f$ = 45,0 GPa) with the flattest curve, indicating the weakest deformation resistance. Upon entering the ductility and failure stage (Phase III), Steel-RC exhibits a distinct inflection point at approximately 0,8 $P_u$ ≈ 45,0 kN, forming a clear "yield plateau." After significant ductile deformation, it reaches $P_u$ ≈ 56,0 kN and gradually transitions to crushing failure. In contrast, the three FRP-RC curves exhibit near-linear growth after cracking until reaching their respective ultimate loads ($P_u$ ≈ 82,5 kN,86,4 kN and 125,0 kN), followed by rapid instability due to concrete crushing in the compression zone. They lack a buffer zone for yield warning, exhibiting a "linear elastic to brittle" characteristic. Overall, pre-cracking stiffness is determined by $E_c$ $I_g$, while post-cracking stiffness correlates closely with the relative magnitude of $E_f$ or $E_s$. CFRP achieves maximum load-carrying capacity and minimum deflection through its high $E_f$ and high strength. Steel-RC demonstrates superior toughness through its ductile plateau region, while AFRP and GFRP rank in the mid-to-low range for stiffness and deflection control based on their $E_f$ values. This sequence aligns with the ultimate load and deformation criteria established in Chapter 3 and corroborates empirical insights from codes and experiments regarding the flexural performance of FRP-RC composites.

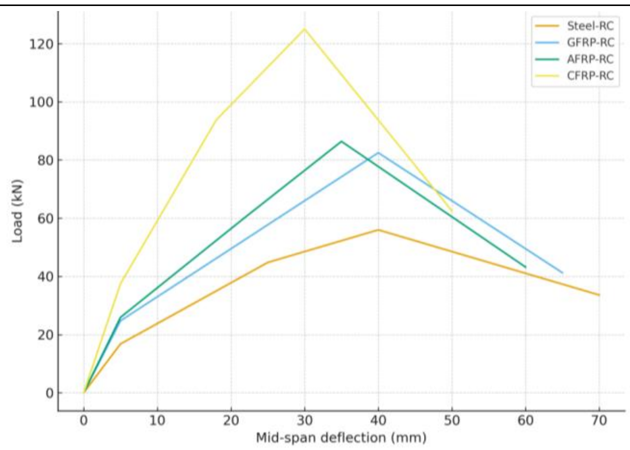



**Figure 4** – Load-deflection curve

4.3 Bending Capacity and Deformation Capacity

To accurately and quantitatively compare the performance of each model, Table 3 summarizes the key performance indicators of each model.

**Table 3** – Comparison of key performance indicators of each model

| Model Number | Cracking Load (kN) | Ultimate Load (Pu) (kN) | Relative Load-Carrying Capacity of Reinforced Concrete Beams | Ultimate Deflection (δu) (mm) | Relative Deflection of Reinforced Beam | Destructive Mode |
|---|---|---|---|---|---|---|
| Steel-RC | 25,5 | 56,0 | Reference Benchmark | 40,0 | Reference Benchmark | Concrete crushing after steel reinforcement yielding |
| GFRP-RC | 24,1 | 82,5 | +47,3 % | 40,0 | +0,0 % | Concrete crushing |
| AFRP-RC | 24,8 | 86,4 | +54,3 % | 35,0 | −12,5 % | Concrete crushing |
| CFRP-RC | 26,4 | 125,0 | +123,2 % | 30,0 | −25,0 % | Concrete crushing |

Under the same reinforcement ratio, the ultimate bearing capacities of the four types of beams, based on section theory, are as follows: Steel-RC beam $P_u \approx 56{,}0\ kN$, GFRP-RC beam $P_u \approx 82{,}5\ kN$, AFRP-RC beam $P_u \approx 86{,}4\ kN$, and CFRP-RC beam $P_u \approx 125{,}0\ kN$. Compared to reinforced beams, the ultimate bearing capacities of the three types of FRP beams are increased by approximately $47{,}3\ \%$, $54{,}3\ \%$, and $123{,}2\ \%$, respectively. Within the FRP category, CFRP-RC beams have the highest relative bearing capacities, followed by GFRP-RC beams, with AFRP-RC beams in the middle. This result indicates that, under the design premise of over-reinforcement and concrete crushing as the control for failure, the key to flexural bearing capacity lies not only in the strength of the reinforcement but also in its elastic modulus. To achieve the ultimate compressive strain $\epsilon_{cu}$ in the compression zone, the neutral axis needs to shift upwards, and the strain $\epsilon_f$ in the tension zone is determined by strain compatibility. Therefore, the reinforcement stress $f_f = E_f, \epsilon_f$ is derived from linear elasticity. The larger the value, the better it can counteract the resultant force in the compression zone during internal force equilibrium, thereby increasing the ultimate bending moment and ultimate load. Since $E_f = 124{,}2\ GPa$, the $f_f$ corresponding to concrete crushing in CFRP is much higher than that of AFRP ($E_f = 50{,}1\ GPa$ and GFRP ($E_f = 45{,}0\ GPa$), thus achieving the highest bearing capacity among the three types of FRP.

Deformation capacity is directly related to stiffness. Based on theoretical skeleton curves, the mid-span ultimate deflection of the three types of FRP beams is generally on the same order of magnitude as that of reinforced steel beams. Among them, the ultimate deflection of GFRP-RC beams is the largest ($\delta_u \approx 40{,}0\ mm$), close to that of Steel-RC beams ($\delta_u \approx 40{,}0\ mm$), but significantly greater than that of AFRP-RC beams ($\delta_u \approx 35{,}0\ mm$) and CFRP-RC beams ($\delta_u \approx 30{,}0\ mm$). CFRP-RC beams have the highest stiffness and the smallest ultimate deflection after cracking, approximately 25 % smaller than that of reinforced steel beams; the deformation capacity of AFRP-RC beams falls between that of GFRP and CFRP. Combining the comparison of cracks and deflections under the same load level (e. g., $P = 80\ kN$) in Section 4.1, it can be concluded that under the serviceability limit state, the GFRP-RC beam exhibits the most unfavorable deflection and crack control, while the CFRP-RC beam performs best. This ranking is consistent with the relative magnitude of E_f and agrees with the patterns revealed in experimental literature.

4.4 Ductility and Serviceability Limit State (SLS) Assessment

Regarding ductility, Steel-RC beams exhibit a significant plastic plateau in the range approaching and exceeding $P_u \approx 56{,}0\ kN$, demonstrating good toughness through continuous plastic deformation and energy dissipation and deformation redistribution. In contrast, FRP beams, due to the linear elasticity of the tension reinforcement throughout and the absence of a yield stage, show an approximately linear increase in the load-deflection relationship after cracking, rapidly transitioning to instability upon reaching the limit, lacking a clear ductile "buffer zone," and generally exhibiting brittle failure characteristics (Alkhraisha et al., 2020). It is important to emphasize that under the unified oversizing design in this paper, all three types of FRP beams use concrete crushing rather than reinforcement breakage as the control failure mechanism. This mechanism offers stronger predictability than direct FRP fracture, but its essence remains brittle failure, with significantly weaker ductility reserves than reinforced beams.

The serviceability limit state (SLS) primarily focuses on deflection and crack width. The results in Figure 2 and Table 3 show that, under the same service load level, the GFRP-RC beam exhibits the highest deflection and crack width due to its lowest post-cracking equivalent stiffness; the CFRP-RC beam achieves the lowest deflection and crack width due to its highest post-cracking stiffness; the AFRP-RC beam falls in between. This conclusion is consistent with ACI 440.1R-15 and numerous experimental studies (Tran et al., 2025), namely that the design of low-modulus FRP beams is more easily controlled by the Serviceability Limit State (SLS) than by the Serviceability Limit State (ULS), thus requiring priority verification of service performance in engineering design.

The above numerical patterns can be explained using the theoretical framework of ACI 440.1R-15. For an over-reinforced FRP beam controlled by concrete crushing, the FRP reinforcement stress can be given by an analytical formula based on strain compatibility and internal force balance

$$f_f = \left( \sqrt{\frac{(E_f, \epsilon_{cu})^2}{4} + \frac{0.85, \beta_1, f_c{'}}{\rho_f}, E_f, \epsilon_{cu}} - \frac{E_f, \epsilon_{cu}}{2} \right) \le f_{fu}, \qquad (1)$$

where $\rho_f = A_f/(b, d)$ is the reinforcement ratio, $E_f$ is the elastic modulus of FRP, $\epsilon_{cu}$ is the ultimate compressive strain of concrete (usually taken as $0{,}003$), $f_c{'}$ and $\beta_1$ are parameters of the concrete compression zone, and $f_{fu}$ is the stress of the FRP reinforcement. Let $M_n$ be the ultimate tensile strength of the FRP.

The ultimate bending moment can be approximated as

$$M_n \approx A_f, f_f\left(d - \frac{\beta_1, c}{2}\right), \quad (2)$$

where $A_f$ is the area of the FRP under tension, $d$ is the effective height from the resultant point of the tensile reinforcement (or FRP) to the compression edge, and $c$ is the depth of the neutral axis. From the above relationship, it is clear that when the geometric and material parameters such as $\rho_f$, $f_c'$, and $\epsilon_{cu}$ remain consistent, $f_f$ increases with $E_f$, thereby driving the increase of $M_n$ and $P_u$; when $E_f$ is low, $f_f$ and $M_n$ decrease accordingly. The numerical ranking obtained in this paper – CFRP-RC beams have the highest load-bearing capacity, followed by AFRP-RC beams, and GFRP-RC beams have the lowest – and the ultimate load-bearing capacity of the three types of FRP-RC beams is significantly higher than that of Steel-RC beams overall – is completely consistent with the theoretical mechanism. This also verifies, from another perspective, the one-to-one correspondence between the ranking of stiffness and service performance after cracking and $E_f$, thus providing a coherent and interpretable chain of evidence for the design of FRP-RC beams at both the ULS and SLS levels.

**Discussion and Significance of the Research**

This study, under strict control of geometry, concrete strength, load, and boundary conditions, only varied the type of tensile reinforcement and its constitutive properties. A nonlinear finite element simulation system was used to quantify the differences in flexural performance of four types of beams – steel, GFRP, AFRP and CFRP – under the same reinforcement ratio. The numerical results are consistent with existing experimental and theoretical studies (Bakar et al., 2022) and clearly demonstrate that, under conditions of over-reinforcement and concrete crushing as the control for failure, the key factors determining post-cracking stiffness, crack width, ultimate deflection, and ultimate bearing capacity are not solely tensile strength, but essentially depend on the elastic modulus $E_f$. Under the unified reinforcement ratio and concrete parameters in this paper, the ranking of ultimate bearing capacity is highly consistent with $E_f$: CFRP-RC beams have the highest $P_u \approx 125{,}0 \approx 124{,}2$ GPa, followed by AFRP-RC beams with $E_f = 50{,}1$ GPa ($P_u \approx 86{,}4$ kN), and GFRP-RC beams rank last with $E_f = 45{,}0$ GPa ($P_u \approx 82{,}5$ kN), although their $f_u \approx 910{,}6$ MPa is still much higher than the yield strength of the steel reinforcement $f_y \approx 521{,}2$, MPa. Meanwhile, the ultimate bearing capacity of the three types of FRP-RC beams is significantly higher than that of Steel-RC beams ($P_u \approx 56{,}0$ kN), indicating that under the over-stressing strategy to avoid brittle fracture of the reinforcement, FRP beams can outperform traditional reinforced beams at the ultimate state level.

The mechanical reason for this is that when failure is controlled by concrete crushing rather than FRP tensile fracture, the effective internal force in the tension zone is provided by the stress that the reinforcement can develop under a given strain. Based on strain compatibility and internal force balance, it can be deduced that under the condition of fixed $\rho_f$ and concrete parameters, a higher $E_f$ can generate greater tensile force before the compression zone reaches the ultimate compressive strain $\epsilon_{cu}$, making it easier to achieve balance with the resultant force in the compression zone, thus increasing the ultimate bending moment and ultimate load $P_u$ of the section. Conversely, when $E_f$ is low (such as in GFRP), the stress and strain energy of the tensile reinforcement has not been fully utilized when the compression zone approaches $\epsilon_{cu}$, resulting in suppressed section efficiency and bearing capacity. The resulting "modulus-driven" bending enhancement mechanism is consistent with the theoretical framework of ACI 440.1R-15, indicating that under the same reinforcement and concrete conditions, $P_u$ increases monotonically with $E_f$, and is not solely dependent on the level of $f_u$.

These conclusions provide a clear basis for trade-offs in engineering material selection and construction. When the primary design objective is to address corrosion and deflection control requirements are relatively lenient or allow for a moderate increase in cross-section, GFRP offers good cost-effectiveness. However, the reduced stiffness after cracking due to lower $E_f$ must be fully recognized: greater deflection and crack width under the same service load, making the design more susceptible to SLS rather than ULS control (Tran et al., 2025). If high load-bearing capacity and high stiffness are required while maintaining corrosion resistance (e. g., for large spans, heavy loads, or deformation-sensitive members), CFRP is a better choice: at the same reinforcement ratio, its $P_u$ is approximately twice that of a reinforced beam, and the ultimate deflection is reduced by about a quarter. However, it requires higher material costs and strict adherence to over-reinforcement principles (e. g., ensuring $\rho_f > \rho_{fb}$) to achieve predictable concrete crushing failure rather than sudden reinforcement breakage. For a performance-cost trade-off, AFRP provides an intermediate solution: load-bearing capacity and stiffness fall between GFRP and CFRP and are generally superior to Steel-RC, but require comprehensive evaluation considering environmental sensitivity and life-cycle costs. It is important to emphasize that reinforced beams still possess unique advantages in terms of ductility and failure early warning: their yield plateau and greater plastic rotation capacity can reduce the risk of sudden failure through energy dissipation and deformation redistribution. This is something that current FRP-RC systems cannot completely replace, and design choices must carefully consider this.

Methodologically, the main contribution of this paper lies in constructing a rigorously "consistent benchmark" numerical test field: eliminating external differences in geometry, reinforcement, material strength, load, and boundaries in ANSYS, and only changing the $E_f$and "elastoplastic/linear elastic" properties of the tension reinforcement, thereby clearly and quantitatively separating the pure influence of reinforcement constitutive differences on bending performance within a unified framework. This systematic comparison across materials and indices transcends the limitations of single-item physical tests in terms of specimen size and controllability of operating conditions, enabling parallel and transparent comparison of multi-dimensional indices such as peak load capacity, post-cracking stiffness, crack control, and ultimate deflection. The evidence obtained not only deepens the understanding of the bending mechanism of FRP-RC components, but also provides a reusable basis for optimized design and specification refinement, and lays a solid foundation for subsequent comprehensive numerical-experimental studies that incorporate the coupling effects of long-term loads, fatigue and environment.

**Conclusion**

This paper utilizes the ANSYS finite element platform to systematically compare the flexural responses of four groups of concrete beams using ordinary steel reinforcement (HRB400), GFRP, AFRP, and CFRP, under the premise of completely consistent geometric dimensions, concrete strength, loads, boundary conditions, and reinforcement ratios of 0,56 %. Only the type of tensile reinforcement and constitutive properties were changed. The numerical results are generally consistent with authoritative experimental literature and section theory analysis (Bakar et al., 2022), indicating that the modeling scheme based on SOLID65 (simulating the Williams–Warnke nonlinear behavior of concrete) and LINK180 (simulating reinforcement) can reliably reproduce the key characteristics of beams with different reinforcement in terms of load-deflection evolution, stiffness degradation, and failure mechanisms. Specifically, the Steel-RC beam exhibits ductile failure dominated by tensile reinforcement yielding, while the FRP-RC beam consistently shows brittle failure controlled by concrete crushing. Furthermore, the theoretical ultimate bearing capacity and the finite element results agree well in terms of order of magnitude and relative order of magnitude. Further performance comparisons clearly show that the type of FRP has a significant impact on flexural performance, and the decisive parameter is not only tensile strength, but also the elastic modulus $E_f$. Under the same reinforcement ratio and over-reinforcement design (with concrete crushing as the control for failure), the flexural stiffness in the post-cracking stage is jointly controlled by "reinforcement modulus + moment of inertia of the cracked section", with the overall ranking as follows: CFRP-RC > Steel-RC > AFRP-RC > GFRP-RC. Regarding ultimate bearing capacity, the ultimate loads obtained based on section theory are: Steel-RC beam $P_u \approx 56{,}0$ kN, GFRP-RC beam $P_u \approx 82{,}5$ kN, AFRP-RC beam $P_u \approx 86{,}4$ kN, and CFRP-RC beam $P_u \approx 125{,}0$ kN. The corresponding performance ranking is: CFRP-RC (125,0 kN) > AFRP-RC(86,4 kN) > GFRP-RC (82,5 kN) > Steel-RC (56,0 kN). Regarding deformation capacity, the estimated mid-span ultimate deflection based on the theoretical skeleton curve is as follows: Steel-RC beam $\delta_u \approx 40{,}0$ mm, GFRP-RC beam $\delta_u \approx 40{,}0$ mm, AFRP-RC beam $\delta_u \approx 35{,}0$ mm, CFRP-RC beam $\delta_u \approx 30{,}0$ mm. The overall order is: GFRP-RC ≈ Steel-RC (≈ 40,0 mm) > AFRP-RC (35,0 mm) > CFRP-RC (30,0 mm). Combining deflection and crack distribution under service loads, it can be determined that GFRP-RC beams exhibit the most unfavorable deflection and crack control from the SLS perspective, while CFRP-RC beams perform the best.

The comparison of failure and ductility characteristics further points to clear design implications. Steel-RC beams undergo a stage of steel bar yielding and plastic development before approaching the ultimate load, exhibiting a clear yield plateau and strong energy dissipation capacity. In contrast, GFRP-RC, AFRP-RC, and CFRP-RC beams all experience failure controlled by concrete crushing. Although this provides some warning compared to sudden reinforcement breakage, their overall ductility is significantly lower than that of Steel-RC beams. Therefore, in engineering applications, over-sizing design and reasonable safety reserves are necessary to compensate for the insufficient ductility. Regarding material selection decisions, CFRP, with its higher $E_f$, can significantly improve load-bearing capacity and stiffness under the same reinforcement ratio: In the case of this study, the ultimate load-bearing capacity of the CFRP-RC beam is approximately 2.2 times that of the Steel-RC beam, and the ultimate deflection is reduced by about one-quarter. It is suitable for components with simultaneously stringent requirements for strength and deformation, but it requires higher material costs and strict adherence to the over-reinforcement principle to ensure the concrete crushing failure mode. Although GFRP can effectively solve the corrosion problem, due to its lowest E_f, the stiffness reduction after cracking is the most significant. Under the same service load, it is more prone to larger deflection and cracks. The design is often constrained by SLS rather than ULS, and the control of deflection and crack limits must be strengthened. AFRP provides a pragmatic trade-off between performance and cost. Its load-bearing capacity and stiffness are between GFRP and CFRP and are generally superior to Steel-RC, making it suitable for scenarios that balance performance and economy. The final engineering selection should comprehensively consider factors such as structural importance, load conditions, environmental erosion level, deformation limits, and life-cycle cost. Based on the specifications, the ULS and SLS should be double-checked to reasonably determine the reinforcement scheme and target performance indicators. In conjunction with key quantitative information such as$E_f$, $P_u$, and $\delta_u$, a design path for balanced optimization of durability, load-bearing capacity, and service performance should be formed.

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# ON THE TASKS OF OPERATIONAL CONTROL OF THE CONDITION OF REINFORCED CONCRETE STRUCTURES OF MUNICIPAL WASTEWATER DISPOSAL SYSTEMS

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**Abstract**

Operational monitoring of the technical condition of reinforced concrete structures (wells, collectors, tanks) in wastewater disposal systems is a set of periodic measures aimed at the timely detection of defects and the prevention of accidents. Its particular importance arises from the structures' operation in an aggressive environment exposed to moisture, temperature fluctuations, stray currents, and mechanical loads. The objectives of operational monitoring include the identification of visible and hidden defects (cracks, chips, delamination of the protective concrete layer, exposed and corroded reinforcement, leaks in joints, and mutual displacement of precast elements), an assessment of the strength and deformation properties of materials (concrete and reinforcement), the degree of corrosion, checking the tightness of the structures, and verifying the compliance of actual parameters with design specifications. Monitoring is implemented using visual and instrumental non-destructive methods, ensuring rapid results. Based on the monitoring results, a report is prepared with measurement protocols, defect diagrams, and recommendations for repair or reinforcement of the structure. Operational monitoring is planned and preventative in nature. According to current regulations, the recommended frequency is at least once a year, and more frequently for facilities showing signs of deformation or in a state of emergency. One of the modern innovative approaches that is beginning to be adopted globally is the digitalization of processes related to the operational monitoring of the technical condition of wastewater disposal systems. However, the implementation of digitalization requires both the development of new regulations and the development of an information infrastructure (systems and specialized equipment for diagnostics in difficult operating conditions, specialized software, etc.).

Therefore, systematic operational monitoring using an integrated approach based on both visual and instrumental methods, including the use of digital systems, is a prerequisite for maintaining the operability of wastewater disposal systems. This will enable a transition from repairs following an accident to preventive technical condition management, significantly increasing the reliability and extending the service life of utility networks.

**Keywords:** operational control, wastewater disposal systems, waste water, reinforced concrete structures, regulatory documents, technical condition assessment, forecasting.

## О ЗАДАЧАХ ОПЕРАТИВНОГО КОНТРОЛЯ СОСТОЯНИЯ ЖЕЛЕЗОБЕТОННЫХ КОНСТРУКЦИЙ КОММУНАЛЬНЫХ СИСТЕМ ВОДООТВЕДЕНИЯ

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**Реферат**

Оперативный контроль технического состояния железобетонных конструкций (колодцев, коллекторов, резервуаров) в системах водоотведения – это комплекс периодических мероприятий, направленных на своевременное выявление дефектов и предотвращение аварий. Его особая важность обусловлена работой конструкций в агрессивной среде под воздействием влаги, температурных перепадов, блуждающих токов и механических нагрузок. В задачи оперативного контроля входит выявление видимых и скрытых дефектов (трещин, сколов, отслоения защитного слоя бетона, оголение и коррозия арматуры, протечки в швах, взаимных смещений сборных элементов), оценка прочностных и деформационных характеристик материалов (бетона и арматуры), степени их коррозии, проверку герметичности конструкций и соответствие фактических параметров проектным решениям. Контроль реализуется с помощью визуальных и инструментальных неразрушающих методов, обеспечивающих быстрое получение результатов. По результатам контроля составляется заключение с протоколами измерений, схемами дефектов и рекомендациями по ремонту или усилению конструкций. Оперативный контроль носит планово-профилактический характер. Согласно действующим нормативным документам, рекомендуемая периодичность – не реже одного раза в год, а для объектов с признаками деформаций или в аварийном состоянии – чаще. Одним из современных инновационных подходов, которые начинают применяться в мировой практике, является цифровизация процессов, связанных с оперативным контролем технического состояния систем водоотведения. Однако внедрение цифровизации требует как разработки новых нормативных документов, так и формирование информационной инфраструктуры (систем и специального оборудования для диагностики в сложных условиях эксплуатации, специализированного программного обеспечения и т. д.).

Таким образом, систематический оперативный контроль с применением комплексного подхода, основанного как на визуальных, так и инструментальных методах с использованием, в том числе цифровых систем, является необходимым условием для поддержания работоспособности конструкций систем водоотведения. Он позволит перейти от ремонтов по факту аварии к превентивному управлению техническим состоянием, значительно повышая надежность и продлевая срок службы инженерных сетей.

**Ключевые слова:** оперативный контроль, системы водоотведения, сточные воды, железобетонные конструкции, нормативные документы, оценка технического состояния, прогнозирование.

**Introduction**

According to general technical practice, a municipal wastewater disposal system (WDS) can be classified as a complex of interconnected engineering structures designed to collect, transport polluted wastewater (WW) outside settlements, and purify and neutralize it before discharging it into reservoirs. About 2,700 wastewater treatment plants (TP) operate in the Republic of Belarus to organize wastewater discharge into the environment, of which about 300 are undergoing artificial biological treatment with release into surface water bodies. At the same time, today the service life of the main part of the existing water management networks ranges from 20 to 55 years. At the same time, about 30 % of them are in dilapidated or disrepair, and a significant part of pumping stations require modernization (reconstruction). The situation is complicated by the fact that industrial enterprises, as a result of the lack of local effective technologies for industrial wastewater treatment and disposal of their precipitation, discharge highly concentrated wastewater into centralized sewerage systems, the harmful substances of which violate the technological regulations for wastewater treatment and are not removed during biological treatment. At the same time, at the stage of WW transportation, such pollutants with significant redox properties destroy WDS structures – the release of corrosive gases from wastewater, for example, hydrogen sulfide, has a particularly negative effect. As a result of this extremely negative impact, material and energy costs increase, which leads to an increase in electric energy costs for transportation and wastewater treatment, and, consequently, an increase in the cost of services, and the key is unacceptably reduced reliability, especially of reinforced concrete structures, up to the occurrence of emergency situations [1].

At the same time, wastewater disposal systems of water supply and sewerage companies (CWW) de facto belong to critical infrastructure (most of which are concrete elements), since as a result of possible emergencies, conditions are created for man-made pollution of territories, the development of diseases and epidemics with potential catastrophic effects on people and the environment. In accordance with the internal regulatory documents of water utilities organizations CWW, the following strict time intervals are allowed during their work: no more than 8 hours (in total) during one month, 4 hours at a time (including in case of an accident) [1, 2].

Thus, the scientific and practical task of operational control of the condition of reinforced concrete structures of the WDS is relevant and of national importance.

**Setting the task.** Substantiation of approaches to operational control of the condition of concrete structures of municipal wastewater disposal systems, primarily collectors, using modern automated tools and mathematical modeling in order to reduce the risks of abnormal (catastrophic) technological situations and increase the ecological safety of sanitation in populated areas.

**Analysis of the existing regulatory framework in the Republic of Belarus and research by other authors on the issue of monitoring the condition of reinforced concrete structures of WDS**

To monitor the normal functioning water drainage network (WN) WDS constant monitoring should be carried out on it, including [3]: external inspection of the network; technical inspection of the network; technical inspection of the main highways, storm drains, duckers and emergency outlets; inspection of the internal cavities of drainage pipes; inspection of tunnel collectors.

At the same time, the Resolution of the Council of Ministers of the Republic of Belarus dated September 4, 2019 № 594 "On Approval of the Rules for the Technical Operation of drinking water supply and sanitation (sewerage) systems in settlements" [3] defines that "the operation of sanitation (sewerage) systems in settlements includes organizational and technical measures for inspection, technical inspection, technological and technical control, maintenance, maintenance and repair carried out according to the schedule of scheduled preventive maintenance and elimination of accidents and malfunctions, approved by the chief engineer of the water supply company. The procedure for carrying out scheduled preventive maintenance on centralized drinking water supply and sanitation (sewerage) systems is determined by the Ministry of Housing and Communal Services". This regulatory document (paragraph 158 [3]) also states that "a technical inspection of the internal condition of the drainage (sewerage) network, structures and devices on it is performed for: inspection wells and emergency outlets – once a year; collectors and channels – once every two years. Technical inspection of gravity collectors and channels with diameters of 1,500 millimeters or more is carried out by passing through them, provided that the wastewater supply is completely or partially stopped. Technical inspection of pressure collectors is carried out by checking valves, plungers and sewer outlets".

An intra-industry document is Resolution № 22 of the Ministry of Housing and Communal Services of the Republic of Belarus dated May 12, 2006 "On the procedure for carrying out scheduled preventive maintenance on centralized drinking water supply and sanitation (Sewerage) systems" [4], which defines the procedure for carrying out scheduled preventive maintenance on centralized drinking water supply and sanitation (sewerage) systems. Within its framework, the schedule of scheduled preventive maintenance system is presented as a complex of "technical and organizational and technical measures aimed at maintaining and (or) restoring the operational, structural, engineering, and aesthetic properties of structures and devices as a whole and (or) individual components of equipment, structural units, and elements of centralized sanitation systems (sewerage)". In Chapter 4, "Planning and organization of the schedule of scheduled preventive maintenance" of this Resolution [4], it is established that "the list of facilities subject to capital and routine repairs is determined by the technical council CWW on the basis of defective statements compiled based on the results of inspections, journal entries for the operation of water facilities and devices, as well as the results of surveys of commissioning organizations and modernization and technical re-equipment projects". At the same time, "when planning preventive maintenance and routine repairs, it is necessary to be guided by the timing of the frequency of repair work (inter-repair periods) according to the appendix, as well as the time standards for repair work, developed and approved in accordance with the established procedure. The required number of inspections is assigned, after which routine repairs are planned; structures, devices and equipment that require major repairs or replacement, including the relocation (reconstruction) of pipelines".

Collectors and pipelines made of reinforced concrete structures of WDS [6, 7] are especially critical in terms of reliability [5] and durability. The annex to the Decree of the Ministry of Housing and Communal Services [4] defines the following frequency and emphasis of inspection of collectors:

– at flow rate WW of more than 3 $m^3/s$: frequency once every 12 months; the degree of filling, the presence of backup (flooding), blockages and other violations visible from the surface of the earth is checked; the presence of gases in wells; the presence of a drainage surface or other water in the reservoir;

– at flow rate WW of more than 1–3 $m^3/s$: frequency once every 12 months; inspections are carried out during internal inspection of collectors and channels with a diameter of 1,5 m or more, changes in the geometric shape of the section, the presence of drains, cracks, through holes, voids for cladding, corrosion of concrete, reinforcement;

– at flow rate WW is less than 1 $m^3/s$: the frequency is once every 24 months; the precipitation of individual pieces of concrete and the subsidence of individual sections are checked.

Thus, it is possible to formulate the directions that need to be significantly improved in the framework of ensuring the control of all WW WDS, based on the regulatory framework currently in use (Figure 1).

Such inertia and a significant duration of inspection periods leads to uncontrolled and unpredictable decommissioning, including collapses, of collectors made of reinforced concrete structures. Their opening often shows that there are characteristic failures of the arch due to chemical corrosion of concrete and reinforcement.

An option to overcome this problem may be the introduction of a television inspection in systems of water supply and sewerage companies (CWW), which acts as one of the technical means of operational inspection and control of the technical condition of sewage systems. This allows you to remotely detect clogging sites, determine the presence of stationary objects, cracks, and identify areas of highway deformation and damage to reinforced concrete structures without dismantling or partially dismantling communications. At the same time, the use of such a technical tool only allows you to visually fix defects – decision-making without external support is carried out by a specialist of water supply and sewerage companies (CWW).

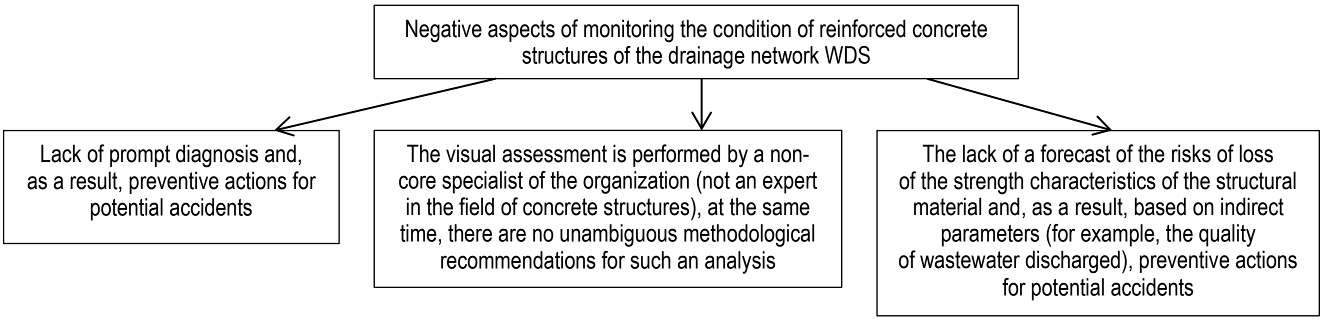


**Figure 1** – The reasons causing a significant decrease in the controllability of the condition of reinforced concrete structures of drainage networks of municipal wastewater systems

At the same time, there is a potential possibility of integrating such remote operational control technologies into the control room control system. There is no Resolution of the Council of Ministers of the Republic of Belarus dated September 4, 2019 № 594 [3] it is stated that "the general operational management of the operation of centralized drinking water supply and sanitation (sewerage) systems, maintenance of the established modes of their operation are assigned to the dispatching service" and "the structure of the dispatching service of the of water supply and sewerage companies (CWW) organization is determined depending on the location of the premises and the performance of the sewerage systems, the length of the network and the complexity of technological processes".

**Analysis of solutions for operational control of the condition of reinforced concrete structures in other industries**

The methodological foundations and principles of assessing the technical condition of reinforced concrete structures, based on ensuring structural reliability in accordance with СТБ ISO 2394 [8], are currently set out in the new edition of СТБ ISO 13822 [9] in the Republic of Belarus. In accordance with the new requirements, the assessment of the technical condition of existing structures can be performed in the following cases:

– in case of an intended (planned) change in the purpose of an object (building, structure) or an extension of its service life or during structural reliability checks (for example, with the intensity of processes in the material of structures under various influences, the appearance of new influences, etc.) in the case of requirements of supervisory authorities, owners and buildings, etc.;

– wear of structures with degradation of material properties due to prolonged exposure and environmental influences (for example, corrosion or other damage, etc.).

Currently, in the Republic of Belarus, the main regulatory document for the inspection of buildings and structures is CH 1.04.01-2020 "Technical condition of buildings and structures" [10], which replaced the previous ТКП 45-1.04-305-2016 [11]. The document establishes the basic requirements for the technical condition of buildings and structures and the procedure for their assessment.

At the same time, when assessing the technical condition of building structures, other building codes and regulations apply, such as SP 1.04.02-2022 "General provisions for the inspection of building structures of buildings and structures" [12], SP 1.04.03-2022 "Inspection and reinforcement of stone and reinforced stone structures" [13], SP 1.04.04-2023 "Inspection and reinforcement of steel structures" [14] and others. The additional standards detail the examination procedures, supplement and clarify the general requirements, and suggest reinforcement options for specific types of structures.

The main objective of the survey is to develop recommendations and technical solutions for restoring the lost operational qualities of building elements or giving them new qualities in the changed operating conditions during repair or reconstruction. In some cases, it is necessary to assess the remaining service life of the building and develop restoration measures with an assessment of the feasibility of their implementation, or develop only supportive (temporary) measures to ensure the safe operation of the facility for a specific limited period of time set by the customer, etc. [15].

According to [10], the inspection of the technical condition of buildings and structures is carried out in three main stages: **stage 1** – preliminary inspection of the building; **stage 2** – general inspection (according to external signs); **stage 3** – detailed (instrumental) inspection.

A preliminary inspection of the building is carried out in order to draw up a technical specification for conducting a general survey, clarify the goals and objectives of the work, pre-determine the scope and timing of work, the amount of available design, executive and operational documentation, and access conditions to the building elements being examined.

The general survey is carried out for a general assessment of the technical condition of construction structures, adjusting the goals and objectives of the work, determining the actual volumes of the structures being examined and drawing up a detailed survey program. The general survey includes a general assessment of the structural scheme and compliance of the building with the design documentation in terms of spatial planning and design solutions, the type and nature of loads, and operating conditions. During the general examination, a visual inspection of all structures is carried out with the use of tools and devices, if necessary. The main purpose of the general (visual) inspection is to examine and record all damages or structural inconsistencies, their location, and includes verifying the reliability of the original drawings or determining basic information about the object; determining the main deviations not represented on the original construction documents; determining visible structural damage, such as cracks and delamination, as well as checking the quality of structures; determining the potential risk of falling of non-load-bearing structures, etc.; examination of the condition of soils and foundations; generating a report on the current status with photos. If necessary, tests and measurements are performed to obtain additional data on the condition of structures: an approximate assessment of the strength of concrete and its density, measurement of the opening width and depth of the most characteristic cracks, selective measurement of the largest deviations of the main dimensions from the design documentation, etc. [18]. Based on external signs (visually), an orientation assessment of the category of technical condition of individual structures is assigned with the determination of the need for emergency measures (if necessary).

A general inspection of the technical condition of structures (visual inspection) is the first and most effective method of preliminary assessment of the technical condition and identification of typical defects and damages. It is designed for a quick inspection of the structure and assessment of its general condition and provides valuable information to an experienced engineer regarding the quality of the construction, serviceability and mechanism of further destruction, and therefore is the basis for a detailed plan of further actions and a quantitative assessment of the degree of damage.

A detailed inspection of the building according to SP 1.04.02 [12] includes: detailed measurements of structures and their interconnections, geodetic survey (if necessary), measurement of cracks, deflections, slopes of elements; determination of reinforcement and assessment of the degree of corrosion wear; determination of the actual characteristics of structural materials by non-destructive methods or by testing samples selected from them; final schematization and classification of defects; obtaining data on the parameters of operational environments; clarification of the initial data required to perform structural calculations, including the determination of actual loads and impacts, clarification of actual design schemes, taking into account the actual characteristics of structures and their interconnections, etc.; analysis of survey results and development of recommendations for the repair of structures and (or) engineering systems, for their further safe operation; development of technical solutions for strengthening building structures (if necessary).

Based on the results of the survey and calculation, a certified building survey specialist justifies and formulates the necessary measures for repairing and strengthening structures, necessary changes in the operating mode, sets deadlines for their implementation, the duration and type of the next survey taking into account their frequency. If necessary, specific technical solutions are developed, on the basis of which the necessary project documentation should be developed in the future.

If the results of the assessment of the technical condition of structures are insufficient to make decisions based on the results of surveys in accordance with 12.1.1 [18], in addition to safety issues, in some cases it is advisable to take into account the results of economic, environmental, social and other consequences of failures and planned restoration measures [18, 21].

In general, according to table B.1 of Appendix B [18], for engineering water supply and sewerage systems, it is recommended to conduct an inspection once every 3–6 years, but at least once a year, depending on the operating conditions (the frequency of technical inspections within the established interval is determined by the operating organizations based on the technical condition and local conditions).

**The concept of operational control of the condition of reinforced concrete structures of the WN WDS and the stages of its implementation are presented**

One of the modern approaches by which a significant increase in the level of automation is achieved, and hence the efficiency of control and decision-making, is the digitalization of technological processes with the synthesis of digital twins (CD). In the international normative document ISO 23247 "Automation systems and integration – Digital twin framework for manufacturing" [17]. "Digital Twin" [17] is defined by "a digital model of a specific physical element or process with data connections that ensures convergence between physical and virtual states with an appropriate synchronization rate". In a practical context, the introduction of such virtual models in production facilities, including the introduction of operational approaches to monitoring the condition of reinforced concrete structures of VSS, requires very significant financial and material costs for the formation of information infrastructure and specialized software [18, 19]. Thus, it is necessary to create conceptual models of data centers, where new investments would be minimized while using an already working information base – a "non-destructive implementation" would be performed.

1. Maintaining the operability of existing systems.
2. Combining different types of technical platforms.
3. Multiple connection and simultaneous use.
4. Loading the database of objects of working data warehouses.
5. Rapid deployment of the system.
6. Low financial, time and personnel investments.

The proposed block diagram formalizes such a cross-programmatic approach and allows for integration into a single dispatching system of water supply and sewerage companies (CWW) (Figure 2).

One of the advantages of the structure (see Figure 2) is its platform type, which makes it possible to connect other specialized services (for example, wastewater treatment plant management, quality control of wastewater, maintenance and repair, environmental risk forecasting), with the creation of a single software environment for the organization of water supply and sewerage companies (CWW). The "Information and analytical module for monitoring the condition of concrete structures" is part of the "Service for monitoring municipal wastewater disposal systems", which allows integrated collection and processing of information not only based on the results of inspection by specialists, but also using technical means such as a television inspection. An additional significant factor in reducing the inertia of the observability of the condition of concrete structures is the use of mathematical modeling, which makes it possible to indirectly predict the negative impact of WW pollutants on the elements of sewage networks in populated areas [20].

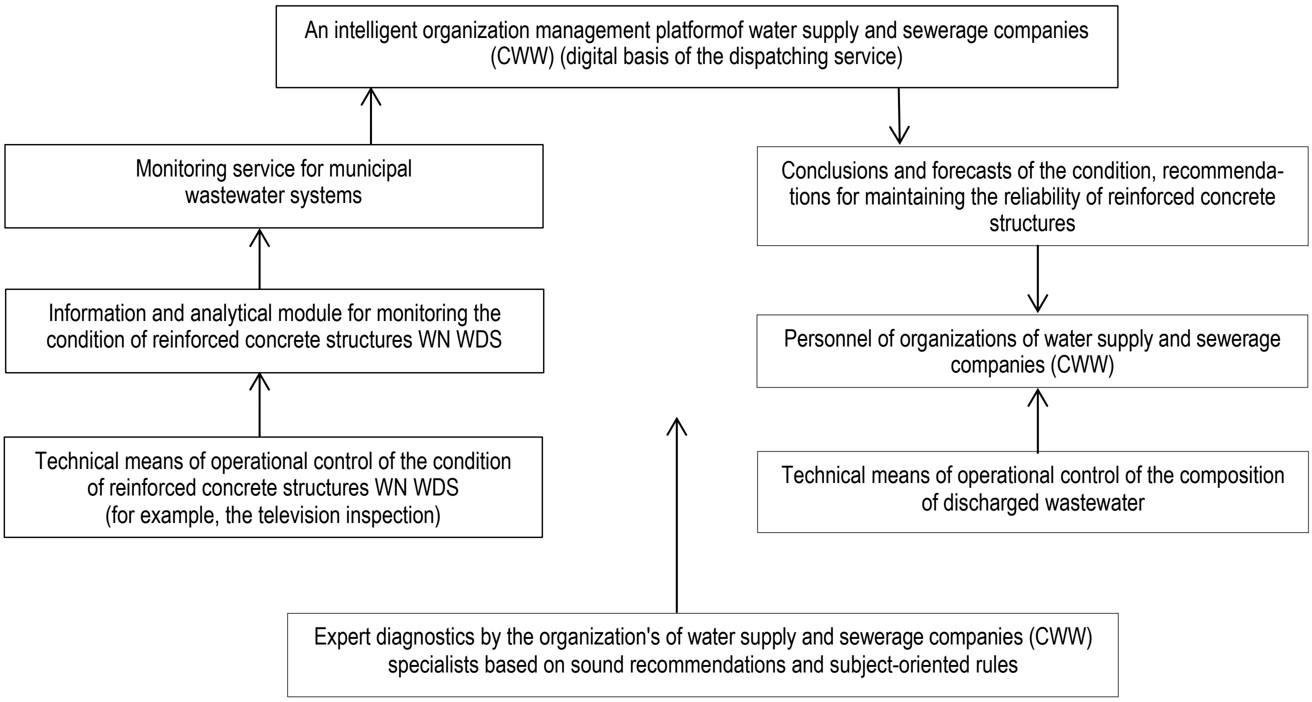


**Figure 2** – The general structure of the implementation of operational information and analytical control of the condition of concrete structures of drainage networks of urban drainage systems

At the same time, in order to form a sufficient scientific and technological foundation for a sound structure for such information analytical operational control (see Figure 2), it is necessary to solve a number of interdisciplinary tasks.

1. System analysis of the theoretical basis of the reliability of concrete structures of WN WDS.
2. Formation of a database of typical defects in concrete structures of WN WDS.

3. Creation of a knowledge base on the influence of parameters and modes of operation of WN WDS systems on their concrete structures, including depending on wastewater quality indicators.

4. Creation and parameterization of mathematical models for assessing and predicting the condition of concrete structures all of WN WDS depending on the disturbing effects of internal and external nature.

5. Development of methodological recommendations for an expert assessment of the condition of concrete structures of the VSS.

6. Formation of a methodology for using hardware and technical means to analyze the condition of concrete structures of WN WDS.

7. Creation of technological regulations for the operational control of the condition of concrete structures of WN WDS.

8. Substantiation and development of a software and hardware complex for an information and analytical module for operational control of the condition of concrete structures of WN WDS.

9. Testing and adaptation on real objects of the software and hardware complex of the information and analytical module for monitoring the condition of concrete structures of WN WDS.

10. Substantiation and creation of methodological support for the unification and scaling of the application of the information and analytical module for operational control of the condition of concrete structures for the organization of water supply and sewerage companies (CWW) in the water supply organizations of the Republic of Belarus.

**Conclusions**

The article substantiates the need to implement prompt and adequate monitoring of the condition of drainage networks of municipal wastewater disposal systems, primarily made of iron-concrete structures, while focusing on the potential catastrophic consequences of their destruction. An analysis of the existing regulatory framework for such monitoring in the Republic of Belarus indicates the inconsistency of approaches adopted at the level of a number of ministries, while suggesting a direction for improving control over the technical condition of buildings and structures in the context of reducing the inertia of decision-making and increasing their adequacy. The structure of the implementation of operational information and analytical control of the condition of reinforced concrete structures of drainage networks of municipal wastewater disposal systems of the platform type is substantiated with the synthesis of mathematical models based on expert opinions, the use of television inspection and indicators of the quality of wastewater discharged; the scientific and practical tasks of implementing such a monitoring system are systematized.

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# INNOVATIVE APPROACHES AND PRACTICES OF INFORMATION TECHNOLOGY FOR THE TECHNICAL CONDITION ASSESSMENT OF BUILDING STRUCTURES

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**Abstract**

The accelerated digitalization of the construction industry emphasizes the need for developing accurate and efficient methods for assessing the technical condition of buildings and structures. Despite the growing adoption of Building Information Modeling (BIM) and Digital Twin (DT) technologies, their potential for diagnostic purposes and forecasting the residual service life of structures remains underutilized. This paper presents the results of a systematic literature review aimed at identifying and analyzing specific approaches at the intersection of BIM, DT, the Internet of Things (IoT), and Artificial Intelligence (AI) methods, specifically focused on condition assessment. The SLR procedure, covering 100 relevant publications, enabled structuring the research field along three aspects: types of monitoring data and sensors used, methods for integrating diagnostic data with digital models, and analysis algorithms for damage detection and degradation forecasting. The results indicate a transition from passive digital models to active diagnostic systems operating in near real-time. However, a key barrier remains the fragmentation of solutions: data on physical condition often exist in isolation from the semantic context of the BIM model, while analysis algorithms are not adapted to handle spatially distributed and multi-parametric information streams. Based on the conducted analysis, the article proposes a conceptual framework for building comprehensive diagnostic DT systems. This framework includes the semantic enrichment of models with condition attributes, unified protocols for streaming sensor data, and hybrid analytical algorithms combining physical degradation models with machine learning. This research contributes to the systematization of knowledge in the field of IT-enabled structural health monitoring and outlines directions for further applied development.

**Keywords:** building information modeling (BIM), digital twin, structural health monitoring (SHM), internet of things (IoT), artificial intelligence (AI), systematic review.

## ИННОВАЦИОННЫЕ ПОДХОДЫ И ПРАКТИКИ ИНФОРМАЦИОННЫХ ТЕХНОЛОГИЙ В ОЦЕНКЕ ТЕХНИЧЕСКОГО СОСТОЯНИЯ СТРОИТЕЛЬНЫХ КОНСТРУКЦИЙ

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**Реферат**

Ускорение цифровизации строительной отрасли актуализирует задачу разработки точных и эффективных методов оценки технического состояния зданий и сооружений. Несмотря на растущее внедрение технологий информационного моделирования (BIM) и цифровых двойников (Digital Twin, DT), их потенциал для целей диагностики и прогнозирования остаточного ресурса конструкций раскрыт не полностью. В данной статье представлены результаты систематического обзора литературы, выполненного с целью выявления и анализа специфических подходов на стыке BIM, DT, интернета вещей (IoT) и методов искусственного интеллекта (ИИ), ориентированных именно на оценку технического состояния. Процедура SLR, охватившая 100 релевантных публикаций, позволила структурировать исследовательское поле по трем аспектам: типы используемых данных и сенсоров для мониторинга, методы интеграции данных диагностики с цифровыми моделями, алгоритмы анализа для выявления повреждений и прогнозирования износа. Результаты указывают на переход от пассивных цифровых моделей к активным диагностическим системам, функционирующим в режиме, близком к реальному времени. Однако ключевым барьером остается фрагментарность решений: данные о физическом состоянии зачастую существуют изолированно от смыслового контекста BIM-модели, а алгоритмы анализа не адаптированы к работе с пространственно-распределенными и многопараметрическими потоками информации. На основе проведенного анализа в статье предлагается концептуальная рамка для построения комплексных диагностических DT-систем, включающая семантическое обогащение моделей атрибутами состояния, унифицированные протоколы потоковой передачи данных с датчиков и гибридные аналитические алгоритмы, сочетающие физические модели деградации с машинным обучением. Данное исследование вносит вклад в систематизацию знаний в области ИТ-обеспечения мониторинга состояния конструкций и задает направления для дальнейших прикладных разработок.

**Ключевые слова:** информационное моделирование зданий (BIM), цифровой двойник, мониторинг технического состояния конструкций (SHM), интернет вещей (IoT), искусственный интеллект (ИИ), систематический обзор.

**Introduction**

The dynamics of the modern construction industry are characterized not only by the pursuit of optimizing construction processes but also by increasing demands for safety, operational reliability, and lifecycle management of existing buildings and structures. In this context, Structural Health Monitoring (SHM) is evolving beyond periodic instrumental surveys into a task of continuous, data-driven analysis [1]. The «Construction 4.0» paradigm, integrating IoT, AI, and big data, creates the technological foundation for this transformation, as discussed in detail in review works on this topic [2, 3]. However, as researchers note, the technological arsenal itself does not guarantee results; its targeted orientation towards solving specific engineering problems, such as damage identification and residual life prediction, is critically important.

BIM has established itself as the standard for the digital representation of the physical and functional characteristics of an asset. However, the traditional BIM model, while being a rich source of static information on geometry, materials, and components, is not inherently designed to work with dynamic data concerning the actual behavior and condition of structures under load and over time [4]. This is precisely the limitation that the Digital Twin (DT) concept aims to overcome, proposing the creation of a connected, synchronized, and continuously updated digital copy of a physical asset [5]. Thus, the DT presents itself as an ideal platform for SHM, potentially capable of enabling a shift from reactive to predictive maintenance, which is particularly relevant in light of global trends in sustainable development and lean asset management [1].

Despite the obvious synergistic potential, research at the intersection of BIM, DT, and SHM remains fragmented. A significant volume of work is devoted to the general principles of DT in construction, their architecture, or specific implementation cases [6, 7]. At the same time, questions regarding *what specific data* on structural condition is most informative, *how* it should be semantically linked to BIM model elements, and *by which algorithms* diagnostically significant conclusions can be extracted from this data remain insufficiently studied. A clear gap exists in the systematization of technological pipelines that transform the abstract DT concept into a working tool for a diagnostics engineer. This problem is partially addressed in works dedicated to interoperability and standardization, but the focus in them is often shifted towards general data rather than highly specialized condition parameters [8, 9].

The aim of this article is to structure and critically analyze existing research and practical approaches to using information technologies (BIM, DT, IoT, AI) for the tasks of assessing the technical condition of building structures. To achieve this aim, a systematic literature review (SLR) was conducted to answer the following questions: 1) What are the dominant data types and sources in modern IT systems for SHM? 2) Which architectural and technological solutions are used to integrate monitoring data streams with digital models? 3) Which analytical methods are applied to interpret data and assess condition? The results of this analysis will reveal prevailing trends, identify bottlenecks, and define promising directions for creating holistic, interoperable, and effective diagnostic systems.

**Research Methodology**

To achieve the stated aim, the Systematic Literature Review (SLR) method was applied, following established protocols that have proven effective in technical sciences [10]. The process was divided into clear stages: planning, search, selection, analysis, and synthesis. This approach minimizes subjectivity and ensures the reproducibility of results.

**Planning.** The three points outlined above were formulated as Research Questions (RQs). They are aimed at identifying technological components and their interrelationships in the SHM context, shifting the focus from general rhetoric about digitalization to specific technical implementations.

**Search.** The search for relevant publications was conducted in the Scopus, Web of Science, and IEEE Xplore databases, which have high citation indices in technical and computer sciences. The search period was limited to the last decade (2014–2024) to cover the period of active development of DT and IoT. However, to understand the evolution of some basic concepts, earlier fundamental works were also consulted. A combination of key terms, grouped into thematic clusters, was used:

1) *objective*: «structural health monitoring» OR «condition assessment» OR «damage detection» OR «structural integrity»;

2) *technology*: «digital twin*» OR «BIM» OR «Building Information Modeling»;*

3) *tools: («IoT» OR «sensor*» OR «artificial intelligence» OR «machine learning».

This search strategy allowed covering the interdisciplinary nature of the topic.

**Selection.** The initial search yielded 412 results. After automatic and manual removal of duplicates, 378 publications remained. At the preliminary screening stage based on titles and abstracts, works not meeting the inclusion criteria were excluded: articles had to be peer-reviewed, written in English, and directly describe the application of BIM/DT/IoT/AI for monitoring, diagnosing, or predicting the condition of building structures (buildings, bridges, tunnels). Works focused solely on energy efficiency [5, 11], comfort management, or general project management issues without an emphasis on structural condition were excluded. After this stage, 152 publications remained in the pool.

**Analysis and Synthesis.** The full texts of these 152 articles were examined for compliance. Ultimately, 100 publications that most fully and substantively answered the research questions were included in the final selection for in-depth qualitative analysis. Data from the selected articles were extracted into a structured table by categories: structure type, sensors and data used, method of integration with BIM/DT, applied analytical algorithms, key findings. Information synthesis was carried out through thematic analysis and comparison of the identified approaches, which allowed not just listing technologies but identifying patterns in their application and mutual influence.

**Results and Analysis**

The literature analysis allowed for the identification of three interconnected technological layers in condition assessment systems based on DT: the *data* layer, the *integration* layer, and the *analytics* layer. Each layer has its own development logic and set of problems, but their effectiveness is determined precisely by the coherence of interaction.

**1. Data Layer. Sources and Types of Condition Information.** The dominant data source is a network of heterogeneous IoT sensors, installed either permanently or used mobile. Several categories can be distinguished, each covered in a number of studies.

- **Geometric Data.** Laser scanning (LiDAR) and photogrammetry provide high-precision point clouds for detecting deformations, deflections, and cracks [12]. Their primary value lies in creating an up-to-date geometric «shell» for the DT, which is the first step towards detecting macro-damage.
- **Dynamic and Vibration Data.** Accelerometers, gyroscopes, and strain gauges record the structural response to static and dynamic loads (wind, traffic, operational impacts). Analysis of frequency characteristics and mode shapes is a classical method for identifying changes in stiffness and the emergence of damage, as confirmed by both fundamental and applied works [13, 14].
- **Physico-Chemical Data.** Corrosion, humidity, temperature sensors, and acoustic emission sensors (for crack detection) provide information on material degradation processes and the environment [15]. This data often has a local character but is critically important for assessing progressive damage. A critical problem at this layer, noted by many authors, is the uncertainty in selecting the optimal sensor type, quantity, and placement for specific structure types, as well as ensuring the long-term autonomy and calibration of measurement systems. A dilemma exists between sensor network density and the economic feasibility of its deployment.

**2. Integration Layer. Linking Data with the Digital Model.** The integration problem extends beyond simply «attaching» a sensor reading to coordinates in the model. It concerns the semantic enrichment of BIM/DT, i. e., endowing digital objects with the ability to «understand» incoming condition data. Two main approaches have been identified, which often compete and sometimes complement each other.

- **Extension of Data Standards.** Attempts to extend the open IFC (Industry Foundation Classes) format with classes and attributes for storing monitoring data, maintenance history, and condition assessments [8]. This is a «heavy» but potentially the most interoperable path, as it relies on an already existing ecosystem. However, the standardization process is extremely slow and often lags behind the pace of technological development.
- **Use of Ontologies and Linking Models.** Creating separate semantic models (e. g., based on the Brick Schema developed for buildings) that act as an intermediate layer linking raw sensor data to BIM model concepts [7, 16]. This allows for flexible description of complex relationships (e. g., that a group of vibration sensors belongs to a specific beam, which in turn is part of the load-bearing frame) but creates the problem of ontology multiplicity. The main challenge here remains the lack of a unified, widely accepted standard for describing the «condition» of a structural element in a digital representation, which hinders data exchange between different software platforms and creates barriers to scaling solutions [9]. Moreover, as shown by the research of Seghezzi et al. [8], even when technical solutions exist, the key obstacle can be the absence of clear organizational information management processes.

**3. Analytics Layer. From Data to Diagnostic Insights.** This is where the role of AI and physical modeling is fully realized. The analysis showed an evolution from simple to complex hybrid methods, with each stage having its niche application.

- **Threshold Methods and Physical Models.** The basic level, where an alarm is triggered when a predefined limit (e. g., strain) is exceeded. Detailed finite element analysis (FEA) models, embedded in the DT, allow for simulating structural behavior and comparing it with reality, performing so-called virtual load testing [16]. These methods are well interpretable but require precise knowledge of material properties and boundary conditions.


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- **Machine Learning (ML) and Deep Learning (DL).** These methods dominate contemporary research, as clearly seen in the dynamics of publications. Unsupervised learning techniques, such as clustering or principal component analysis (PCA), are used to detect anomalies in data streams without prior knowledge of damage, which is convenient for monitoring complex objects with non-obvious degradation modes [10]. Supervised learning methods, e. g., convolutional neural networks (CNN), are applied for automatic classification of damage types in images or vibration spectra, demonstrating impressive accuracy in controlled conditions [6, 18]. Recurrent neural networks (RNN) are effective for analyzing time series and forecasting future trends (e. g., deformation development or accumulation of fatigue damage).
- **Hybrid (Physics-Informed) Models.** The most promising direction, where physical laws (equations of solid mechanics) are embedded into neural network architectures or used to generate synthetic data for their training [14]. This helps overcome the «data hunger» characteristic of purely data-driven approaches in SHM and improves the explainability of results, which is a critical requirement for engineering practice. Such approaches essentially create a digital twin that not only reflects but also «understands» the physics of the process.

**Case Study. A Retrospective View of Shanghai Tower from an SHM Perspective.** Although the Shanghai Tower project [19] is often cited as a benchmark for BIM application, its potential for continuous condition monitoring was only partially realized. The integration of BIM with Building Management Systems (BMS) was primarily focused on energy and climate. However, viewing this model as a foundation for a future DT reveals key points for SHM implementation. For example, elements of the complex facade and the high-rise structures, subject to significant wind and seismic loads, are ideal candidates for equipping with a network of fiber optic strain sensors and accelerometers. Data streams from these sensors, integrated into the BIM platform via a semantic layer, could enable real-time tracking of stress levels, identification of fatigue phenomena, and prediction of the need for targeted intervention, minimizing risks and maintenance costs for the unique structure. This example illustrates the evolution from BIM as an archival model to DT as an active diagnostic system. Interestingly, a similar approach, but for bridge structures, is demonstrated in the work of Tita et al. [20], indicating the universality of the identified principles for different types of infrastructure.

**Figure 1** – Schematic diagram of the BIM model structure of Shanghai Tower

**Conclusion and Future Research Directions**

The conducted systematic review confirms that the convergence of BIM, Digital Twin, IoT, and Artificial Intelligence is shaping a new paradigm in the field of technical condition assessment for building structures. IT is ceasing to be merely a visualization tool and is becoming the core of predictive analytics systems. A key conclusion is the recognition that the value of DT for SHM is determined not by the complexity of 3D graphics, but by the depth of semantic connections between model elements and data streams, as well as by the intelligence of the algorithms interpreting this data. The application of these technologies, as shown in various studies, covers a wide spectrum of tasks – from virtual design and safety management [18] to structural health monitoring [14] and even modeling the spread of hazardous substances in buildings [6].

The analysis revealed several persistent problems hindering widespread industrial adoption. These problems are systemic in nature and require interdisciplinary efforts.

1. **Semantic Gap.** The lack of unified ontologies for describing structural condition and its linkage to monitoring data. Existing works, such as [8], offer partial solutions, but there is no industry-wide consensus.
2. **The «Last Mile» Data Problem.** The difficulty of automatic, reliable, and cost-effective collection of high-frequency data from distributed sensor networks over decades of operation. Issues of power supply, data transmission, and physical durability of sensors in aggressive environments remain relevant [15].
3. **The «Black Box» of Analytics.** Insufficient explainability of decisions proposed by complex machine learning models, which is critically

important for making engineering decisions in the realm of safety. An engineer must understand the basis on which the system recommends an inspection or structural strengthening.

4. **Ecosystem Fragmentation.** Incompatibility between proprietary platforms for BIM, IoT, and analytics, leading to the creation of «siloed» solutions, as rightly mentioned in the context of the construction industry as a whole [9].

As directions for future research, based on the synthesis of the reviewed works, it is proposed to focus efforts on the following areas:

- **development and validation of open, industry-focused ontologies**, focusing specifically on condition attributes, damage, and diagnostic metrics, rather than general building descriptions. This work should be carried out by consortia involving all stakeholders;
- **investigation of hybrid analytical architectures** that combine physical fidelity (e. g., reduced-order FEA models) with the adaptability of machine learning methods for working with incomplete and noisy data, characteristic of real-world operation [14];
- **conducting long-term pilot projects** on real assets, aimed not at demonstrating individual technologies, but at quantitatively assessing the effectiveness of comprehensive DT-based SHM systems in terms of enhancing safety, reducing maintenance costs, and extending the service life of structures. Such projects should be accompanied by careful collection and analysis of economic indicators;
- **exploring economic models and regulatory aspects** of implementing such systems, including issues of liability for decisions made based on AI recommendations, risk insurance, and updating building codes considering the new possibilities of digital monitoring. Without solving these issues, even the most advanced technologies will remain within the framework of laboratory experiments.

Thus, the path from the concept of a Digital Twin to an everyday tool for a diagnostics engineer lies through solving not so much technical as systemic and methodological challenges. This requires close and equal cooperation among specialists in structural mechanics, computer sciences, data theory, and industry management. Only such a comprehensive approach will allow realizing the transformative potential embedded in Construction 4.0 technologies for creating a sustainable and safe living environment.

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# CURVATURE MATTERS: UNRAVELING THE EARTHQUAKE RESPONSE OF BOX-GIRDER BRIDGES

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**Abstract**

The paper proposes a simpler technique for producing an idealization of curved box-girder type bridge decking under dynamic stresses produced by earthquake related excitation. The analysis focuses on two types of bridge decks with curved cellular structures, examining both single-cell and multiple-cell configurations. This approach may be used to rectangular and trapezoidal box-girder sections with both equal and unequal dimensions of cells. The proposed element "Panel Element (PE)" is coded as Component Element (CE) and has proved to be capable of modeling a full plane panel of a curved cellular deck in its three-dimensional behavior by one element only. For verification purpose and to demonstrate the range of applicability of the new idealization technique, a comparative study was made with the Finite Element Method (FEM), as a standard procedure, used to idealize the box-girder bridge decks. Different configurations of curved box-girder bridge decks are considered to provide a thorough understanding of the dynamic behavior of the curved bridge deck when acted upon by earthquake-based excitation besides the validation purposes. A computer program using (MATLAB R2012b) is specially written using the proposed algorithm of the new idealization technique to evaluate the earthquake analysis results. Comparison was made with those evaluated by the finite element approach using the ready software (ANSYS 12.0) to check the adequacy and suitability of the proposed element in analyzing the box-girder concrete bridge decks. The results showed that the Panel Element Method (PEM) has proved to be valid in estimating the earthquake response for both cases of single and double cell bridge decks, for all the ranges of the aspect ratios; the results obtained by the Panel Element Method (PEM) are acceptable, with an error of less than (12 %) in deflection and less than (18 %) in moments and shear forces for the cases of very large aspect ratios. This research demonstrates the validity of the proposed method "Panel Element Method (PEM)" with wide range of applicability for the dynamic behaviors of free and forced vibration response analysis and the approximate earthquake response analysis of the curved box-girder type of bridge decks of different configurations.

**Keywords:** curved box-girder bridges, seismic response, panel element method, finite element method, box girder, box-girder bridges.

## КРИВИЗНА ИМЕЕТ ЗНАЧЕНИЕ: РАСКРЫВАЯ СЕЙСМИЧЕСКИЙ ОТКЛИК СОТОВЫХ МОСТОВ

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**Реферат**

В статье предлагается упрощенная методика идеализации криволинейных сотовых пролетных строений мостов при динамических нагрузках, вызванных сейсмическими воздействиями. Анализ сосредоточен на двух типах пролетных строений с криволинейными ячеистыми структурами: одно- и многосоточных конфигурациях. Данный подход может быть применен к прямоугольным и трапецеидальным ячеистым сечениям с ячейками как равных, так и неравных размеров. Предложенный элемент «Панельный элемент» программно реализован в виде компонентного элемента и доказал свою способность моделировать полноразмерную панель криволинейного сотового настила в трехмерном поведении всего одним элементом. С целью верификации и демонстрации диапазона применимости новой методики идеализации было проведено сравнительное исследование с методом конечных элементов (МКЭ), который используется в качестве стандартной процедуры для идеализации сотовых пролетных строений. Рассматривались различные конфигурации криволинейных сотовых мостовых настилов для получения всестороннего понимания динамического поведения криволинейного пролетного строения при сейсмических воздействиях, помимо целей валидации. С использованием предложенного алгоритма новой методики идеализации была специально написана компьютерная программа на (MATLAB R2012b) для оценки результатов сейсмического анализа. Проведено сравнение с данными, полученными методом конечных элементов с использованием готового программного обеспечения (ANSYS 12.0), для проверки адекватности и пригодности предложенного элемента для анализа сотовых железобетонных пролетных строений. Результаты показали, что метод панельных элементов (МПЭ) доказал свою состоятельность в оценке сейсмического отклика как для одно-, так и для двухсотовых пролетных строений во всем диапазоне значений коэффициентов форм; полученные с помощью метода панельных элементов (МПЭ) результаты приемлемы, с погрешностью менее (12 %) для прогибов и менее (18 %) для моментов и поперечных сил в случаях очень больших коэффициентов форм. Данное исследование демонстрирует обоснованность предложенного метода «Метода панельных элементов (МПЭ)» с широким диапазоном применимости для анализа динамического поведения при свободных и вынужденных колебаниях, а также для приближенного анализа сейсмического отклика криволинейных сотовых пролетных строений различных конфигураций.

**Ключевые слова:** криволинейные сотовые мосты, сейсмический отклик, метод панельных элементов, метод конечных элементов, коробчатая балка, сотовые мосты.

**Introduction**

The safety of highway bridges is essential to the sustainable economic prosperity of our community. Highway bridge shapes may vary greatly depending on the practical requirements of the project. Curved bridges are commonly selected over linear bridges due to their lower cost and ease of construction. (Tao and Guan, 2023) [1]. Curved bridges are often observed in urban and mountainous areas due to their favorable compatibility with the surrounding terrain and their capability to permit grade crossings and overpasses with limited space (Kahan et al., 1996) [2]. Furthermore, in order to mitigate the build-up of driver fatigue resulting from driving on lengthy and straight bridges with similar conditions, an increasing number of curved bridges are being employed as substitutes for long linear bridges. Curved bridges are occasionally constructed to harmonize with the surrounding environment for aesthetic reasons. Curved overpass bridges are increasingly favored as a solution to the city's significant traffic problems (Tao and Guan, 2023) [1]. Curved bridges of different kinds have a significant impact on managing urban traffic. Nevertheless, these bridges are more vulnerable to damage caused by earthquakes compared to traditional bridges, mostly due to their irregular shape and uneven distribution of weight. Research has demonstrated that the spatial asymmetry of ground movements would negatively impact curved bridges.

The cellular cross section of the curved box-girder bridge (Figure 1) increases its efficiency by resisting the high torsional moment. Aesthetics, economy, stability, efficacy, and utility all contribute to the curved bridge's widespread recognition. Circular plans with transition curves are common when choosing these. Since curved bridges in the plan experience both bending and torsion due to the curvature of the girders, their analysis is more involved than that of straight bridges. According to Agarwal et al. (2023) [3], a curved bridge's optimal section for design should possess strong torsional stiffness.

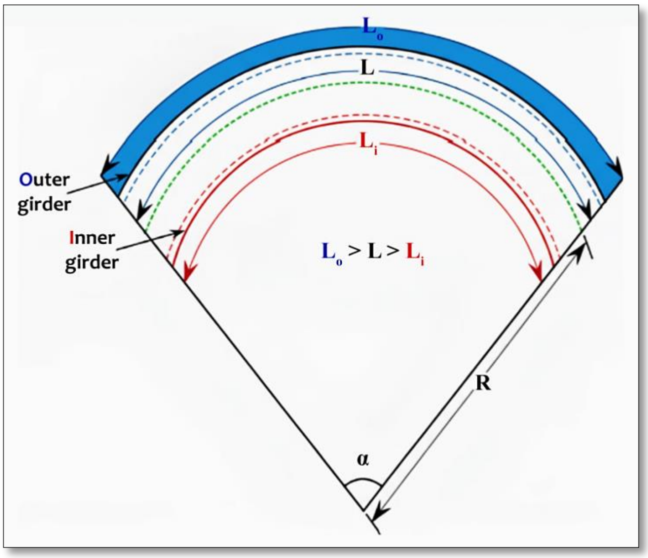



**Figure 1** – Curved box-girder bridge deck (Agarwal et al., 2023) [3]

**Literature review**

Few studies have been conducted on the seismic behavior of curved bridges subjected to ground motion exhibiting spatial variation. Sextos et al. (2004) [4] examined the seismic behavior of curved bridges subjected to multi-support excitation. They achieved this by creating synthetic multi-support ground motion. A study conducted by Burdette et al. (2008) [5] examined the impact of incoherence and traveling waves on the seismic response of both straight and curved bridges. Using the finite element-based software ANSYS, Fangping and Jianting (2012) [6] studied the impact of curvature on prestressed tendons deformation in curved bridges. The mid-span deflections were assessed by modeling and analyzing five distinct curved bridges. Cho et al. (2013) [7] demonstrated the load distribution in straight prestressed concrete (PSC) girder bridges using Finite Element Method (FEM). The GDF was evaluated against the AASHTO LRFD, AASHTO standard factors, and the findings of finite element calculations. Formulas have been proposed to predict the distribution of live loads in PSC girder bridges for preliminary design purposes. Chen and Wang (2014) [8] studied the behavior of curved girder bridges under spatially varying ground motion, with special emphasis on studying random vibration angles. Cheng et al. (2016) [9] used shaking table tests to show how important it is to think about the multi-support excitation effect when analyzing irregular high-rise curved girder bridges for earthquakes. Bahadur et al. (2017) [10] studied the stresses and deflections of a curved, rectangular plate that had only one side supporting it in 2017 and observed how the curve angle, span-thickness ratio, and aspect ratio affected the plate. Curved bridges are more susceptible to travel wave influence, according to shaking table experiments conducted by Li et al. (2017) [11]. Said and Khalaf (2018) [12] looked at a horizontally bent box girder bridge and found the live load moment distribution factor using experimental data that was loaded with AASTHO loads. Agarwal et al. (2019) [13] investigated the maximum bending moment and shear strength in a single cell inclined box girder bridge using finite element analysis. The researchers examined the effect of span, beam spacing, and span depth ratio on a skewed box girder bridge. In their study, Yuan et al. (2022) [14] investigated the mechanical properties and torsional behavior of a curved square-girder bridge. Further finite element analyses have quantified the response of curved girder and box-girder bridges to various loads, examining parameters such as curvature angle and span-depth ratio [10].

More lately, Temimi, et al. (2025), focused on the vibration characteristics of 3D curved box-girder bridges by using the Panel Element Method, and using the finite element method by ANSYS program for many deck types of box-girder bridges under earthquake loads [15].

Collectively, this body of literature confirms that curvature fundamentally alters a bridge's seismic and structural response, necessitating specialized analysis that accounts for both spatial ground motion variation and unique curvature-induced effects.

**Research Importance**

The majority of curved bridge assessments currently concentrate on static and linear dynamic evaluations, which take into consideration parameters such as natural frequencies, modal shapes, and damping conditions. This analysis aims to suggest recommendations for structural design and spectrum analysis, including support arrangements. The relationship between natural frequency, bridge connections, and dynamic performance in basic box girder curved bridges, as well as the effect of radius curvature, has been studied before (Jeon et al., 2016) [16]. It is important to study how different properties affect the typical shapes of curved bridges.

In present times, design codes often advise examining various seismic inputs and using the highest allowable values for design objectives. Applying this technique is tedious and requires significant computing costs. Creating a more efficient technique for identifying the inputs most susceptible to a curved bridge design is very challenging. It is important to determine the seismic input parameters that are most susceptible to damage and the corresponding main seismic interactions for curved bridges. The investigation focused on the dynamic reactions of curved bridges by the utilization of finite element analysis and parametric studies. A framework for seismic design of a curved bridge was developed based on a thorough investigation by providing a new simplified procedure and an alternative reliable idealization technique for dynamic and earthquake response analysis of curved box-girder type bridge decks.

**Scope of Study**

This study deals with the dynamic analysis of curved box-girder bridges subjected to earthquake base excitation, which is characterized by two orthogonal components, each of which is perpendicular to the longitudinal axis, but one is assumed to be in the vertical Y-direction and the other in the horizontal transverse X-direction. The 20 February 1990 modified smooth pseudo-acceleration design spectrum of AL-Hindya Earthquake characterizes each base excitation component. Due to the lack of acceleration records in the vertical Y-direction, the same response spectrum that is used in the analysis of bridge decks is acted upon by lateral base excitation, the same spectrum is assumed for the vertical earthquake analysis or using El-Centro components (scaled down). It is also assumed that the motion of all supports of the bridge has phase excitation, that is, all supports are acted upon by the same base excitations simultaneously. Since the box-girder bridges considered in this study are curved in plan, the lack of symmetry results in a coupled response. Therefore, any base excitation component produces a combined response of bending and torsion, even under lateral excitation.

**Problem Statement**

The increasing demand for reducing traffic congestion has led to the construction of additional highway bridges, particularly curved bridges. There has been much study of the structural performance of curved bridges since they were first designed and built. The structural intricacy of curved bridges causes them to react dynamically differently than straight bridges. Between the 1970-s and 1990-s, many powerful earthquakes resulted in extensive destruction and economic losses for curved bridges in numerous nations globally. Subsequently, various countries have intensified their endeavors in the realm of curved bridge seismic analysis (Tao and Guan, 2023) [1]. Curved bridges have distinct dynamic reactions, particularly in the case of small-curvature bridges, as compared to linear bridges and exhibit a mix of moments and torsion when subjected to both vehicular loads and horizontal seismic forces. When examining the curved bridge's reaction in both the horizontal and vertical orientations, it is difficult to separate the moment-torsion combination. Developing a reasonable theoretical dynamic analysis of a curved bridge is a challenging task due to the curvature and torsional vibration complexity. Because of the significant actions that linear bridges show in these X-Y directions, earthquake input tests that are both horizontal and vertical are generally carried out. Curved bridges are not as resistant to seismic damage as regular bridges, mostly because of their irregular mass distribution and irregular structure. Earlier studies have established that the spatial variation of ground motion has a detrimental impact on curved bridges (Kahan et al., 1996) [2]. Several curved bridges have experienced substantial destruction during earthquakes, but none of the existing seismic specifications – like the 2008 Highway Bridge Seismic Design Specifications [17], the Caltrans Seismic Design Standard (Caltrans 2025) [18], and the American AASHTO Seismic Design Guide (AASHTO 2023) [19] – have made recommendations or used techniques to avoid these issues. This is attributed to a lack of understanding of the dynamic actions of curved bridges during earthquake occurrences. (Wang et al., 2010) [20].

The objective of the present research is to analyze the longitudinal and transverse earthquake motion of the bridge and to determine the design forces and moments at the supports bases by the Finite Element Method (FEM) and the Panel Element Method (PEM). Then a comparative study of the design forces and moments found from these two methods has been made. It is expected that the findings of this study will lead to a better understanding of the behavior of bridges under seismic loading. For simplicity of the analysis, linear material behavior is assumed in this study.

**Idealization of Curved Box Girders Using Panel Element Method**

A curved box-girder bridge deck of a square or rectangular and trapezoidal in cross-section typically consists of planar units or non-planar units interconnected to each other to form a three-dimensional structural system.

An idealization procedure for modeling box-girder type bridge decks designated as the Panel Element Method (PEM) is proposed in this work. The Finite Element Method (FEM) idealization procedure, as used in this study for validation purposes.

**The Panel Element Method (PEM) Idealization Method**

This paper presents the Panel Element Method (PEM), an idealization approach for panel elements (PE). Because the fundamental component is derived via altering an element utilized in an existing comparable frame technique, this process might be categorized as an analogous frame approach.

The derivation and modification of the Panel Element Method (PEM) take into consideration the following assumptions that are found to be necessary for the formulation of the problem.

1. The bridge is assumed to be an assemblage of a finite number of flat plates or wall panels.
2. Each wall or slab panel is modeled by the conventional space frame element.
3. The analysis takes into account the flexural and shear deformations of each individual panel element (PE) in the plane.
4. Every panel element's (PE) out-of-plane flexural and shear deformations are also taken into account.
5. Diaphragms are regarded as eternally unyielding inside their own planes and flexible when positioned outside of those planes.
6. A partially rigid interface is assumed between panel elements and diaphragm in both X-Y directions, that is; relative rotational, is allowed between the panel element and the diaphragm only in the plane of panels with no distortion of the cross-section.

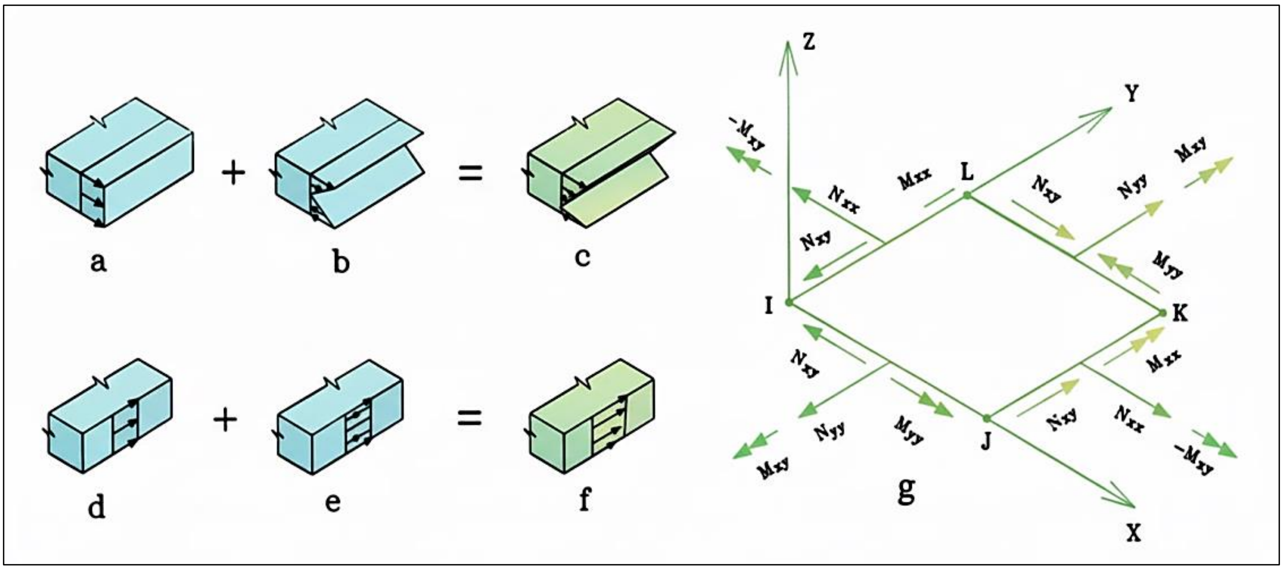
**Finite Element Idealization Method**

The present work employs the finite element idealization process to verify the efficacy of the suggested Panel Element Method (PEM) and to facilitate comparisons. The finite element idealization approach is employed for the analysis utilizing the ANSYS12 program and the CivilFEM12 software for ANSYS12.

A box-girder bridge deck normally consists of top and bottom slabs, vertical webs, and transverse members (rigid diaphragms). All these parts are modeled by an assemblage of the general four nodes flat shell element as shown in Figure 2.

Transverse members, also known as rigid diaphragms, are assumed to be rigid in one plane and flexible in another. This prevents the in-plane degrees of freedom (d. o. f.) of the transverse member's nodes from being slavishly controlled by a master set of in-plane d. o. f. defined at the mass center of the box-girder bridge deck cross-section. However, all degrees of freedom which are not in-plane of diaphragms are not constrained to this transformation.

For the numerical examples of earthquake response analysis that were considered, a specific mesh size is chosen to represent the building at the outset, and then the mesh is fine-tuned until two consecutive solutions achieve a maximum difference of less than 2 %. This process guarantees convergence and accurate results.




a) axial stress; b) bending stress; c) total in plane stress; d) shear stress; e) twisting stress; f) total shear stress; g) stress conventions for thin plane shell element (Iraq Specification, 1978) [21]

**Figure 2** – Three-dimensional plane shell element

**Dynamic Analysis of Curved Box-Girder Bridges Subjected to Earthquake**

In the dynamic analysis, the main techniques currently used.

**Response Spectrum Techniques**

This approach is founded on the mode superposition methodology. The general procedure is to compute the response of each of the structure's individual modes and then to combine these responses to obtain the overall response. Only a few modes can be included in computing any particular response of the system. The specific modes, which must be considered, depend upon the properties of the structures and the particular quantity, which is being computed, that is, the modal mass participation factors in each mode.

**Direct Integration Techniques**

The direct integration of the equations of motion is derived through a systematic and sequential process. This approach is applicable to any seismic motion on a structure, wherein moment and force diagrams may be obtained at specified intervals throughout the applied motion for both linear elastic and nonlinear elastic material behavior. This method is the more nearly complete dynamic analysis technique so far devised and is unfortunately correspondingly expensive to carry out.

**Normal Mode Technique**

The normal mode technique is a more limited approach than direct integration, as it depends on an artificial combining of the forces and displacements associated with a chosen number of them using modal superposition.

**Equation of Earthquake Motion**

In a typical dynamic problem, the motion of a system excited by an external dynamic load, and the complete set of forces acting on the system in addition to the external forces are inertia, damping and elastic forces which resist the motion and are proportional to the accelerations, velocities and displacements of the system, respectively. Thus, the equation of dynamic equilibrium of all forces acting on a multi-degree of freedom system at any time (t) can be written as follows

$$\left[\mathrm{M}\right]\cdot\left\{\ddot{\mathrm{U}}\right\}+\left[\mathrm{C}\right]\cdot\left\{\dot{\mathrm{U}}\right\}+\left[\mathrm{K}\right]\cdot\left\{\mathrm{U}\right\}=-\left[\mathrm{M}\right]\cdot\left\{\mathrm{R}\right\}\cdot\ddot{\mathrm{U}}_g . \quad (1)$$

In which [M], [C] and [K] denote, respectively, the mass, damping and stiffness matrices of the bridge deck, corresponding to the structure degrees of freedom {U}; the variable {R} represents an earthquake effect vector that is composed of both positive and negative values. Positive values indicate the degree of freedom in the direction of the base excitation component, while negative values indicate other directions. The vibration mode of the structure may be obtained by transforming Equation (1) into the normal coordinates, that is

$$\ddot{\mathrm{Y}}_n+2\zeta\omega_n\cdot\dot{\mathrm{Y}}_n+\omega_n^2\cdot\mathrm{Y}_n=\frac{\ell_{nr}}{\mathrm{M}_n}\cdot\ddot{\mathrm{U}}_{gr}\left(t\right), \quad (2)$$

where $M_n=\Phi_n^T . M . \Phi_n$ is the generalized mass at mode (n);

$l_{nr}=\Phi_n^T . M . R_n$ is the modal earthquake excitation factor in the r-direction (r = X, Y).

And $\ddot{\mathrm{U}}_{\mathrm{gr}}\left(\mathrm{t}\right)$: The time varying base acceleration component in the r-direction. The solution of the equation (2) may be written as

$$\mathrm{Y}_n\left(t\right)=\frac{\ell_n}{\mathrm{M}_n\cdot\omega_n}\cdot V_n\left(t\right), \quad (3)$$

where, $V_n(t)$ the earthquake-response integral, defined as

$$V_n(t)=\int_0^t\ddot{\mathrm{U}}_g(\tau)\cdot\exp\left[-\zeta\omega_n(t-\tau)\cdot\mathrm{Sin}\,\omega_n(t-\tau)\right]d\tau . \quad (4)$$

If the response spectrum of the ground motion is available, the maximum response of the system at each node can be obtained from it, depending upon the natural time-period and the damping ratio of the structure. The response could be spectral acceleration, velocity, or displacement, for which

$$V_{\max}(\zeta,\mathrm{T})=\frac{1}{\omega}\cdot S_a(\zeta,\mathrm{T}), \quad (5)$$

where T: Natural period, and $S_a$: the spectral acceleration or more properly, the spectral Pseudo-acceleration because it is not exactly the peak acceleration value in general, denoting the maximum acceleration of the structure relative to the ground.

Then, substituting equation (5) into equation (3) gives

$$\mathrm{Y}_{n,\max}=\frac{\ell_n}{\mathrm{M}_n\cdot\omega_n^2}\cdot S_a(\zeta,\mathrm{T}) . \quad (6)$$

The calculated displacements ($U_n$) may be determined by multiplying the mode shape ($\Phi_n$) with the generalized coordinate amplitude ($Y_n$). Therefore, the total displacements can be expressed as follows

$$\left\{U_{nr}\right\}=\Phi_n\cdot\frac{\ell_{nr}}{\mathrm{M}_n}\cdot\frac{S_{a_r}(\zeta,\mathrm{T})}{\omega_n^2} . \quad (7)$$

The elastic forces (Fs) corresponding to the relative displacements may be derived by directly multiplying the relative displacements by the stiffness matrix, such that

$$\mathrm{F_s}\left(t\right)=\mathrm{K}\,.\,\mathrm{U}\left(t\right)=\mathrm{K}\,.\,\Phi\,.\,\mathrm{Y}\left(t\right). \quad (8)$$

Expressing these forces in terms of the corresponding inertia forces created in the undamped vibration is a more convenient approach (Clough and Penzien, 1993) [22] such that

$$\left\{F_{S_{nr}}\right\}=\omega_n^2\cdot\left[\mathrm{M}\right]\cdot\left\{U_{nr}\right\}=\left[\mathrm{M}\right]\cdot\left\{\Phi_n\right\}\cdot\frac{\ell_{nr}}{\mathrm{M}_n}\cdot S_{a_r}(\zeta,\mathrm{T}) . \quad (9)$$

**Structural Response**

It should be pointed out that, in practice, the superposition of the mode responses is usually done in one of three ways (Dilger et al., 1988) [23]. The most conservative approach that yields an upper limit is to numerically add the response of the modes. This approach yields reasonable results for cases where the contribution of the fundamental mode predominates. For many problems this is usually true.

A less conservative approach is to take the sum of the fundamental mode response plus the square root of the sum of the squares of the higher modes. This will yield more reasonable results for cases where the contributions of the higher modes are appreciable.

A third approach is to obtain a total maximum response by taking the root mean square, that is, the square root of the sum of the squares of the maximum responses. The third approach is considered in the present study; thus, the maximum forces are approximated by

$$F_{S_{\max}}=\sqrt{(F_{S_1})_{\max}^2+(F_{S_2})_{\max}^2+\cdots\cdots\cdots\cdots+(F_{S_n})_{\max}^2} , \quad (10)$$

where ($F_{S1max}$, $F_{S2max}$, …, $F_{Snmax}$) are calculated from equation (9).

The resulting force vector corresponds to the free degrees of freedom (d. o. f). The reaction at support is obtained by the static approach, thus

$$\left[\mathrm{K}\right]\cdot\left\{e\right\}=\left\{F_{S_{\max}}\right\}, \quad (11)$$

where [K] denotes the stiffness matrix of the overall structure after applying boundary conditions and {e}, denotes the displacement vector produced by the static analysis of bridge deck subjected to the maximum force vector {$F_{Smax}$}, which are obtained from the response spectrum analysis. Back substitution is applied to evaluate the reactions at supports.

**Materials and methods**

This study investigates the seismic response of curved box-girder bridge decks using a newly proposed Panel Element Method (PEM), validated against the conventional Finite Element Method (FEM). The research methodology involved numerical modeling and simulation of various curved box-girder bridge configurations.

**Computer Programs by MATLAB and ANSYS Software**

A computer program was written for the dynamic analysis of the box-girder bridge decks by using the proposed Panel Element (PE) method. Dynamic analysis which has been adopted consists of free and forced vibration (earthquake response analysis).

The program group of "FSPE-DYNAMIC" is coded in MATLAB language by using a PC-computer. This program is used to analyze the curved box-girder bridge decks for any support condition and under any live load type.

Material properties were defined by an Elastic Modulus of 23,5 x $10^6$ kN/m², a Weight Density of 24,517 kN/m³, and a Poisson's Ratio of 0,20. The important material properties of MATLAB models (Linear, Elastic and Isotropic) that are used in the studied cases which are shown in Table 1.

**Table 1** – Material properties of MATLAB program

| No. | Material Properties | Values |
|---|---|---|
| 1 | Elastic Modulus (E) | 23,5 x 106 kN/m² |
| 2 | Weight Density (γ) | 24,517 kN/m³ |
| 3 | Poisson's Ratio (υ) | 0,20 |

The finite element modeling and analysis conducted in this work were carried out using program ANSYS. The calculations conducted in this study were executed utilizing ANSYS version 12,0.

The Shell and Beam elements (ANSYS, 2025) [24] that are used in this method of modeling.

1. Shell 63 (elastic shell).
2. Beam 4 (3-D Elastic Beam).

The important material properties of ANSYS models (Linear, Elastic, and Isotropic) that are used in the studied cases are shown in Table 2.

There are primarily four case studies of cross-sectional areas of curved box-girder bridges that are modeled in ANSYS for the current study as shown below.

**Description of Case Studies**

The case studies which are presented in this work include two types of curved bridges, two types of box-girder deck bridge, and two types of cross-sections of the box-bridge. The types of studied curved bridges are as follows: the first type of bridge is a curved bridge with (20 m) span lengths, and acute angle of (20° degree) and radius of curvature (57,3 m), as shown in Figures 3 c and 5 c, while the second type of curved bridge is (30 m) span length, with acute angle of (30° degree) and radius of curvature (57,3 m), as shown in Figures 4 c and 6 c.

The types of studied cellular decks are as follows: the first type is a single cell as shown in Figures 3 d and 5 d, while the second is a double cell curved deck as shown in Figures 4 d and 6 d. The types of studied cross-sections of the box-bridge are as follows: the first type is a rectangular cross-section, as shown in Figures 3 a and 5 a, while the second is a trapezoidal cross-section curved deck, as shown in Figures 4 a and 6 a.

Typical layout and cross-section dimensions for each type are shown in Figures 3, 4, 5, 6 and the material properties are listed in Tables 1 and 2.

These decks are the major decks of an existing bridge at Baghdad city (Ur-Qaherah bridge). For the purpose of the present analysis, it is assumed that each bridge is of a single (simply supported) span of length and central angle shown in Figures 3 c and 4 c. It is worth mentioning that each deck is curved in the longitudinal direction by a central angle (θ = 20° and θ = 30°) and in the vertical direction by the profile described in Figures 3 b and 4 b. All bridge decks, which are studied in the following numerical case studies, are assumed to be of reinforced concrete, which is assumed to be a linear elastic material. The required material properties in the analysis are shown in Tables 1 and 2.

**Table 2** – Material properties of ANSYS models

| No. | Material Properties | Values |
|---|---|---|
| 1 | Elastic Modulus (E) | 23,5 x 103 N/mm² |
| 2 | Weight Density (γ) | 2,500 kg/m³ |
| 3 | Poisson's Ratio (υ) | 0,20 |

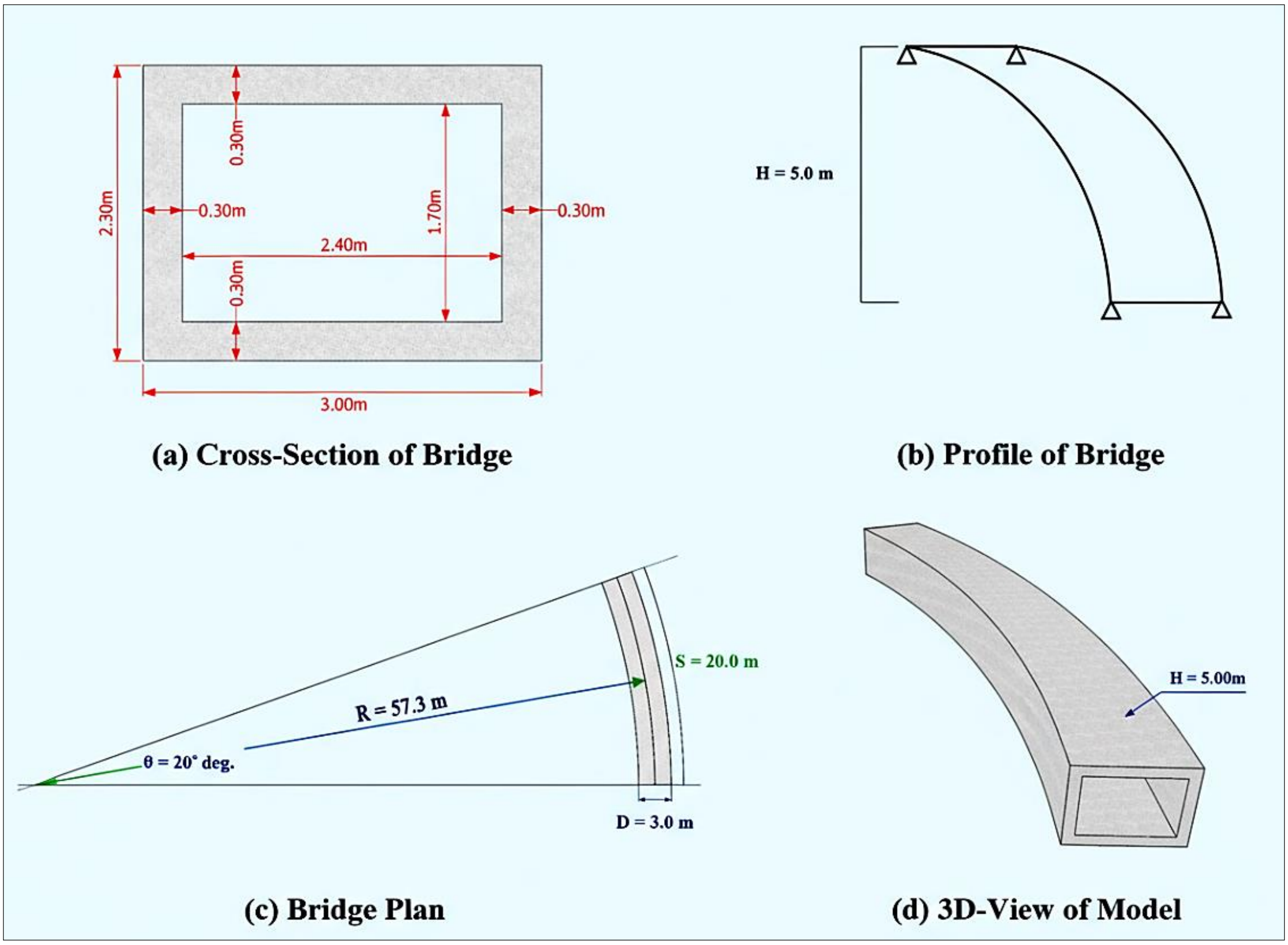



**Figure 3** – Case Study No. 1. Rectangular single cellular curved box-girder bridge

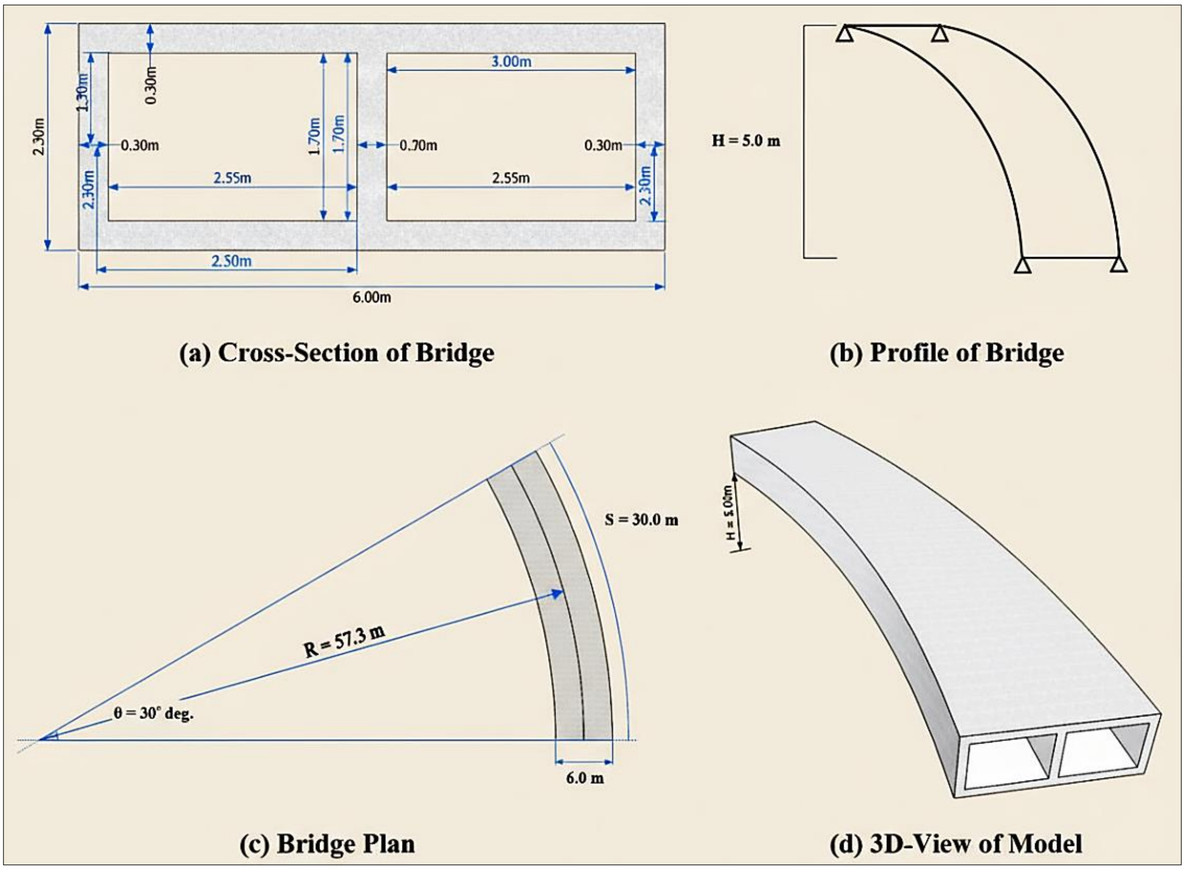



**Figure 4** – Case Study No. 2. Rectangular double cellular curved box-girder bridge

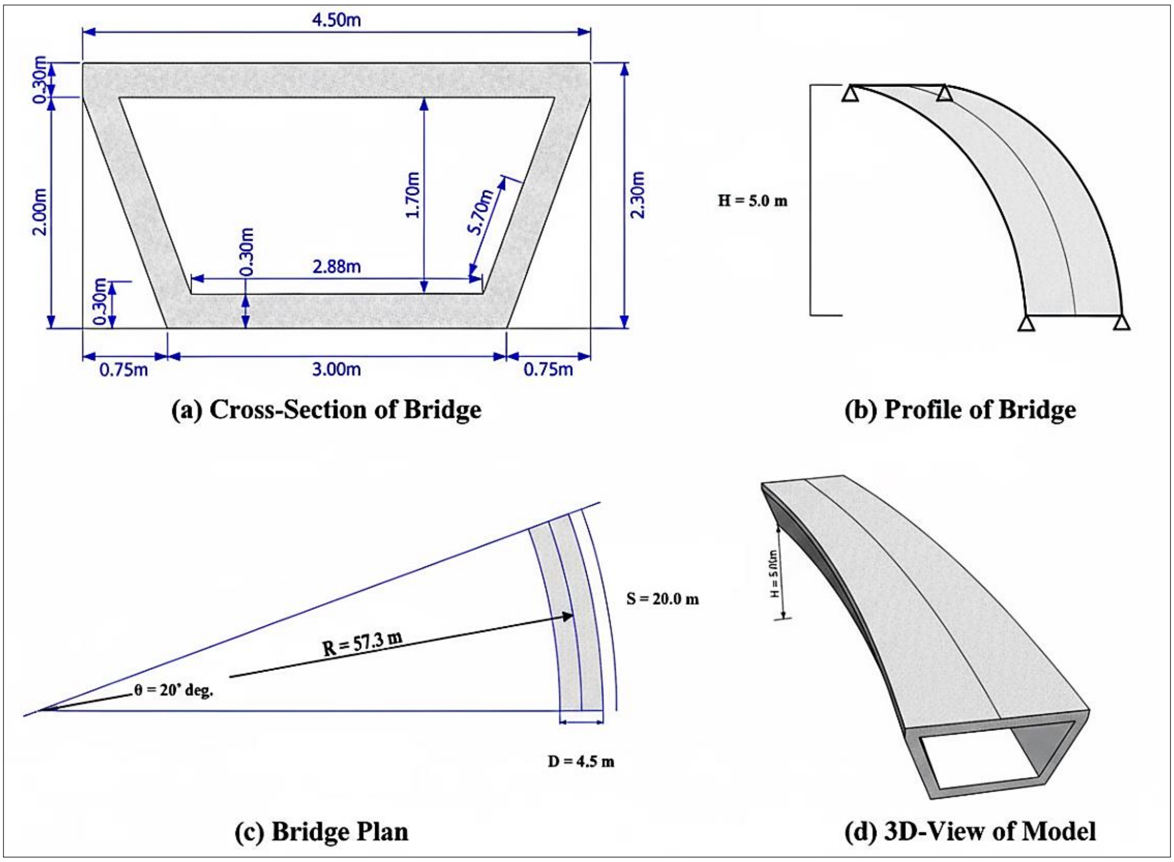



**Figure 5** – Case Study No. 3. Trapezoidal single cellular curved box-girder bridge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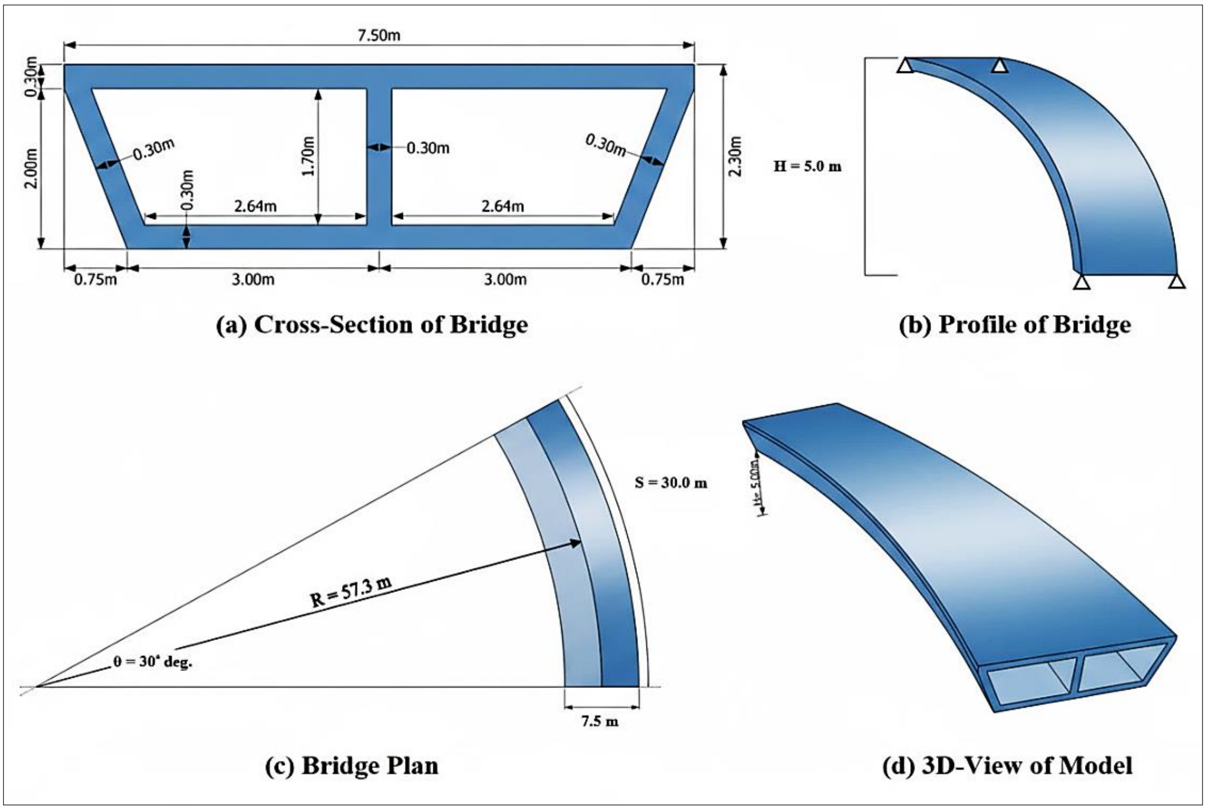


**Figure 6** – Case Study No. 4. Trapezoidal double cellular curved box-girder bridge

**Numerical Case Studies**

The bridge decks were analyzed for their earthquake response when acted upon by a lateral base excitation (orthogonal to the longitudinal tangential axis of the bridge at its mid-span) and a vertical base excitation. All these bridges are analyzed using both the proposed Panel Element (PE) approach and the results are compared to those obtained by the Finite Element (FE) procedure using the ready software ANSYS. For more details see (Al_Temimi F., 2014) [25].

The resulting moments and shear forces of each case study are given in two ways and as follows:

1) absolute response that is, the maximum moment and maximum shear force;

2) normalized response, that is, the resulting moment and shear forces are normalized to:

a) total mass of the bridge (m*);

b) the product of (m*) times the span length of the bridge (L).

**Research Results**

Some parametric studies are carried out to provide a better idea about the behavior of curved box girder bridges including four main factors of: number of cells, web to flange thickness ratios, number of diaphragms and live load effects, to provide a better idea about the behavior of curved box girder bridges. The comparative analysis between PEM and FEM demonstrated the validity and efficiency of the proposed method. The results, summarized across multiple parametric studies, are as follows.

**Effects of Number of Cells Variation**

Two types of cell bridges (single and double) are considered for verification purposes. A cantilever deck of (20 m) span length, (2,3 m) depth and (3 m) width of each cell and element thicknesses of (0,3 m) is studied for their earthquake response.

The absolute and normalized moments, shear forces and deflections of a cantilever deck are given in Tables 3 and 4 for base excitation in (X and Y-directions), respectively.

Analysis showed that a maximum difference of less than (12 %) in deflection, base shears and bending moments is encountered between the proposed Panel Element Method (PEM) of analysis and the finite element (FE) procedure of ANSYS software irrespective of the direction of earthquake base excitation.

**Table 3** – Maximum response of a cantilever bridge deck of single and double cell (base excitation in lateral X-direction)

| No. of Cells | Analysis Method | Max. Bending Moment | | | Max. Shear Force | | Max. Deflection (mm) |
|---|---|---|---|---|---|---|---|
| | | Abs. (kN.m) | Nor. to m* (m) | Nor. to m* x L | Abs. (kN) | Nor. to m* | |
| 1 | FEM | 614,742 | 0,244 | 0,012 | 75,672 | 0,030 | 1,273 |
| | PEM | 691,992 | 0,275 | 0,014 | 81,152 | 0,032 | 1,312 |
| 2 | FEM | 705,600 | 0,510 | 0,026 | 92,369 | 0,067 | 1,639 |
| | PEM | 750,600 | 0,543 | 0,027 | 95,969 | 0,069 | 1,837 |

**Table 4** – Maximum response of a cantilever bridge deck of single and double cell (base excitation in vertical Y-direction)

| No. of Cells | Analysis Method | Max. Bending Moment | | | Max. Shear Force | | Max. Deflection (mm) |
|---|---|---|---|---|---|---|---|
| | | Abs. (kN.m) | Nor. to m* (m) | Nor. to m* x L | Abs. (kN) | Nor. to m* | |
| 1 | FEM | 956,133 | 0,380 | 0,019 | 315,773 | 0,126 | 4,077 |
| | PEM | 1023,383 | 0,407 | 0,020 | 325,925 | 0,130 | 4,369 |
| 2 | FEM | 1016,064 | 0,735 | 0,037 | 404,571 | 0,293 | 5,535 |
| | PEM | 1056,912 | 0,764 | 0,038 | 407,235 | 0,295 | 5,700 |

**Effects of Web to Flange Thicknesses Ratio**

The bridge decks are studied here for their earthquake response characteristics. A single cell deck is considered with a depth of (2,3 m) and a width of (3,0 m), then a double cell deck is considered with a depth of (2,3 m) but a width of 6,0 m (3,0 m for each cell). The bridges under consideration are of (20 m) single span with partially and fully restrained supports, the radius of curvature of the bridge span is (57,3 m). The thickness ratios varied from (0,5 to 2,0). To demonstrate the range of applicability of the proposed idealization procedure of the Panel Element Method (PEM) to different ranges of (web thickness: Slab thickness) ratio. The single cell bridge deck fully restrained at supports which is discussed in chapter five is used here for earthquake response in two directions (X and Y directions) transverse to the longitudinal axis of the deck (Z-axis).

The results are presented in Figures 7 and 8 for the cases of a single cell and double cell bridge deck. Results reveal that the proposed idealization procedure of the Panel Element Method (PEM) works well in evaluating the response of bridge decks subjected to earthquake base excitation as compared with the Finite Element Method (FEM) with errors not more than (10 %) in the deflection and no more than (17 %) in moments and shear forces when the (tw/ts) thickness ratio reaches (2).

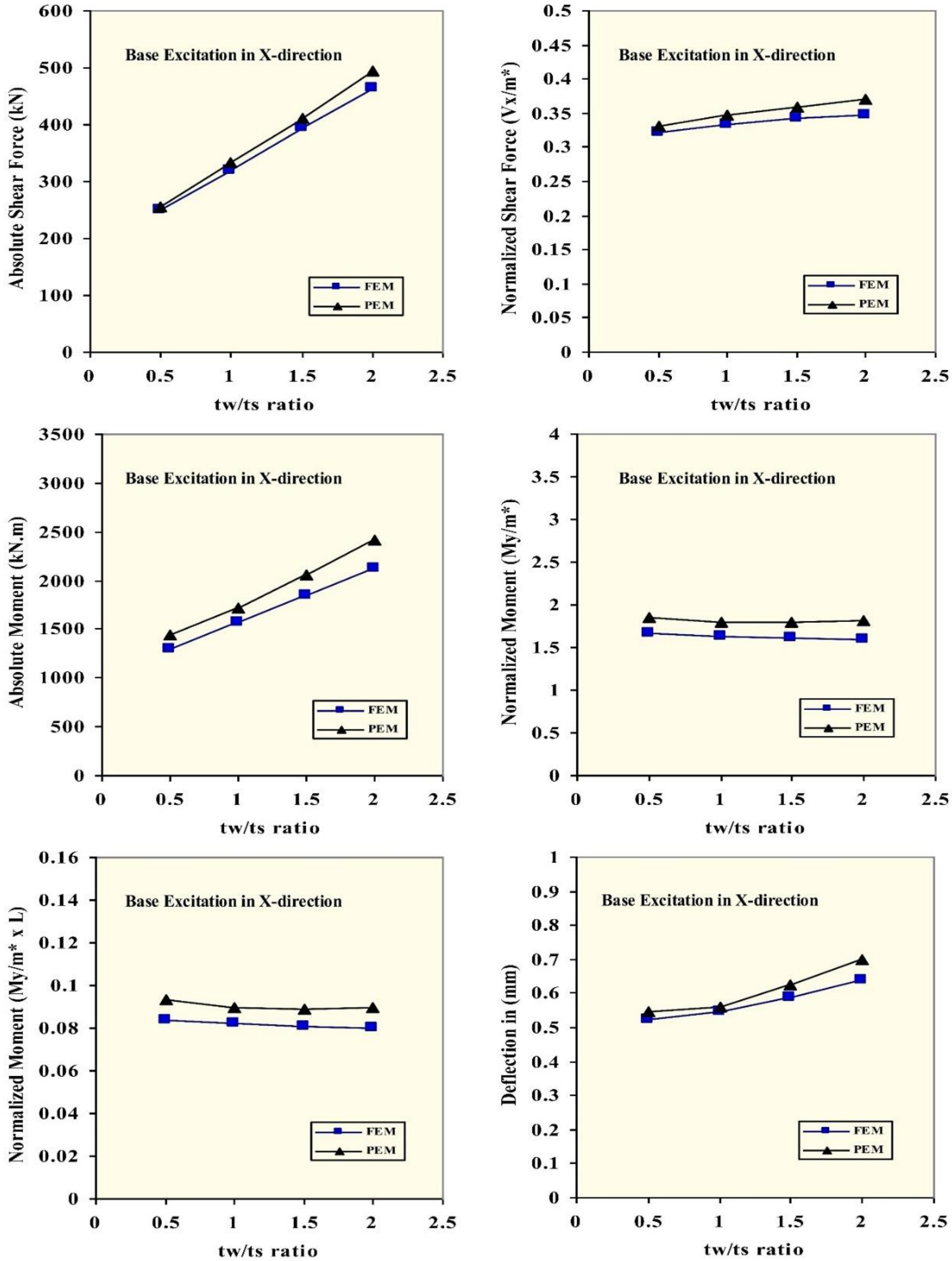


**Figure 7** – Maximum response variation with (web thickness: slab thickness) ratio for single curved bridge deck fully restrained at supports (base excitation in lateral X-direction)

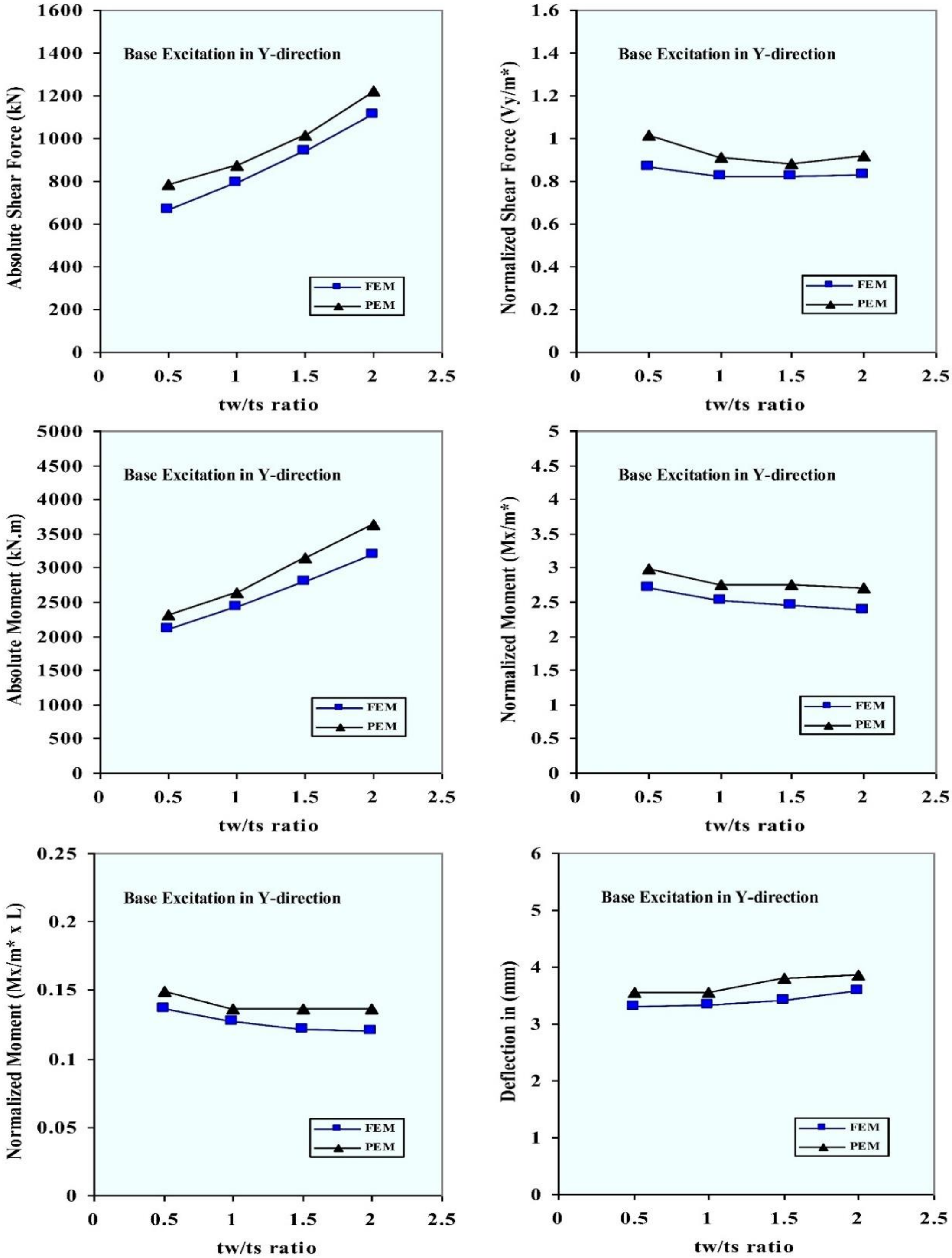


**Figure 8** – Maximum response variation with (web thickness: slab thickness) ratio for single curved bridge deck fully restrained at supports (base excitation in vertical Y-direction)

**Effects of Number of Diaphragms**

Next is a parametric study on the effect of number of diaphragms along the constant span length on the earthquake response behavior of curved bridges to demonstrate the range of applicability of the proposed panel element (PE) idealization scheme for two cases of earthquake base excitation, namely, in a lateral X-direction normal to mid-span tangent and in the vertical Y-direction. The numbers of panels are changed from (2 to 10). In this case, the number of diaphragms represents the number of panels where each panel represents a segment between two diaphragms.

Maximum moments and deflections at mid-span and maximum shear forces at supports as a response of the bridge deck when acted upon by base excitation are shown in Tables 5, 6, 7 and 8, for both partially and fully restrained support conditions for earthquake base excitation in X and Y-directions, respectively.

It can be seen clearly from the results that variation of number of panels results in significant change in the value of the deflection for both X and Y directions and boundary condition types, with errors not more than (12 %) in the deflection and no more than (18 %) in moments and shear forces when the number of diaphragms reaches (10). It is also concluded that the proposed idealization procedure of the Panel Element Method (PEM) is valid for all the range of numbers of diaphragms considered in the study.

**Table 5** – Maximum response variation with (number of diaphragms: span) ratio for single cell bridgdeck partially restrained at supports (base excitation in lateral X-direction)

| No. of Cells | Analysis Method | Max. Bending Moment | | | Max. Shear Force | | Max. Deflection (mm) |
|---|---|---|---|---|---|---|---|
| | | Abs. (kN.m) | Nor. to m* (m) | Nor. to m* x L | Abs. (kN) | Nor. to m* | |
| 2 | FEM | 3494,16 | 2,527 | 0,126 | 1157,76 | 0,837 | 0,931 |
| | PEM | 4109,6 | 2,972 | 0,149 | 1343,68 | 0,972 | 1,007 |
| 4 | FEM | 3229,2 | 2,335 | 0,117 | 1285,74 | 0,930 | 0,898 |
| | PEM | 3799,2 | 2,748 | 0,137 | 1507,04 | 1,090 | 0,957 |
| 6 | FEM | 3600 | 2,603 | 0,130 | 1494,36 | 1,081 | 0,980 |
| | PEM | 4022,4 | 2,909 | 0,145 | 1725,408 | 1,248 | 1,040 |
| 10 | FEM | 3895,2 | 2,817 | 0,141 | 1598,94 | 1,156 | 1,053 |
| | PEM | 4233,96 | 3,062 | 0,153 | 1778,544 | 1,286 | 1,092 |

**Table 6** – Maximum response variation with (number of diaphragms: span) ratio for single cell bridge deck fully restrained at supports (base excitation in lateral X-direction)

| No. of Cells | Analysis Method | Max. Bending Moment | | | Max. Shear Force | | Max. Deflection (mm) |
|---|---|---|---|---|---|---|---|
| | | Abs. (kN.m) | Nor. to m* (m) | Nor. to m* x L | Abs. (kN) | Nor. to m* | |
| 2 | FEM | 2088,6 | 1,510 | 0,076 | 649,2 | 0,469 | 0,515 |
| | PEM | 2459,4 | 1,779 | 0,089 | 753,2 | 0,545 | 0,564 |
| 4 | FEM | 2082,24 | 1,506 | 0,075 | 689,04 | 0,498 | 0,558 |
| | PEM | 2401,92 | 1,737 | 0,087 | 813,16 | 0,588 | 0,591 |
| 6 | FEM | 2314,08 | 1,674 | 0,084 | 741,96 | 0,537 | 0,607 |
| | PEM | 2600,06 | 1,880 | 0,094 | 877,8 | 0,635 | 0,627 |
| 10 | FEM | 2498,4 | 1,807 | 0,090 | 787,8 | 0,570 | 0,650 |
| | PEM | 2720,4 | 1,967 | 0,098 | 918 | 0,664 | 0,653 |

**Table 7** – Maximum response variation with (number of diaphragms: span) ratio for single cell bridge deck partially restrained at supports (base excitation in vertical Y-direction)

| No. of Cells | Analysis Method | Max. Bending Moment | | | Max. Shear Force | | Max. Deflection (mm) |
|---|---|---|---|---|---|---|---|
| | | Abs. (kN.m) | Nor. to m* (m) | Nor. to m* x L | Abs. (kN) | Nor. to m* | |
| 2 | FEM | 3744 | 2,708 | 0,135 | 1379,556 | 0,998 | 5,502 |
| | PEM | 4425 | 3,200 | 0,160 | 1610,8 | 1,165 | 6,194 |
| 4 | FEM | 3542,04 | 2,562 | 0,128 | 1499,2 | 1,084 | 6,376 |
| | PEM | 4094,64 | 2,961 | 0,148 | 1729,232 | 1,251 | 6,830 |
| 6 | FEM | 4046,4 | 2,926 | 0,146 | 1568,34 | 1,134 | 7,029 |
| | PEM | 4572,18 | 3,307 | 0,165 | 1819,2 | 1,316 | 7,326 |
| 10 | FEM | 4432,8 | 3,206 | 0,160 | 1666,8 | 1,205 | 7,590 |
| | PEM | 4923,72 | 3,561 | 0,178 | 1954,08 | 1,413 | 7,755 |

**Table 8** – Maximum response variation with (number of diaphragms: span) ratio for single cell bridge deck fully restrained at supports (base excitation in vertical Y-direction)

| No. of Cells | Analysis Method | Max. Bending Moment | | | Max. Shear Force | | Max. Deflection (mm) |
|---|---|---|---|---|---|---|---|
| | | Abs. (kN.m) | Nor. to m* (m) | Nor. to m* x L | Abs. (kN) | Nor. to m* | |
| 2 | FEM | 2665,32 | 1,928 | 0,096 | 982,4 | 0,710 | 2,099 |
| | PEM | 3126,8 | 2,261 | 0,113 | 1129,56 | 0,817 | 2,313 |
| 4 | FEM | 2506,36 | 1,813 | 0,091 | 998,16 | 0,722 | 2,049 |
| | PEM | 2966,04 | 2,145 | 0,107 | 1182,06 | 0,855 | 2,247 |
| 6 | FEM | 2868,84 | 2,075 | 0,104 | 1055,7 | 0,763 | 2,300 |
| | PEM | 3243,4 | 2,346 | 0,117 | 1207,08 | 0,873 | 2,412 |
| 10 | FEM | 3145,68 | 2,275 | 0,114 | 1122 | 0,811 | 2,492 |
| | PEM | 3487,32 | 2,522 | 0,126 | 1234,8 | 0,893 | 2,534 |

**Effect of Live Load**

To explain the effect of live load, simple load cases are considered according to the Iraq's Specifications for Bridge Loading (Iraq Specification, 1978) [21].

1. Lane loading, where loads are distributed uniformly over the deck and knife edge load is considered at mid-span to give the maximum response. This load condition is designated the fast load case (load case I).
2. Military Loading, two classes of this loading are studied as follows:

a) class 100 (Tracked), one tracked at mid-span. This load condition is designated the second load case (load case II);

b) class 100 (Wheeled), one wheeled at mid-span. This load condition is designated the third load case (load case III).

The uniformly distributed lane load is considered as an additional mass added to the mass density of the structures. The other types of live loads are considered as lumped masses added to the corresponding degrees of freedom in the horizontal transverse (X-direction) and vertical (Y-direction).

All the results, which represent the dynamic response of the bridge deck subjected to earthquake base excitation in X and Y-directions and for both partially and fully restrained boundary conditions are given in Tables 9, 10, 11 and 12.

It can be seen from the above-mentioned tables that a good agreement with response predicted by the finite element is demonstrated out of these numerical case studies, with errors not more than (10 %) in the deflection and no more than (16 %) in moments and shear forces.

Also, the tables give more evidence of the validity of the proposed idealization procedure of the Panel Element Method (PEM).

**Table 9** – Maximum response for different live load cases on a single cell bridge deck partially restrained at supports (base excitation in lateral X-direction)

| Load Case No. | Analysis Method | Max. Bending Moment | | | Max. Shear Force | | Max. Deflection (mm) |
|---|---|---|---|---|---|---|---|
| | | Abs. (kN.m) | Nor. to m* (m) | Nor. to m* x L | Abs. (kN) | Nor. to m* | |
| I | FEM | 5210,4 | 3,768 | 0,188 | 958,2 | 0,693 | 1,63 |
| | PEM | 5731,8 | 4,145 | 0,207 | 1030,224 | 0,745 | 1,7 |
| II | FEM | 5688,12 | 4,114 | 0,206 | 1068,12 | 0,772 | 1,729 |
| | PEM | 6022,08 | 4,355 | 0,218 | 1136,16 | 0,822 | 1,766 |
| III | FEM | 6368,72 | 4,606 | 0,230 | 1207,44 | 0,873 | 1,898 |
| | PEM | 6915,16 | 5,001 | 0,250 | 1232,04 | 0,891 | 2,019 |

**Table 10** – Maximum response for different live load cases on a single cell bridge deck fully restrained at supports (base excitation in lateral X-direction)

| Load Case No. | Analysis Method | Max. Bending Moment | | | Max. Shear Force | | Max. Deflection (mm) |
|---|---|---|---|---|---|---|---|
| | | Abs. (kN.m) | Nor. to m* (m) | Nor. to m* x L | Abs. (kN) | Nor. to m* | |
| I | FEM | 2685,6 | 1,942 | 0,097 | 703,44 | 0,509 | 0,749 |
| | PEM | 3027,96 | 2,190 | 0,109 | 764,604 | 0,553 | 0,825 |
| II | FEM | 3192,48 | 2,309 | 0,115 | 884,76 | 0,640 | 1,013 |
| | PEM | 3566,88 | 2,580 | 0,129 | 924,84 | 0,669 | 1,095 |
| III | FEM | 3877,32 | 2,804 | 0,140 | 1006,56 | 0,728 | 1,135 |
| | PEM | 4045,68 | 2,926 | 0,146 | 1037,64 | 0,750 | 1,234 |

**Table 11** – Maximum response for different live load cases on a single cell bridge deck partially restrained at supports (base excitation in vertical Y-direction)

| Load Case No. | Analysis Method | Max. Bending Moment | | | Max. Shear Force | | Max. Deflection (mm) |
|---|---|---|---|---|---|---|---|
| | | Abs. (kN.m) | Nor. to m* (m) | Nor. to m* x L | Abs. (kN) | Nor. to m* | |
| I | FEM | 4883,76 | 3,532 | 0,177 | 1486,44 | 1,075 | 7,85 |
| | PEM | 5149,76 | 3,724 | 0,186 | 1617,6 | 1,170 | 8,642 |
| II | FEM | 4907,16 | 3,549 | 0,177 | 1633,68 | 1,181 | 8,642 |
| | PEM | 5287,24 | 3,824 | 0,191 | 1769,88 | 1,280 | 9,137 |
| III | FEM | 5026,13 | 3,635 | 0,182 | 1862,64 | 1,347 | 9,863 |
| | PEM | 5513,64 | 3,987 | 0,199 | 1920,24 | 1,389 | 10,655 |

**Table 12** – Maximum response for different live load cases on a single cell bridge deck fully restrained at supports (base excitation in vertical Y-direction)

| Load Case No. | Analysis Method | Max. Bending Moment | | | Max. Shear Force | | Max. Deflection (mm) |
|---|---|---|---|---|---|---|---|
| | | Abs. (kN.m) | Nor. to m* (m) | Nor. to m* x L | Abs. (kN) | Nor. to m* | |
| I | FEM | 4620 | 3,341 | 0,167 | 1342,08 | 0,971 | 6,684 |
| | PEM | 5316,3 | 3,845 | 0,192 | 1383,48 | 1,001 | 7,029 |
| II | FEM | 4666,8 | 3,375 | 0,169 | 1503,6 | 1,087 | 6,798 |
| | PEM | 5432,4 | 3,929 | 0,196 | 1542 | 1,115 | 7,117 |
| III | FEM | 4965,6 | 3,591 | 0,180 | 1656,6 | 1,198 | 7,029 |
| | PEM | 5744,76 | 4,155 | 0,208 | 1670,4 | 1,208 | 7,458 |

**Conclusions**

In order to assess the efficiency and accuracy of the proposed idealization procedure designated the Panel Element Method (PEM) for earthquake response analysis of curved box-girder deck bridge structures, a number of examples of case studies are analyzed.

Different configurations of curved box-girder bridge decks are considered to verify the proposed Panel Element Method (PEM) against the Finite Element Method (FEM) for both free and forced vibrations. According to the case studies considered in the present research, the major conclusions are drawn.

1. The Panel Element Method (PEM) of idealizing curved box-girder type bridge decks is verified for the dynamic analysis of earthquake response of almost all-practical deck configurations, which are considered.
2. At the same time, a varied reduction in the number of elements and hence, the degrees of freedom (d. o. f) is gained when using the proposed idealization procedure of panel element (PEM) to model the behavior of the bridge under consideration as compared to the traditional finite element (FE) procedure.
3. Moreover, since the number of degrees of freedom needed by the proposed element is limited, the number of equations and iterations are largely reduced and hence less error is encountered.
4. The Panel Element Method (PEM) has proved to be valid in estimating the earthquake response for both cases of single and double cell bridge decks.
5. For all the ranges of the aspect ratios; the results obtained by the Panel Element Method (PEM) are acceptable, with an error of less than (12 %) in deflection and less than (18 %) in moments and shear forces for the cases of very large aspect ratios. It can be seen that the proposed Panel Element Method (PEM) predicts good estimates of cases of small aspect ratios. The normalized value shows good compatibility in response especially in the values of moments when normalized to the product of total mass and the span of the decks.
6. Variation of the number of diaphragms for a constant span length of a bridge deck results in almost no change in the deflection. The errors encountered in estimating the deflection of bridge decks are inversely proportional to the number of panels. The number of diaphragms has proved to be of insignificant influence on the moment and shear force responses of curved bridge decks when acted upon by earthquake base excitations.

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UDC 692.4

# STUDY OF STRENGTH PERFORMANCE, CONNECTIONS OF ETFE FILM FOR ENCLOSING STRUCTURES OF LARGE-SPAN STRUCTURES

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**Abstract**

Up-to-date architectural and engineering tasks require application of innovative materials, granting not only enhanced performance, but also compliance with criteria of energy efficiency, eco-and technology-friendliness. Ethylene tetrafluoroethylene (ETFE) film is one of such materials. ETFE was initially developed as a lightweight heat resistant film in the aerospace industry. However, it has been successfully applied in the construction industry for many years, including as translucent enclosing structures.

Within design development of the biosphere string tent shed the properties of ETFE film were studied, while the material enables covering over significant spans at minimal weight. Moreover, ETFE film has a whole range of unique properties, such as high strength, UV resistance, high translucency, including the light spectrum necessary for photosynthesis. That makes ETFE film an ideal candidate for creation of closed complexes with manmade manageable ecosystems.

In course of computer modelling of ETFE film serving as a roofing element of the tent shed an issue arose with regard to its properties, i. e. whether to consider the film as a linear isotropic material, thus facilitating the calculation, but it might stretch the reality of stress-strain behaviour, or whether to consider it as nonlinear anisotropic material, thus facilitating more correct description of ETFE film behaviour under different loads.

Herein, the strength parameters of ETFE film were defined in different directions. Dependency of action of temperature on strength performance, as well as influence of cyclic loads on the material was set.

The appropriate tests were conducted, which results formed the basis for the design solutions for the tent shed covering in order to choose the most effective methods to interconnect the film sheets, including the ones via welding and mechanical connections.

**Keywords:** polymer films, ETFE, uniaxial and biaxial testing, adhesive joints, mechanical connections.

## ИССЛЕДОВАНИЕ ПРОЧНОСТНЫХ ХАРАКТЕРИСТИК, СОЕДИНЕНИЙ ПЛЁНКИ ETFE ДЛЯ ОГРАЖДАЮЩИХ КОНСТРУКЦИЙ БОЛЬШЕПРОЛЕТНЫХ СООРУЖЕНИЙ

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**Реферат**

Современные архитектурные и инженерные задачи требуют применения инновационных материалов, способных обеспечить не только высокие эксплуатационные характеристики, но и соответствие критериям энергоэффективности, экологичности и технологичности. Одним из таких материалов является плёнка из этилен-тетрафторэтилена (ETFE). Изначально она разрабатывалась для нужд авиационной и космической промышленности. Однако уже на протяжении многих лет она успешно применяется в строительстве – в том числе в качестве ограждающих светопрозрачных конструкций.

В рамках разработки биосферного струнного шатра было проведено исследование свойств плёнки ETFE, поскольку данный материал позволяет перекрывать значительные пролёты при минимальном весе и обладает рядом уникальных характеристик, таких как высокая прочность, устойчивость к ультрафиолетовому излучению и высокая светопропускная способность, включая спектр, необходимый для фотосинтеза. Это делает его идеальным кандидатом для создания замкнутых комплексов с контролируемой искусственной экосистемой.

В процессе численного моделирования плёнки как элемента покрытия шатра возник вопрос назначения характеристик материала – учитывать ли плёнку как линейный изотропный материал, что упрощает расчёт, но может искажать реальную картину напряжённо-деформированного состояния, или же учитывать её как нелинейный анизотропный материал, позволяющий более корректно описать работу плёнки под действием различного вида нагрузок.

В настоящем исследовании были определены прочностные характеристики плёнки ETFE в различных направлениях. Была установлена зависимость влияния температуры на прочностные характеристики, а также влияние циклических нагрузок на материал.

С целью выбора наиболее эффективных способов соединения полотен плёнки между собой, в том числе на основе сварки и механических креплений, были выполнены соответствующие испытания, результаты которых легли в основу проектных решений по формированию оболочки шатра.

**Ключевые слова:** полимерные плёнки, ETFE, одноосное и двухосное испытание, клеевые соединения, механические соединения.

**Introduction**

During design development of the biosphere tent shed with manageable inner ecosystems, large spans shall be covered over while ensuring translucency, energy efficiency, and technology friendliness while erecting [1]. Structural solutions with optimal combination of strength, weight and operational parameters are required to solve such tasks. So, application of ETFE film with unique parameters is a viable solution.

Its unique parameters enable application of ETFE film as a covering material for large-span structures with LBE (load-bearing elements) made of tightened steel strips, wire ropes or spatial trusses. So that, a string-membrane shell is created where ETFE film serves as an enclosing translucent element enabling covering of large areas and creating closed sustainable ecosystems due to enhanced translucency (including UV spectrum), weather resistance, ability to be engaged in heat exchange.

Due to low density (cca. 0.15–0.25 kg/m²) and adequate strength, the material significantly reduces loads acting on foundations and supporting systems, as well as consumption of materials, also facilitates transportation and assembly. Extra advantage of ETFE film comparing with other translucent roofing materials (PE, canvas, synthetic fabric) is that it is highly fire-resistant, chemically inert, UV-resistant and durable [2, 3].

Nevertheless, despite the obvious advantages of the material, application of ETFE film as an LBE of a roof structure shall be structurally justified with regard to actual loads, temperature conditions and operational modes.

**Brief overview of fluoroplastic films**

Fluoroplastic thermoelectricity polymers that undergo treatment and molding procedures are used to produce films. Basing on the applied polymer component different kinds of films with different parameters are created. For instance, ETFE film is made from fluoropolymer-40, while PVDF is from fluoropolymer-2M, etc. Let's review the most widely-spread fluoroplastic films [4–6].

ETFE film type is made from fluoropolymer-40. That is ethylene-polytetrafluoroethylene copolymer. It is characterized by high UV-resistance, tensile strength, chemical resistance, high translucency within a visible light and UV spectrum.

PVDF film type is made from fluoropolymer-2M. Its characteristics are moderate strength, enhanced UV-, chemical and radiation resistance.

PTFE film type is also a product of TFE with the properties different from that of ETFE. It was invented before ETFE, but has the advantage over ETFE at a working temperature range of –269 °C up to +260 °C and even at a higher temperature. Despite its melting point at +327°C it does not transit into a state of viscous flow. However, it has clear disadvantages, such as lower strength, much lower elasticity modulus and restricted translucency.

FEP film type is made from fluoropolymer-4MB. It is a copolymer of hexafluoropropylene and tetrafluoroethylene. The material is characterized by high resistance to UV, alkalis, and concentrated inorganic acids, dielectric properties. However, FEP ranks below in strength and rigidity comparing with ETFE, thus restricting its application in highly-loaded structures. Besides that, its lower elasticity reduces its effectiveness in flexible systems and membrane coverings.

PFA film type is made from fluoropolymer-50. It is a copolymer of tetrafluoroethylene and perfluoroether. It is UV- and corrosive-resistant, keeps stable at a wide temperature range from –196 °C to +250 °C and has superior dielectric properties.

ETFE film is characterized by the following particular properties [4–8]:

- low density: its density is 1,700 kg/m$^3$, which is the lesser of the counterparts;
- anti-drop property: excludes condensation formation on the surface;
- recycling: grants the opportunity to recycle the film wastes into new materials;
- translucency: it transits 90–95 % of a visible, as well as UV light spectrum;
- chemical resistance: it is resistant to alkalis, concentrated acids;
- enhanced strength: its tensile strength is up to 65 MPa;
- repair-suitable with special adhesive tapes and sheets (patches);
- fire resistance: due to its properties and structure, in case of fire the film does not create fire drops that could jeopardize people's health. Moreover, in case of big fire the membrane destroys itself and releases smoke and other combustion products, thus decreasing the indoor temperature and lessening the risk of structure failure. The film is rated G1 of flammability class under GOST 30244–94, i. e. it refers to a low-flammable material.

All these properties refer to the pluses of the material. However, the potential issues with regard to them arise. For instance, the tensile strength heavily depends on an operating temperature and could be significantly lower, than the value mentioned herein [8]. Besides that, the anti-drop property and chemical resistance hinder glueing or welding of the material.

**Materials and testing procedure**

200-microns-thick ETFE film with the declared tensile strength ranging from 39–65.2 MPa was tested. The film is manufactured under Technical Specifications 22 21 30-015-46708974-2022.

The following tests were conducted to check the strength values of the film

1. Uniaxial tensile test in 2 orthogonal directions at a temperature of –50 °C, –25 °C, 0 °C, +25 °C, +50 °C.
2. Cyclic uniaxial tensile test of the film;
3. Biaxial tensile test of the film.

Shear tests of the following options were conducted to study the behaviour of film connections:

1. Adhesive connection of the film;
2. Connection of the film with a special adhesive tape [9];
3. Welding film-to-film connection [10, 11];
4. Mechanical film-to-steel plate connection.

The film was tested in the Metal-Polymer Research Institute of the National Academy of Sciences of Belarus.

**Strength test**

Routine test schedule of the samples for uniaxial tensile tests is described in GOST 14236-81 [12]. Test bench of the uniaxial tensile test is illustrated in Figure 1. Stress-strain behaviour was defined during the uniaxial tensile test at a different temperature: –50 °C, –25 °C, 0 °C, +25 °C, +50 °C (min. 5 samples at each temperature). As tested, the stress-strain relation schedules at different temperatures were made (ref. to Figure 2–6).

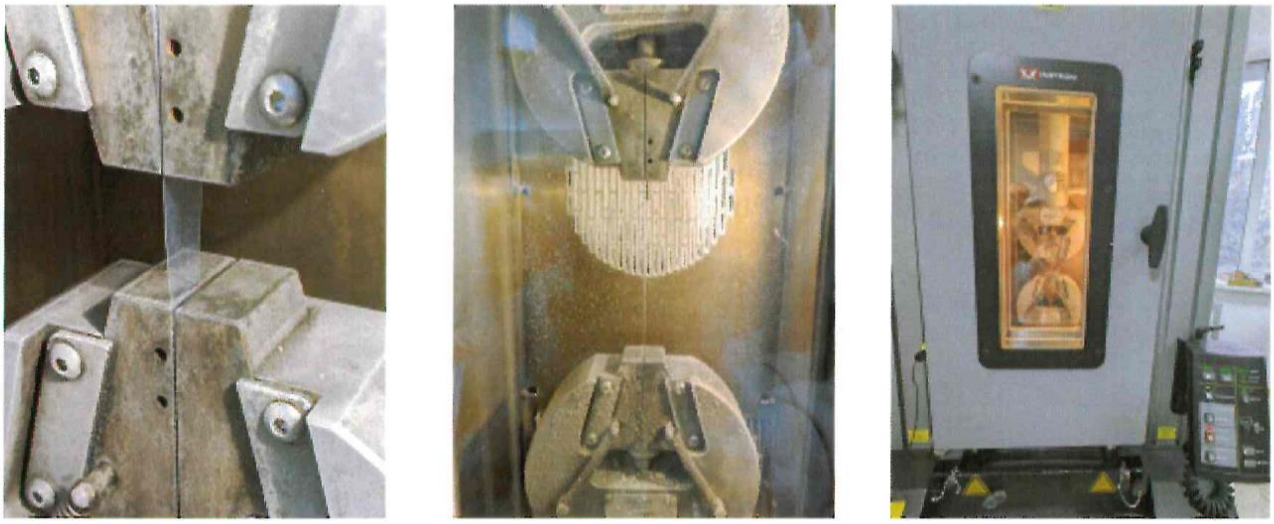

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**Figure 1** – Sample placement between the grips (a), sample stretching (b) inside the Instron environmental chamber (c)




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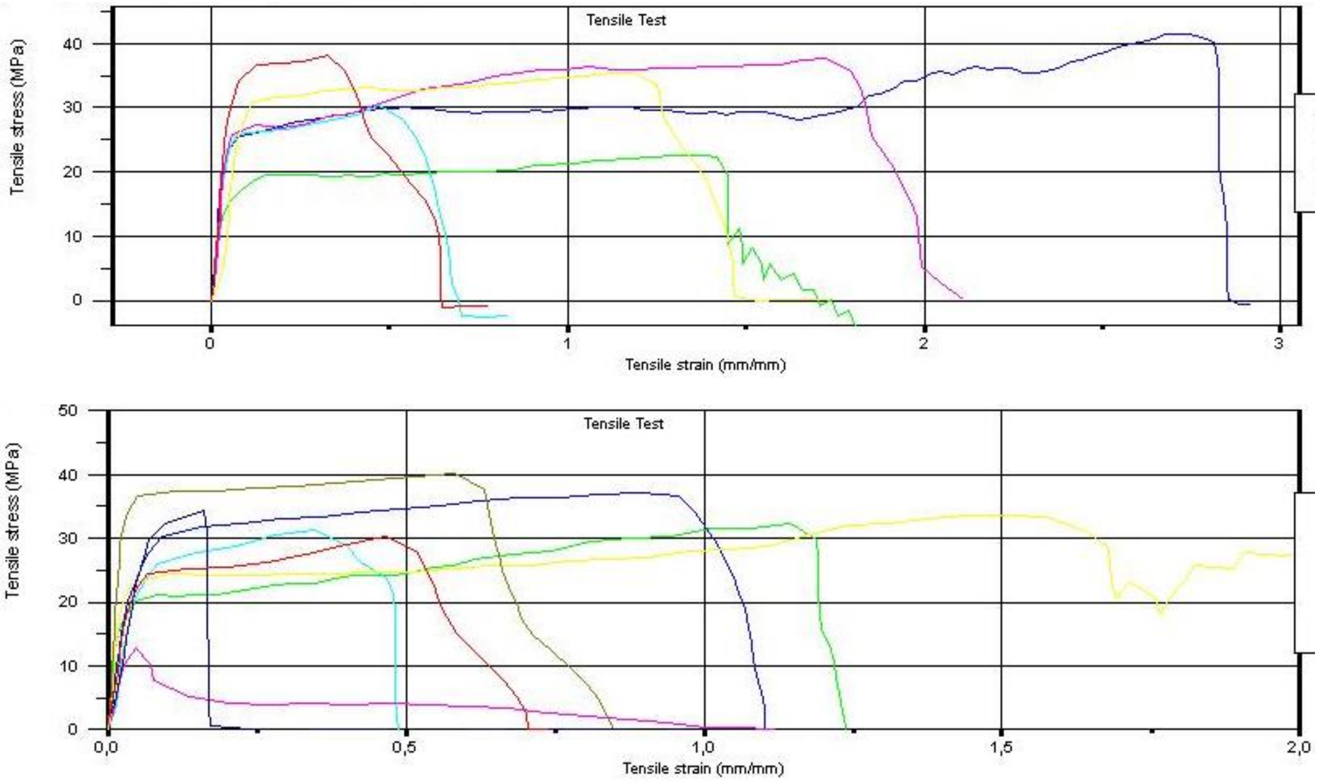



**Figure 2** – Stress-strain relation for the samples in direction 1 (top) and 2 (bottom) at a temperature of –50 °C

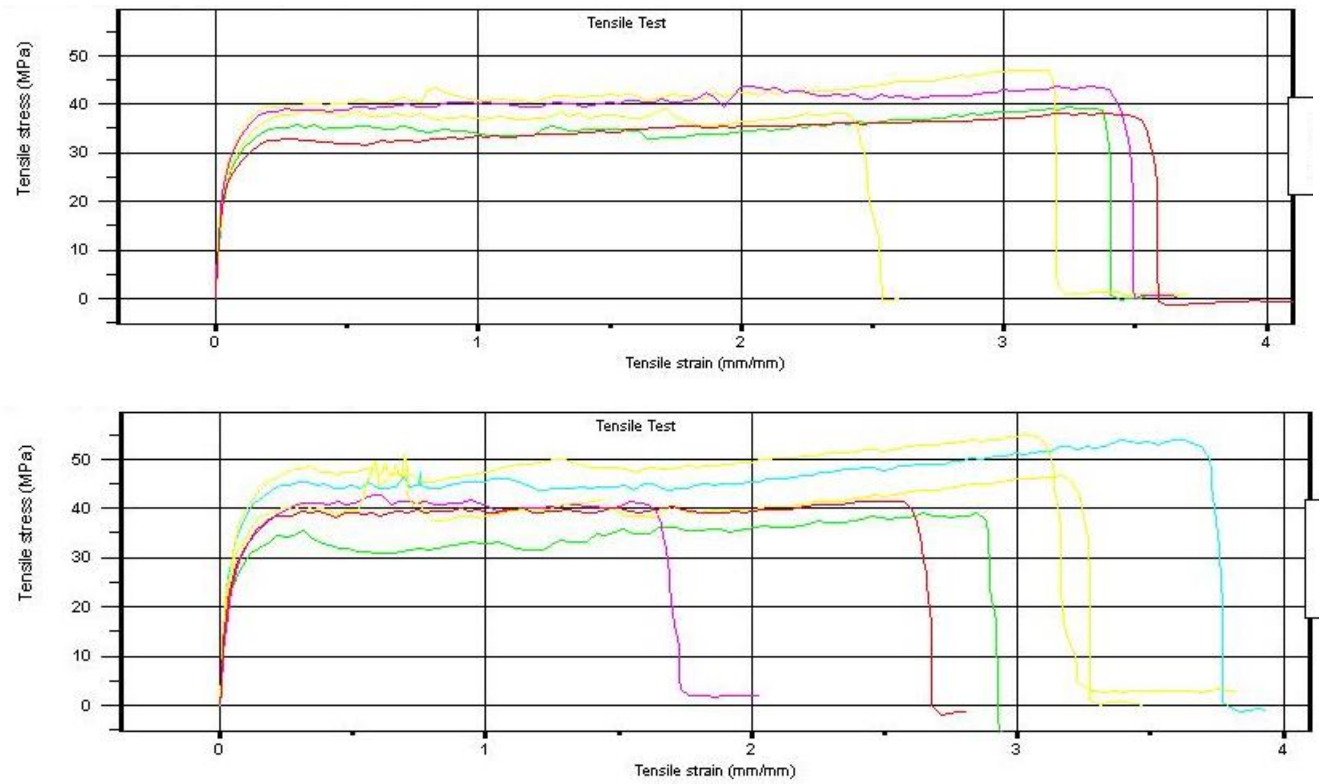



**Figure 3** – Stress-strain relation for the samples in direction 1 (top) and 2 (bottom) at a temperature of –25 °C

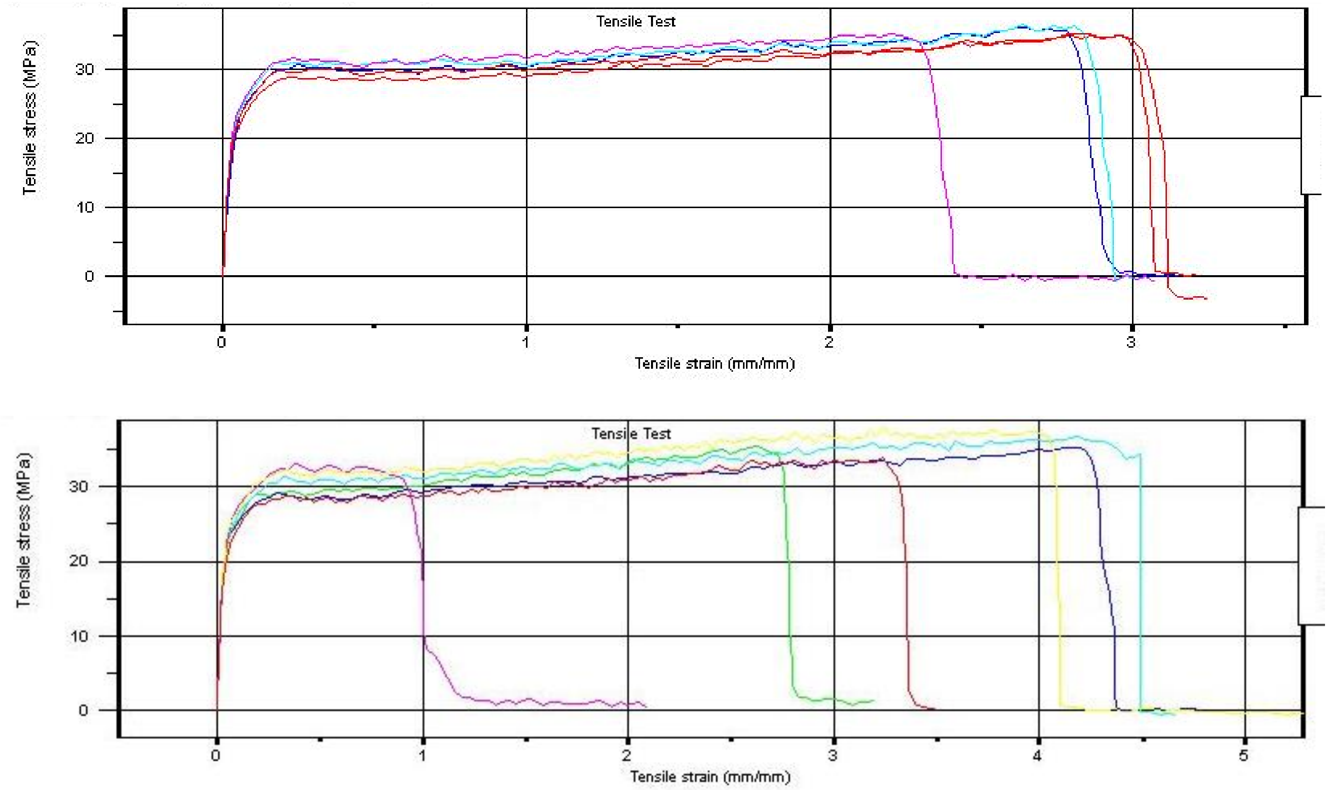



**Figure 4** – Stress-strain relation for the samples in direction 1 (top) and 2 (bottom) at a temperature of 0 °C

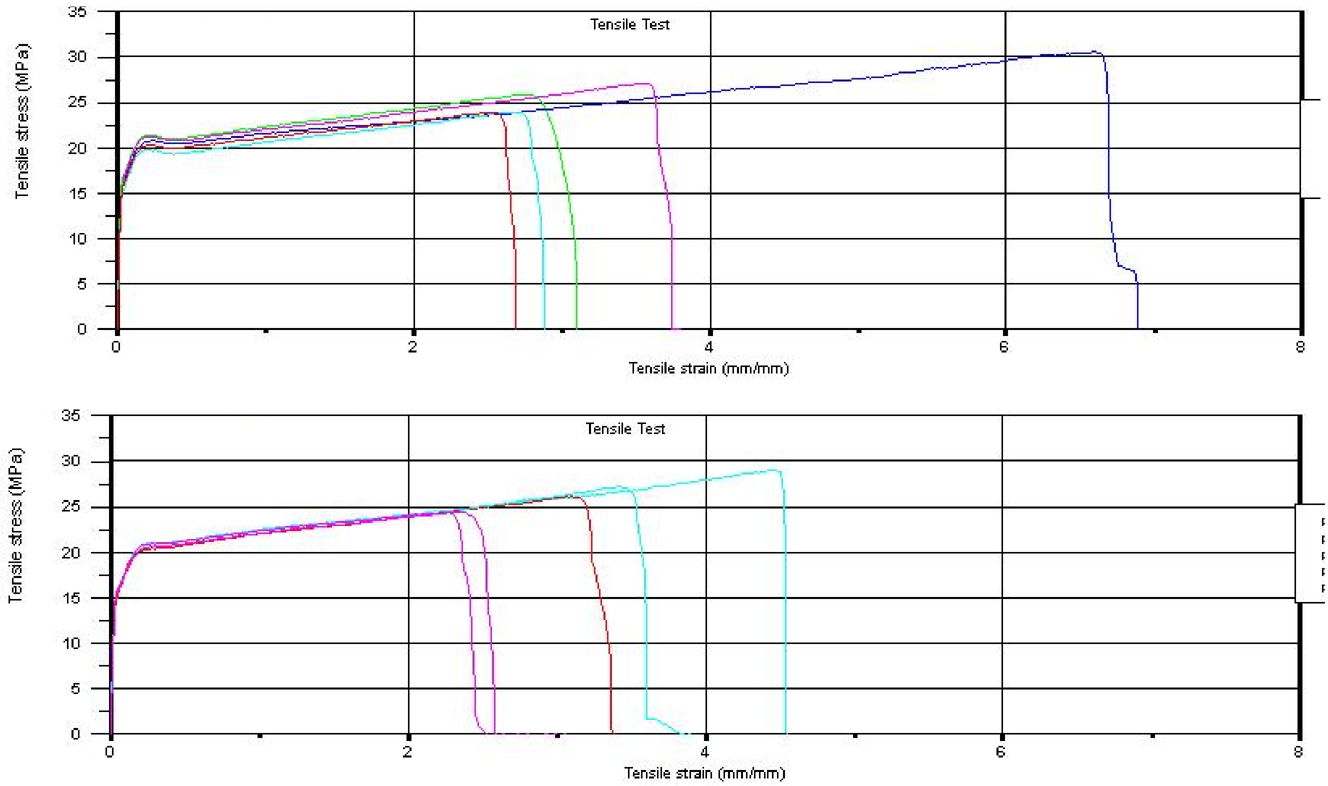



**Figure 5** – Stress-strain relation for the samples in direction 1 (top) and 2 (bottom) at a temperature of +25 °C

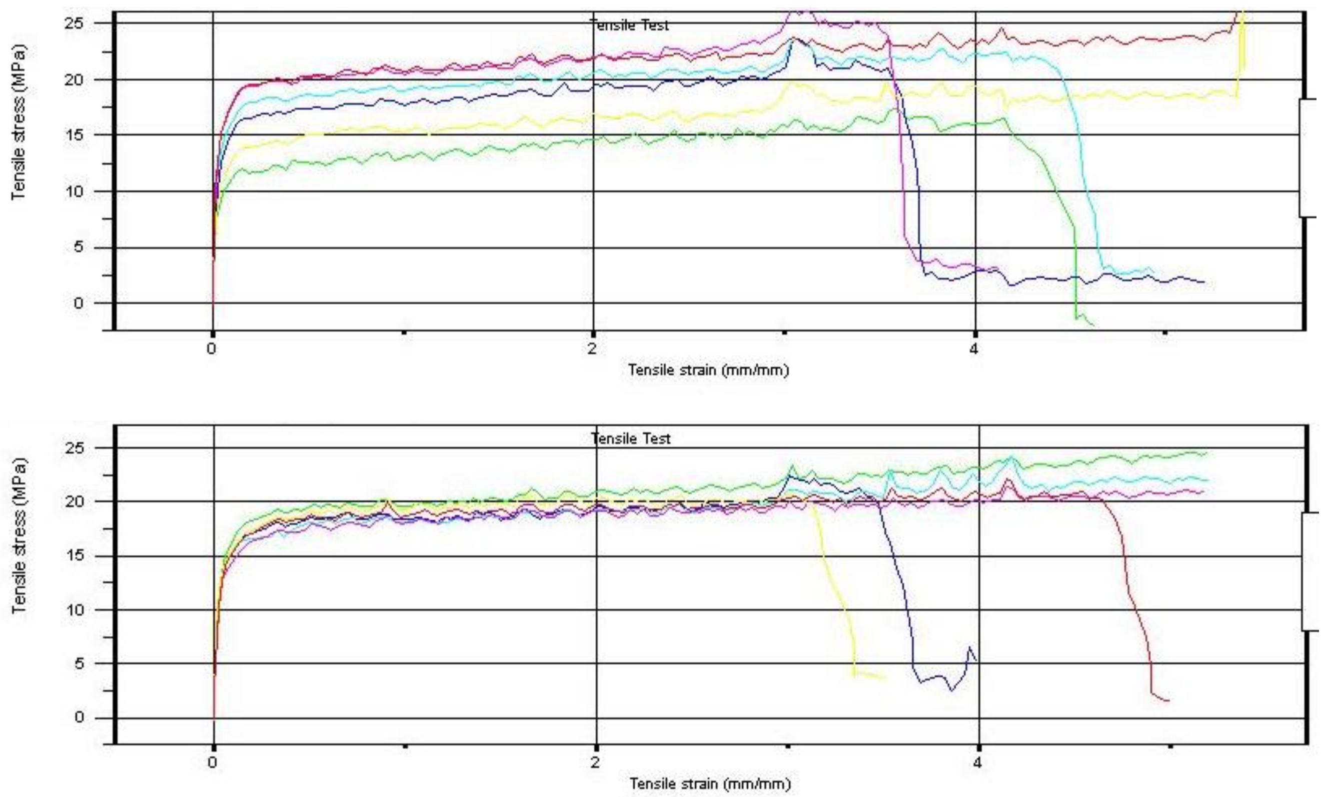



**Figure 6** – Stress-strain relation for the samples in direction 1 (top) and 2 (bottom) at a temperature of +50 °C

**Table 1** – Characteristics and main use of fluoroplastic films [4–6]

| Parameters | PVDF | ETFE | PTFE | FEP | PFA |
|---|---|---|---|---|---|
| Density, kg/m$^3$ | 1,750 | 1,700 | 2,120 | 2,150 | 2,150 |
| Tensile modulus, MPa | 2,350 | 1,000 | 410 | 550 | 550 |
| Break elongation, % | 200–420 | 200–510 | 250–500 | 200–300 | 250–340 |
| Working temperature, °C | from –50 to +130 | from –200 to +180 | from –269 to 260 | from –150 to +200 | from –196 to +250 |
| Tensile strength, MPa | 44.1–55.0 | 40–65 | 14–34 | 17.0–35.0 | 17.0–24.0 |
| Translucency, % | 80–90 | 90–95 | 50–80 | 94–96 | 90 |
| Self-cleaning ability (anti-adhesive properties) | High | High | High | Average | High |
| UV resistance | Excellent | Excellent | Excellent | Excellent | Excellent |
| Main use | Facades, protective coatings | Architecture, roofs, green houses | Non-stick coatings, medical industry | Electronics, solar panels | Chemical and medical industry |

Refer to Figure 7 for the test results in 2 orthogonal directions as the mean values of UTS (ultimate tensile strength) $\sigma_p$ and relative break elongation ε at different temperatures. By comparing the test results, it is apparent that the higher the temperature is, the lower the strength of the sample and the strain increases. Direction of the sample testing did not significantly influence the test results.

Due to the fact that the uniaxial tensile test results of the samples cut in different directions appeared to be close in their values, the biaxial tensile tests were conducted to compare the strength values.

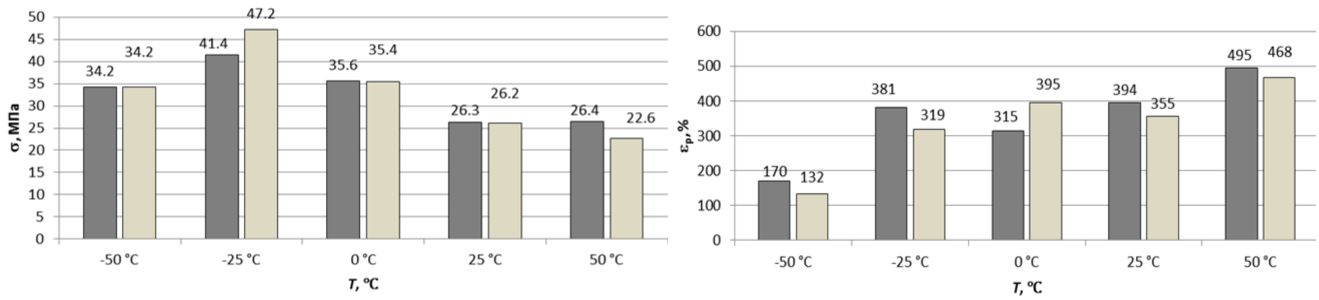



**Figure 7** – Histograms of UTS $\sigma_p$ (from the left) and relative break elongation ε (from the right) in direction 1 and 2 at different temperatures

Bubble inflation test was conducted to define the tensile modulus and strength of ETFE film at biaxial stretching. The principle of the test lies in gradual pressurization of the film sample with air or liquid accompanied with simultaneous record keeping of created bending (buckling) of the film [13–17]. In particular, effectiveness of the method is stated in the paper [16] using $SiO_2/Si_3N_4$ films as an example. The tests were conducted at a temperature of +25 C on 5 square-shaped samples 250×250 mm.

At biaxial tensile test the film sample was fixed with a steel ring flange to the air pressurization chamber. A sensitive distance gauge was installed at an arbitrary distance from the sample. The gauge was directed on the non-transparent mark on the sample (Figure 8). The distance between the mark on the sample and the sensitive distance gauge was measured before pressurization. Such a value (the distance) served as the reference of vertical displacements that were caused by biaxial deformation of the film in course of gradual pressurization.

In course of testing the air was supplied into the chamber and, simultaneously, the pressure, as well as displacement of the film were measured and recorded. On a rather small initial area under pressure ETFE film deformed elastically without any significant plastic deformation. The bigger the "bubble" was, the more irreversibly (plastically) deformed the film: noticeable reduction in its thickness at an increasing speed. That caused a fast growth of the "bubble" volume and growth slowdown of the pressure at permanent air supply (pump capacity). The sample was pressurized until it failed.

**Figure 8** – Test bench for the bubble inflation test of the film sample

Table 2 illustrates vertical displacements, $w$ of 5 film samples and mean values of displacements at pressure varying, $p$ in increments of 40 mmHg. It is apparent that the test results are highly stable.

**Table 2** – Results of vertical displacements of the mark on the samples at pressure increase in the chamber

| Pressure, *p* | | Vertical displacement *w*, m | | | | | |
|---|---|---|---|---|---|---|---|
| *p*, mmHg | *p*, MPa | № 1 | № 2 | № 3 | № 4 | № 5 | Mean value |
| 40 | 0.0053 | 0.008 | 0.008 | 0.008 | 0.008 | 0.008 | 0.008 |
| 80 | 0.0107 | 0.011 | 0.011 | 0.011 | 0.011 | 0.011 | 0.011 |
| 120 | 0.0160 | 0.016 | 0.014 | 0.014 | 0.014 | 0.014 | 0.014 |
| 160 | 0.0213 | 0.020 | 0.019 | 0.019 | 0.019 | 0.018 | 0.019 |
| 200 | 0.0267 | 0.023 | 0.022 | 0.023 | 0.022 | 0.022 | 0.022 |
| 240 | 0.0320 | 0.027 | 0.026 | 0.025 | 0.025 | 0.025 | 0.026 |
| 280 | 0.0373 | 0.030 | 0.029 | 0.029 | 0.028 | 0.029 | 0.029 |
| 320 | 0.0427 | 0.033 | 0.032 | 0.032 | 0.033 | 0.032 | 0.032 |
| 360 | 0.0480 | 0.043 | 0.044 | 0.044 | 0.082 | 0.081 | 0.059 |

The relation between of the biaxial modulus of elasticity and pressure was calculated from the obtained values (ref. to Table 3). The modulus of elasticity under biaxial tension was determined based on the relation (1) between the bending of a thin membrane, $w$ and the excess pressure $P$, given in the paper [18]:

$$P = C_1 \frac{\sigma_0 hw}{a^2} + C_2 \frac{Ehw^3}{(1-\mu)a^4}, \quad (1)$$

where $P$ – pressure, MPa;

$\sigma_0$ – residual stress in the film, where $P$ = 0, MPa;

$h$ – membrane thickness, m;

$w$ – membrane bending, m;

$a$ – membrane radius, m;

$E$ – Young's module, MPa;

μ – Poison's ration.

**Table 3** – Results of displacements at pressure increase in the chamber

| Pressure, *p* | | Module *E*, MPa | | | | | |
|---|---|---|---|---|---|---|---|
| mmHg | MPa | № 1 | № 2 | № 3 | № 4 | № 5 | Mean value |
| 40 | 0.0053 | 2,182 | 2,182 | 2,182 | 2,182 | 2,182 | 2,182 |
| 80 | 0.0107 | 1,695 | 1,695 | 1,695 | 1,695 | 1,695 | 1,695 |
| 120 | 0.0160 | 823 | 1,229 | 1,229 | 1,229 | 1,229 | 1,148 |
| 160 | 0.0213 | 561 | 655 | 655 | 655 | 770 | 659 |
| 200 | 0.0267 | 463 | 529 | 463 | 529 | 529 | 503 |
| 240 | 0.0320 | 343 | 384 | 432 | 432 | 432 | 405 |
| 280 | 0.0373 | 291 | 322 | 322 | 358 | 322 | 323 |
| 320 | 0.0427 | 250 | 275 | 275 | 250 | 275 | 265 |
| 360 | 0.0480 | 127 | 119 | 119 | 18 | 19 | 80 |

Values of ratio $C_1$ and $C_2$ depend on a membrane shape. For round membranes $C_1$ = 4 and $C_2$ = 8/3 could be set. The relation $P(w)$ consists of 2 sections that differ in inclination. Steep section corresponds to small bendings (the first addend of the relation (1) is much greater than the second one).

Biaxial modulus of elasticity $E/(1–\mu)$ is calculated on a flat section of the relation (1) at large values of membrane bending, $w$, when the value of the first addend could be neglected. The following formula (2) shall be used in such a case:

$$\frac{E}{1-\mu} = \frac{Pa^4}{C_2 hw^3}. \quad (2)$$

By applying the formulae of stress-strain calculation under the article [14], the stresses could be determined at biaxial tension for the mean result (Table 4). Stress is determined from the formula:

$$\sigma_x = \sigma_y = \frac{p \cdot R}{2 \cdot t_p}; \quad (3)$$

$$R = \frac{a^2 + h^2}{2 \cdot h}; \quad (4)$$

$$\varepsilon_x = \varepsilon_y = -\frac{1}{2} \cdot \varepsilon_z = -\frac{1}{2} \cdot \ln\left(\frac{t_p}{t_0}\right) = \ln\left(1 + \frac{h^2}{a^2}\right); \quad (5)$$

$$\varepsilon_x = \varepsilon_y = \ln\left(1 + \frac{h^2}{a^2}\right); \quad (6)$$

$$t_p = t_0 \cdot \left(1 + \frac{h^2}{a^2}\right)^{-2}, \quad (7)$$

$R$ – "bubble" radius (from the point on its surface up to its theoretical center), m;

$h$ – height from the fixation plane up to the top of the "bubble", m;

$a$ – distance from the center up to the start point of fixation (circle radius, in case of fixation with a ring flange – use the inner radius of the ring flange), m;

$\varepsilon_x$, $\varepsilon_y$ – relative deformation of the sheet;

$t_0$, $t_p$ – thickness of the initial and deformed sample, m;

Calculation results under formulae 3–7 are presented in Table 4.

**Table 4** – Results of biaxial stretching

| Formula | Value of the indicator for the sample | | | | | Mean value |
|---|---|---|---|---|---|---|
| | № 1 | № 2 | № 3 | № 4 | № 5 | |
| $\sigma_x = \sigma_y = \dfrac{p \cdot R}{2 \cdot t_p}$, MPa | 27.93 | 27.76 | 27.76 | 33.21 | 32.82 | 27.47 |
| $R = \dfrac{a^2 + h^2}{2 \cdot h}$, m | 0.180 | 0.178 | 0.178 | 0.124 | 0.125 | 0.145 |
| $\varepsilon_x = \varepsilon_y = \ln\left(1 + \dfrac{h^2}{a^2}\right)$ | 0.127 | 0.132 | 0.132 | 0.400 | 0.391 | 0.227 |
| $t_p = t_0 \cdot \left(1 + \dfrac{h^2}{a^2}\right)^{-2}$, m | 0.00016 | 0.00015 | 0.00015 | 0.00009 | 0.000091 | 0.00013 |

Refer to Table 5 for the results of uniaxial and biaxial tensile tests at a temperature of +25 °C.

**Table 5** – Results of displacements at pressure increase in the chamber

| Indicator at break | Mean value of the indicators for direction 1 and 2 at uniaxial tension | Indicators at biaxial tension | Divergence of the results, % |
|---|---|---|---|
| Tensile strength, MPa | 26.3 | 27.47 | Cca. 5 % |

Cyclic uniaxial tension of the 200-micron-thick film in 2 orthogonal directions at a temperature of +25 °C (2 sets of 5 samples per each., total Qnty is 10 samples) was conducted under GOST 14236 [12]. Maximum stress per cycle was set equal to the yield limit at static tension which mean value under the diagram "stress-strain" is 15 MPa (Figure 5). The samples were subject to 10 cycles of loading. Refer to Figure 9 for the test results of one of the samples.

As illustrated in Figure 9, each load relief of the material was accompanied with increase of residual strain. Maximum value of the residual deformations (5 samples) upon completion of the 10th loading cycle was 3.95 %.

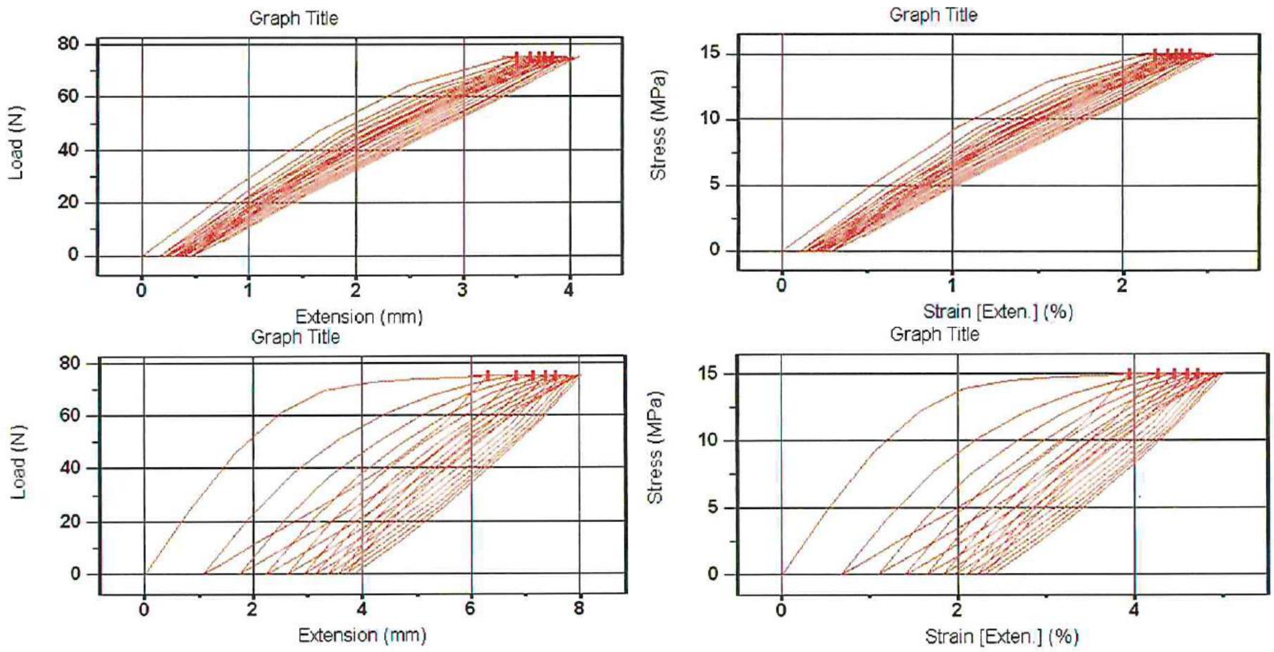



**Figure 9** – Cyclogram "force-displacement" (from the left) and "stress-strain" (from the right). From the top into direction 1 of the film, from the bottom into direction 2

**Film connection testing**

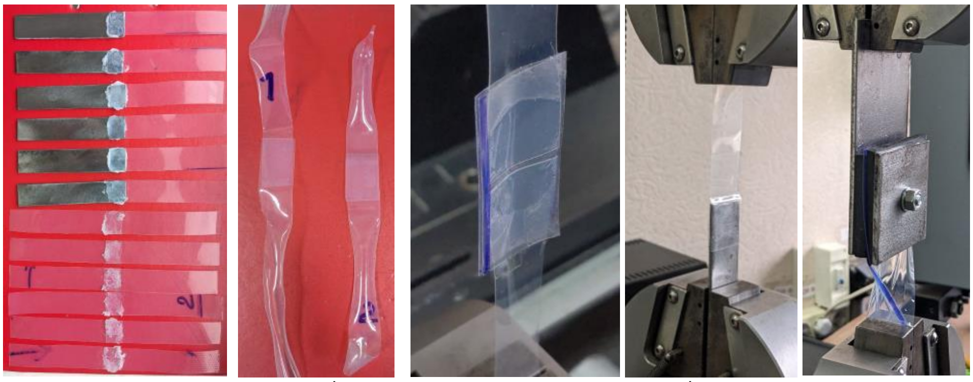
Essence of the shear tests of adhesive, mechanical, welded connections of the film and the connections with an adhesive tape lay in determination of stress limits that caused sample failure. Samples were tested like during uniaxial tensile tests at a temperature of +25 °C under GOST 14759 [19]. One set of 8 samples designated for mechanical connection and 6 samples each for the rest connection types were tested.

Bolted connection complete with a washer and rubber gasket served for testing of a mechanical film-to-steel plate connection.

Partite 7400 [20] glue served for testing of an adhesive connection. The glue was applied on the cleaned surfaces without corona discharge or plasma treatment of the film. CMC 77700 adhesive tape was used for a connection via a special adhesive tape. Test samples are illustrated in Figure 10.

Refer to Table 6 and Figure 11 for the test results of all the connections as the values of ultimate shear stress $\tau$.

As tested, the best results belong to the adhesive connection, however, complexity, labour input and adherengce to the surface preparation requirements, as well as keeping of the glued sample during the closed assembly time for such a connection type is impossible to perform on-site. Welding unit could be used while assembling rather small areas or low-rise buildings/facilities. Use of the adhesive tape is a too costly solution. Moreover, it is recommended to be applied as a repair material. Bolted connection is easily assembled on any areas, does not require any special equipment. However, the surface of a bolted connection could accumulate snow, icing, dirt. The choice of one or another film connection type is prompted by the quantity and area of a connection.



a b c d e

a) adhesive film-to-film and metal-to-film; b) welded film-to-film; c) with an adhesive tape film-to-film; d) with an adhesive tape metal-to-film; e) bolted metal-to-film

**Figure 10** – Connection samples

**Table 6** – Results of the tests of different connections

| Sample No. | Connections | | | | | |
|---|---|---|---|---|---|---|
| | Adhesive with metal | Adhesive | Welded | Adhesive with an adhesive tape | Adhesive with an adhesive tape with metal | Bolted |
| | Ultimate shear stress τ, kPa | | | | | |
| 1 | 300 | – | 125 | 85.5 | 77.5 | 109 |
| 2 | 205 | 95 | 127 | 83.2 | 76.3 | 100 |
| 3 | 277 | 179 | 134 | 85.5 | 80.9 | 100 |
| 4 | 101 | 122 | – | 85.7 | 90.7 | 123 |
| 5 | 114 | 130 | – | 88.3 | 83.7 | 127 |
| 6 | 105 | 63 | – | 85.9 | 82.0 | 113 |
| 7 | – | – | – | – | – | 122 |
| 8 | – | – | – | – | – | 106 |
| Mean | 184 | 118 | 128 | 85.7 | 81.9 | 112 |
| MD (mean deviation) | 90.1 | 42.8 | 4.4 | 1.6 | 5.1 | 10.6 |

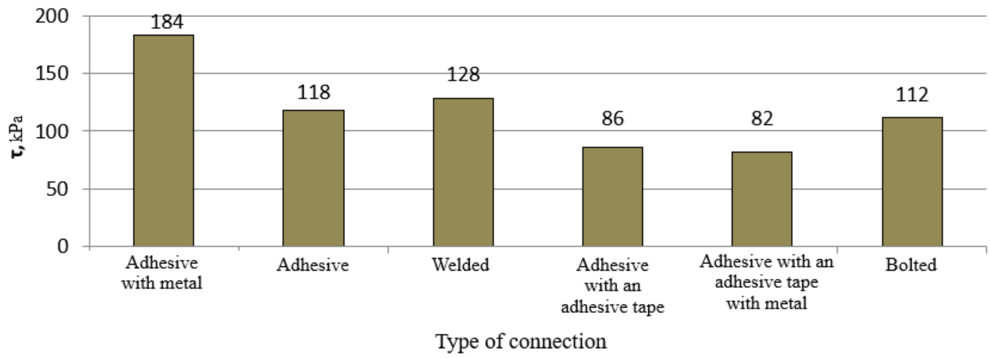



**Figure 11** – Comparison of strength of connections

**Conclusion**

The conducted experimental study of the 200-micron-thick ETFE film provides a rather comprehensive description of its mechanical properties at static and cyclic loading within a rather wide temperature range (–50 °C…+50 °C) that covers its possible application in construction and architecture.

The paper illustrates uniaxial and biaxial tensile tests of ETFE film to determine its strength and yield limits. The relation between the temperature and strength of the film, as well as the influence of cyclic loads on the material was defined. In particular, it was found that ETFE film has sufficiently high strength at uniaxial and biaxial tension that remains in the tested wide enough temperature range.

The paper states different options of film connection and their subsequent shear testing to check their viability in application for large-span structures. Strength limits of different connection types were defined. The highest shear strength τ = 128 kPa belongs to the welded film-to-film connection, while the adhesive connection τ = 184 kPa – to the film-to-metal adhesive connection.

The scientific merit hereof lies in reception of new test data about stress-strain behaviour of ETFE film and about the shear strength of its mechanical, adhesive and welded connections.

The practical relevance hereof lies in consideration of real-life behaviour of ETFE film at calculation and design development of enclosing structures. It is advisable to specify the film as a nonlinear material via diagrams of materials with regard to operating temperature of the film.

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# MECHANICAL CHARACTERISTICS AND FAILURE MECHANISMS OF TIMBER-CONCRETE COMPOSITE CONNECTIONS WITH INCLINED STEEL RODS

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**Abstract**

The application of Timber-Concrete Composite (TCC) structures in long-span floor systems is becoming increasingly widespread, and their collaborative efficiency highly depends on the shear stiffness and load-bearing capacity of the interface shear connectors. Although inclined self-tapping screws significantly improve connection stiffness by utilizing axial tensile force, the mechanism by which the mechanical behavior of large-diameter inclined connections with bolts steel rods, which have higher load-bearing capacity and require greater construction tolerance, is influenced by the constraints of hole clearance and concrete slab thickness remains unclear.

This paper proposes a comprehensive research scheme combining theoretical derivation, full-scale experiments, and high-fidelity numerical simulation for a TCC system composed of a 70 mm thin concrete slab and a 160 mm timber beam. The study aims to quantify the coupling effect of the diameter of the bolts steel rods (d = 6, 8, 12 mm) and inclination angle (α = 30°, 45°, 60°), focusing on solving two key problems: initial slippage caused by the clearance of the bolts steel rods and brittle punching out of thin slabs. In the numerical simulation stage, this study will use ANSYS finite element analysis software to establish a three-dimensional nonlinear solid model. ANSYS's powerful contact algorithms will be used to accurately simulate the closing process of the gap between the shank of the bolts steel rods and the hole wall. Combined with the concrete damage plasticity model (CDP) illustrated in Figure 2a, which can simultaneously, the evolution of failure modes under different working conditions will be predicted.

Expected results show:

1) ANSYS-based contact analysis will reveal that a 30° tilt angle can produce a significant geometric self-locking effect, effectively suppressing the initial stiffness loss caused by pre-drilled hole gaps;

2) in a 70 mm thin plate, 12 mm diameter bolts steel rods easily induce concrete cone failure, and numerical simulation will provide the critical parameter boundary to avoid this brittle failure. The results of this paper will correct the existing European Yield Model (EYM), providing a design basis based on high-precision simulation for the reinforcement and renovation of thin-plate concrete structures in existing timber floor slabs.

**Keywords:** timber-concrete composite structure, inclined bolted connection, ANSYS finite element analysis, slip modulus, bolt clearance, European yield model.

## МЕХАНИЧЕСКИЕ ХАРАКТЕРИСТИКИ И МЕХАНИЗМЫ РАЗРУШЕНИЯ КЛЕЕНЫХ ДЕРЕВЯННО-БЕТОННЫХ СОЕДИНЕНИЙ С НАКЛОННЫМИ СТАЛЬНЫМИ СТЕРЖНЯМИ

**Вей Юй, А. Я. Найчук**

**Реферат**

Применение деревобетонных композитных (ДБК) конструкций в системах монолитных перекрытий с большими пролетами становится все более распространенным, и их совместная эффективность в значительной степени зависит от сдвиговой жесткости и несущей способности соединительных элементов. Хотя наклонные самонарезающие винты значительно повышают жесткость соединения за счет осевой растягивающей силы, механизм влияния ограничений зазора отверстия и толщины бетонной плиты на механическое поведение крупногабаритных наклонных соединений с болтовыми стальными стержнями, которые обладают более высокой несущей способностью и требуют большего строительного допуска, остается неясным.

В этой статье предлагается всеобъемлющая исследовательская схема, сочетающая теоретическое произведение, полномасштабные эксперименты и высокоточное цифровое моделирование для системы TCC, состоящей из тонкой бетонной плиты 70 мм и деревянной балки 160 мм. Исследование направлено на количественное измерение эффекта соединения диаметра стальных прутиков болтов (d = 6, 8, 12 мм) и угла наклона (α = 30). Исследование направлено на решение двух ключевых проблем: первоначальное скольжение, вызванное расщеплением стальных прутиков болтов и хрупкое пробивание тонких плит. На этапе цифрового моделирования в этом исследовании будет использовано программное обеспечение для анализа конечных элементов ANSYS для создания трехмерной нелинейной твердой модели. Мощные алгоритмы контакта ANSYS будут использоваться для точного имитации процесса закрытия разрыва между стволом стальных штанг, болтов и стеной отверстия. В сочетании с моделью пластичности повреждения бетона (CDP), иллюстрированной на рисунке 2а, которая может одновременно предсказать эволюцию режимов сбоя при различных условиях работы.

Ожидаемые результаты показывают:

1) анализ контакта на основе ANSYS покажет, что угол наклона 30° может создать значительный геометрический эффект самоблокировки, эффективно подавляя первоначальную потерю жесткости, вызванную предварительно пробуренными пробелами в отверстии;

2) в тонкой пластине 70 мм, 12 мм диаметра болтов стальные пруты легко вызывают сбой бетонного конуса, и цифровое моделирование обеспечит границу критического параметра, чтобы избежать этого хрупкого сбоя. Результаты этой работы будут корректировать существующую Европейскую модель урожайности (EYM), обеспечивая основу проектирования на основе высокоточного моделирования для армирования и ремонта тонкоплиточных бетонных конструкций в существующих деревянных половых плитах.

**Ключевые слова:** деревобетонная композитная конструкция, наклонное болтовое соединение, анализ конечных элементов ANSYS, модуль скольжения, клиренс болта, Европейский режим урожайности.


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**Introduction**

Against the backdrop of the continuous advancement of green transformation and carbon reduction goals in the global construction field, Timber-Concrete Composite (TCC) is becoming a hot topic in academic research and engineering applications due to its complementary materials and high system efficiency. This system typically connects concrete slabs with excellent compressive performance and timber beams or planks with excellent tensile performance through shear connectors, so that the two materials have clear division of labor and complementary advantages in the same stress system, thereby significantly improving the overall stiffness and load-bearing capacity of the components, and showing better sound insulation and vibration comfort in terms of floor performance [1]. For the reinforcement and renovation of existing timber structures, TCC can improve structural safety reserves and service performance without significantly increasing structural complexity; and in modern multi-story timber structures, TCC floor slabs are also considered a powerful technical path that takes into account structural efficiency and sustainability, thus showing broad potential for promotion [2]. At the same time, the requirements for space utilization and floor height control in architectural design are constantly increasing, making the development trend of "thinner and lighter" floor systems more and more obvious. Driven by this, thin-plate wood-concrete composite structures have gradually entered the research field. For example, the construction form with a concrete slab thickness of only about 70 mm is attractive in practice, but it also brings more stringent connection performance requirements [1]. Under thin-plate conditions, traditional vertical shear connectors often cannot provide sufficient connection stiffness, and interface slip is more likely to accumulate, resulting in limited composite action; at the same time, the reduction in concrete slab thickness directly compresses the anchorage space of the connectors, making the risk of brittle failure such as local crushing, splitting or pull-out of concrete more prominent, which may control the structural bearing capacity and ductility level in advance. Based on the above engineering pain points, the inclined bolts Steel rods as a shear connector is considered to have strong application prospects in thin-plate TCC systems [3]. Based on a systematic review of relevant research, this paper discusses the mechanical performance of inclined connections with bolts steel rods in thin-plate TCC, focusing on its stiffness prediction method, failure mechanism and the influence of factors such as pore defects and long-term load on connection and overall performance, aiming to provide more targeted theoretical basis for the optimization design and safety assessment of this type of structure.

To provide a unified reference for the subsequent discussion, the push-out specimen configuration, inclination-angle cases, and the key geometric details (slab/beam thicknesses, hole clearance, and embedment length) are summarized in Figure 1.

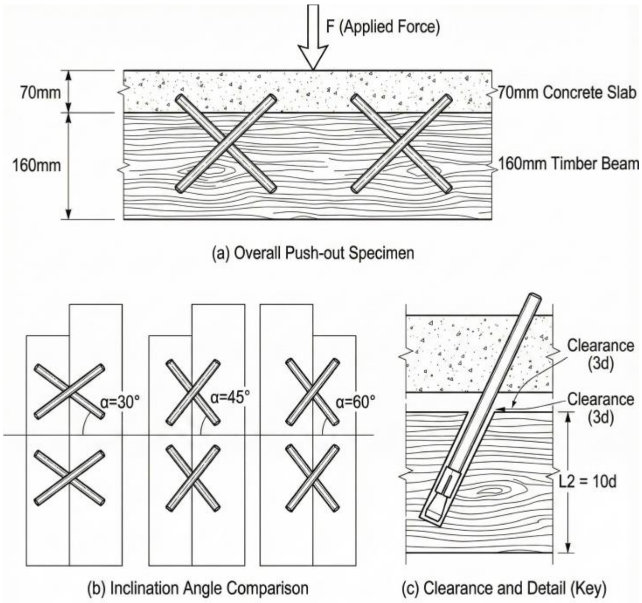



**Figure 1** – Specimen geometry and key details

As shown in Figure 1a, the TCC push-out specimen consists of a 70 mm concrete slab and a 160 mm timber member connected by an X-shaped pair of inclined bolts Steel rods. Figure 1b compares the three inclination angles (α = 30°, 45°, and 60°) considered in this study, while Figure 1c defines the bolt-hole clearance and the embedment length in timber (L2 = 10 d), which are critical to the initial slip response and the potential brittle failure of the thin slab.

**The Development of Timber-Concrete Composite Structures and the Advantages of Inclined Connectors**

Whether a wood-concrete composite structure can achieve efficient collaboration depends on the reliable transmission of interface shear force, and the interface force transmission capacity is directly controlled by the stiffness and strength level of the connectors. Early TCC systems generally used traditional fasteners such as nails, vertical bolts Steel rods or pins. Although these connection forms are convenient to construct and have mature structures, they often have a low slip modulus. Interface slip is more significant under load, making it difficult to fully form the composite section. The structure is closer to "partial composite action" than the ideal full composite action [3]. With the increasing requirements for structural bearing capacity, stiffness and service performance, research has gradually shifted to more efficient connection strategies. Among them, inclined screw or bolts Steel rods connections have received widespread attention due to their unique force path and stronger stiffness potential.

Unlike vertically inserted fasteners that mainly rely on pin groove bearing (Embedment) and fastener bending deformation (Bending) to transmit shear force, inclined connections can more fully mobilize the axial stiffness of the fasteners to participate in interface shear resistance, thereby achieving higher connection efficiency under the same material and construction conditions [1]. When fasteners are arranged at a certain angle along the direction of force (usually about 45° in engineering), the interfacial shear force will decompose inside the fastener and induce significant axial tensile or compressive components, so that the connection no longer relies solely on local bearing and bending energy dissipation, but forms a force transmission characteristic closer to a "tension-compression rod system". Especially for inclined bolts Steel rods on the tension side, their working mechanism can be compared with the tie rod members in the truss system. By leveraging the excellent tensile strength of steel to bear the main internal force, and generating a "rope effect" during deformation, additional normal pressure is introduced at the wood-concrete interface. This normal pressure not only helps to suppress interface opening and relative slippage, but may also further stimulate the contribution of interface friction, so that the shear bearing capacity and stiffness level of the connection are improved simultaneously [4].

Experimental studies have shown that compared with traditional vertical connectors, the use of inclined screws or bolts Steel rods arranged at 45° (X-type) can significantly improve the connection stiffness, with an increase of up to 66 % or even more than 100 %, thereby more effectively restraining interface slippage and significantly enhancing the combined action level [3]. This advantage is even more decisive in thin plate TCC systems, because when the thickness of the concrete slab is reduced to the order of 70 mm, the contribution of the thin plate itself to the bending stiffness is limited, and the overall performance of the structure depends more on efficient interface force transfer to form the effective stiffness of the composite section $EI_{eff}$ [5]. However, it should be emphasized that thin plate construction will also amplify several special challenges of inclined bolts Steel rods connections: the reduction of concrete slab thickness will limit the effective anchorage depth of the bolts Steel rods, thereby weakening the bearing margin of the concrete ends and local areas, and causing the potential failure mode to gradually shift from wood bearing or fastener yielding to concrete local failure or pull-out failure control. Since this type of concrete failure often has more obvious brittle characteristics and is not conducive to structural ductility and safety reserve, in thin plate TCC design, how to avoid or delay brittle concrete failure through structural refinement and parameter optimization often becomes one of the controlling factors affecting the reliability of the system [6].

**Mechanical Mechanism and Stiffness Model of Inclined connection with bolts (steel rods)**

To reliably assess the working mechanism of inclined connection with bolts (steel rods) in thin-plate wood-concrete composite structures, it is insufficient to rely solely on empirical descriptions. A unified explanatory framework must be established from three dimensions: force balance, deformation compatibility, and material constitutive model. This is because inclined bolts Steel rods, under interfacial shear, often simultaneously bear lateral compression and bending effects, and under certain geometric conditions, significantly induce axial tensile and compressive effects. Therefore, the stiffness and load-bearing capacity of the connection are the result of multiple contributing mechanisms. Simultaneously, wood exhibits significant anisotropy and nonlinear embedding characteristics, while concrete displays strong brittleness and size effects in local compression and cracking. When these two factors are coupled with the elastoplastic behavior of the steel bolts Steel rods, the load transfer path, local stress concentration, and potential failure modes of the connection significantly change with factors such as angle, anchorage length, porosity, friction, and long-term effects. Based on this understanding, the core objective of establishing a stiffness prediction model for engineering design is not to pursue formal complexity, but rather to incorporate decisive factors into a clear parameter form under computable conditions. This provides a traceable theoretical basis for SLS deflection and vibration control, as well as the optimization of connection details.

2.1 Stiffness Analytical Model and Component Superposition Method

In serviceability limit state design, the slip modulus $K_{ser}$ of the inclined bolts Steel rods is often considered one of the most critical connection parameters because it directly controls the amplitude of interface slip, which in turn determines whether the composite section can maintain high cooperative efficiency within a small deformation range. When $K_{ser}$ is low, more significant relative slip occurs between the concrete slab and the timber beam, weakening the composite effect, leading to a decrease in effective moment of inertia, and further amplifying deflection and vibration response. When $K_{ser}$ is sufficiently high, relative interface slip is effectively suppressed, the composite section is closer to the ideal cooperative state, and the overall stiffness and service performance are significantly improved. Based on the research of Tomasi et al. and combined with the theoretical treatment of inclined fasteners in the European Timber Structure Design Code (Eurocode 5), the equivalent stiffness of inclined bolts Steel rods can be understood as the result of the synthesis of the axial stiffness component and the lateral pin stiffness component in the shear direction [7]. The key to this idea is that the inclined arrangement changes the way forces are decomposed, so that the connection, which was originally mainly controlled by lateral bearing and bending, can make more use of the axial stiffness of the bolts Steel rods at a certain angle. If the angle between the bolts (steel rods) axis and the normal to the shear plane is $\alpha$, then the total stiffness $K_{total}$ can be approximately written as

$$\mathrm{K_{total}} = \mathrm{K_{ax}} \cdot \sin^2(\alpha) + \mathrm{K_{lat}} \cdot \cos^2(\alpha). \quad (1)$$

In this expression, $K_{ax}$ represents the axial stiffness of the fastener. Its physical source includes not only the axial tensile stiffness $EA/L$ of the bolts Steel rods itself, but also the anchorage and interface interaction of the bolts Steel rods on both sides of the wood and concrete. For the wood side, the pull-out resistance and local indentation deformation around the thread or the shank will change the equivalent length and equivalent stiffness of the axial deformation. For the concrete side, the anchorage length, local crushing, and the tendency of possible splitting or tapered pull-out failure will also limit the extent to which the axial stiffness is exerted. Correspondingly, $K_{lat}$ represents the lateral stiffness component, that is, the traditional pin stiffness, which is mainly controlled by the bearing stiffness of the wood and concrete hole wall, the evolution of local damage to the hole wall, and the bending stiffness of the bolts Steel rods [7]. In the thin plate TCC scenario, due to the small thickness of the concrete plate, the local deformation and cracking on the concrete side are more likely to occur earlier. This will cause the "effective value" of $K_{lat}$ to enter the degradation stage more quickly, which also means that the model parameters need to be reasonably selected in combination with the structure and material state. This component superposition formula further reveals the mechanical nature and angular sensitivity of the inclined arrangement. When $\alpha$ approaches 0°, the $\sin^2(\alpha)$ term is almost zero, and the overall stiffness of the connection is basically controlled by $K_{lat}$. The lateral pin mechanism typically corresponds to larger borehole wall bearing deformation and more significant slip accumulation, thus the equivalent stiffness is often low. When $\alpha$ increases and approaches 45°, the weight of the axial component increases significantly, and the high axial stiffness $K_{ax}$ is more fully incorporated into the shear deformation, resulting in a significant increase in $K_{total}$. It is worth noting that this increase is not unlimited, because whether the axial stiffness can be fully utilized is also constrained by anchorage conditions and local material failure. Especially in thin concrete slabs, insufficient anchorage may cause concrete splitting or prying before the axial force is fully established, thus prematurely "cutting off" the theoretical contribution of axial stiffness.

In order to describe the coupling deformation of fasteners in the two media more precisely in theory, Symons et al. further introduced the Beam on Elastic Foundation (BOEF) theory, which regards bolts Steel rods as beams embedded in two elastic media, wood and concrete. By establishing and solving the corresponding differential equations, analytical solutions are obtained, so as to more clearly consider the difference in stiffness of wood along the grain and across the grain, as well as the influence of local compression deformation of concrete and constraint conditions on the distribution of lateral reaction force in the calculation [8]. Compared with the simple superposition method, the BOEF frame can provide a more reasonable description of the internal force and displacement distribution, and is also more conducive to explaining why, at the same angle, changes in material anisotropy, contact length and boundary conditions lead to significant differences in stiffness and damage mode. For TCC structures characterized by thin plates, such more refined analytical models can also help identify the balance point between "stiffness improvement" and "brittle failure risk", thus providing a more targeted basis for structural design and parameter optimization.

2.2 Contribution of the Rope Effect

The outstanding advantage of inclined bolts Steel rods, especially tension-type inclined bolts Steel rods, in terms of connection bearing capacity is often attributed to the additional shear contribution brought about by the rope effect. The basic mechanism is that when shear slip occurs at the interface and causes deformation of the connector, the inclined arrangement makes the bolts Steel rods more prone to axial elongation, thus generating axial tensile force $F_{ax}$. This axial tensile force directly participates in resisting interface shear through its horizontal component, thereby supplementing the traditional pin bending and hole wall bearing mechanism in the force path; on the other hand, the vertical component of $F_{ax}$ introduces additional compressive stress at the wood-concrete interface, increasing the interface normal pressure, thereby activating and enhancing the Coulomb friction contribution [4, 9]. In this process, the shear capacity of the connection is no longer entirely determined by fastener yield and hole wall bearing, but exhibits a composite mechanism of "axial tensile force and friction synergy", which is one of the key reasons why inclined connections often achieve higher bearing capacity under the same diameter and spacing conditions.

To theoretically incorporate the rope effect into shear capacity calculations, the Extended Kinematic Approach (EKA) is often used to modify Johansen's Yield Theory. Traditional Johansen's theory primarily focuses on the yielding mechanism of fasteners forming plastic hinges under shear stress and the bearing failure mechanism of wood hole walls, combining these mechanisms into expressions for shear capacity corresponding to different yield modes. However, this framework has limited consideration of axial forces. EKA, by introducing the work done on axial tensile forces and the mechanical equilibrium condition, allows the rope effect to be superimposed on the traditional yield capacity as an additional term, thus yielding a modified expression for shear capacity

$$F_{v,Rk} = F_{Johansen} + \Delta F_{rope}. \quad (2)$$

Wherein, $\Delta F_{rope}$ represents the gain of the rope effect on the bearing capacity. It should be emphasized that the rope effect is usually more likely to develop significantly under large deformation conditions. Over-reliance on this effect may lead to unfavorable tendencies in design in terms of ductility and safety margin. Therefore, research and code recommendations usually set an upper limit on the value of $\Delta F_{rope}$ to ensure that the bearing capacity assessment is not based on excessive slip or unacceptable local damage. According to the latest research conclusions and code recommendations, the contribution of the rope effect is usually limited to 25 % to 100 % of the Johansen yield bearing capacity. The specific upper limit is closely related to the fastener type, whether it is threaded, and the anchorage conditions and pull-out control mechanism on both sides [9]. In the thin plate TCC system, the assessment of the rope effect must be more cautious because the thickness of the thin concrete plate limits the anchorage length and the development space of the concrete side bearing zone. The concrete is more likely to experience failure modes such as splitting, local prying out or conical pull-out before the axial tensile force is fully established. Once brittle failure occurs on the concrete side first, the axial tensile force of the bolts Steel rods is difficult to increase continuously, the normal pressure at the interface cannot be maintained stably, and the friction contribution decreases accordingly, making it difficult to achieve the theoretically expected $\Delta F_{rope}$ [10]. Therefore, in thin plate structures, the rope effect should be regarded as a "possible gain term" rather than a "necessary dominant term", and its potential needs to be evaluated in a consistent manner with the thickness of the concrete slab, the edge distance, the reinforcement or local reinforcement measures, and the initial defects caused by construction errors.

2.3 Interface slip and nonlinear behavior

Although linearized models have the advantages of simple calculation and clear parameters in engineering design, a large number of experimental and numerical studies have shown that the real load slip relationship of TCC connection usually exhibits obvious nonlinear characteristics, and this nonlinearity often begins to appear in the early stage. Typical load slip curves can be summarized as the initial approximately linear elastic stage, the subsequent elastoplastic development stage, and the final softening and failure stage [11]. In the initial stage, the connection response is mainly controlled by the elastic modulus of the material, the contact stiffness and the interface friction condition. At this time, the hole wall bearing pressure has not yet caused significant plastic damage, and the bolts Steel rods are mostly in the state of elastic bending or small axial deformation. Therefore, the stiffness is high and the curve slope is relatively stable. As the load continues to increase, the wood hole wall will gradually show local indentation and plastic extrusion. The hole wall damage causes the stiffness of the contact area to decrease. At the same time, the bolts Steel rods gradually enter yielding and form plastic hinges under the combined action of shear and bending. The overall stiffness of the connection begins to continuously degrade, and the curve slope decreases significantly. After entering the later stage, if local damage expands or cracks and spalling occur on the concrete side, the connection may soften after peak or even suddenly become unstable. This stage is highly sensitive to failure mode and structural details, and it best reflects the control role of brittle risk in thin plate structures.

The influence of clearance on nonlinear response is particularly noteworthy. If there is a significant gap between the bolts Steel rods hole and the bolts Steel rods diameter, the connection may mainly rely on frictional force transmission under small loads, and the bearing pressure of the hole wall has not yet formed an effective contact. Once the load exceeds the friction threshold, the bolts Steel rods will move relatively freely in the hole until it contacts the hole wall and re-establishes the bearing pressure transmission path. At this time, the load slip curve often shows a significant slip plateau or a near-zero stiffness section. This phenomenon will not only significantly reduce the initial stiffness and the equivalent value of $K_{ser}$, but will also amplify the slip accumulation under dynamic action or repeated loads, making vibration comfort and fatigue performance face more unfavorable responses [12]. For thin plate TCC, since the overall system stiffness relies more on the connection stiffness to maintain the combined effect, the initial low stiffness section caused by pores may have a more direct impact on SLS deflection and vibration control. Therefore, at the design and construction level, it is usually necessary to reduce the adverse effects of pores by means of pore precision control, grouting or local reinforcement, and to reasonably characterize the initial slip section in the analysis model in order to avoid systematic misjudgment of the structural performance.

**Special Failure Mechanisms in Thin-Plate Structures**

When the thickness of the concrete slab is reduced to approximately 70 mm, the failure control logic of thin-plate TCC systems often undergoes a fundamental change. Traditional design and research of thick-plate TCCs typically assume that the concrete slab has sufficient local load-bearing and anchorage reserves. Therefore, failure in the connection zone is more likely to be dominated by ductile mechanisms such as bearing development through the wood hole walls, bending yielding of fasteners, or tensile yielding of steel. The structure often undergoes sufficient plastic development and deformation redistribution before reaching its ultimate state. However, the geometric constraints of thin plates significantly weaken the anchorage space and crack propagation path on the concrete side, making the connection zone more susceptible to brittle phenomena such as local crushing, splitting, and spalling. Especially in inclined connection with bolts (steel rods), the axial component and leverage effect amplify local stress concentration near the concrete cover and anchorage zone, making brittle failure modes on the concrete side more likely to occur earlier and become the controlling factor. Existing studies have shown that, under thin plate conditions, two types of failure modes characterized by brittle cracking and spalling of concrete, namely concrete cone failure and pry-out failure, often occur before the bolts Steel rods have fully yielded, thereby altering the ductility level of the connection and the available load-bearing capacity [6]. Therefore, for thin plate TCC, identifying and constraining the triggering conditions of brittle fracture of the concrete side is usually more critical than simply pursuing higher connection stiffness or greater steel strength.

3.1 Concrete Pry-out Failure

Pry-out failure is generally considered to be a typical failure mode that is more likely to occur in short-anchored, relatively "short and thick" shear connections under shear loads. In thin plate structures, this mode often has stronger suddenness and destructiveness. When the inclined bolts Steel rods deforms under the action of interface shear force, if its anchorage depth is shallow and the bending stiffness of the connector is relatively large, the bolts Steel rods tends to exhibit a combination of rotation and small translation of an approximately rigid body, rather than forming a long bending deformation zone in the anchorage area. At this time, the rotation of the bolts Steel rods will form an obvious lever effect on the force path, resulting in a strong local action of compression and tension on the concrete side. More specifically, the bolts Steel rods tail area often applies a relatively concentrated compressive stress to the concrete, and the local concrete may first be crushed and crushed; at the same time, in the deep part on one side of the force direction, the bolts Steel rods shank will have a prying effect on the concrete, causing the back concrete to be lifted along the potential crack surface and form a cone or wedge, and finally be "pried out" in the form of overall peeling [6]. Since this process is mainly characterized by concrete cracking and local spalling, the failure often lacks obvious yield warning, and the bearing capacity may drop rapidly after the load reaches its peak, thus significantly weakening the structural ductility and safety redundancy. From a design calculation perspective, the Concrete Capacity Design (CCD) method in ACI 318 or Eurocode 2 provides a commonly used mechanical framework for assessing pry-out failure. This framework typically correlates the shear capacity $V_{cp}$ of pry-out failure with the tensile cone failure capacity $N_{cb}$ of concrete, commonly expressed as

$$V_{cp} = k_{cp} \cdot N_{cb}. \quad (3)$$

Where $k_{cp}$ is the pry-out coefficient, typically used to reflect empirical corrections when the anchorage zone transitions from a tensile cone mechanism to a pry-out mechanism under shear conditions. For connections with shallow anchorage depths and greater susceptibility to rigid body rotation, $k_{cp}$ is often taken on the order of 1,0 or 2,0. $N_{cb}$ is strongly correlated with the effective anchorage depth $h_{ef}$ and is often considered to be proportional to $h_{ef}^{1.5}$. The key problem of thin plate construction is that the 70 mm plate thickness will significantly limit the achievable $h_{ef}$, which will cause the calculated value of $N_{cb}$ to drop sharply, thus theoretically putting the load reserve for pry-out failure at an unfavorable level. In engineering, it is even more troublesome that dense steel mesh is often configured in thin plates to control cracks and improve the overall integrity, but when the protective layer is too thin or the steel reinforcement arrangement near the anchorage zone does not match the cracking path, the steel mesh may act more as "post-crack constraint" rather than "pre-crack enhancement", and may induce the protective layer to peel off or local cracking concentration, resulting in earlier or more sudden pry-out failure [13]. Therefore, in the detailed design of TCC connections in thin plates, pry-out failure is usually considered as one of the control modes to be checked first, and it needs to be specifically suppressed by means of anchorage length, edge distance, local reinforcement or structural thickening.

3.2 Concrete Cone Failure and Edge Effect

Besides pry-out failure, the axial component introduced by inclined bolts Steel rods under shear conditions can also trigger direct pull-out brittle failure on the concrete side, i. e., concrete cone failure. This failure mode is usually characterized by a crack initiation area near the tension end of the fastener, forming a failure cone surface extending from the concrete interior to the free surface. The angle between the cone surface and the concrete surface is often empirically taken as about 35°, eventually leading to the overall detachment of the concrete cone or wedge within a certain range [14]. In thin plate TCC, cone failure is more alarming because, on the one hand, the thickness of the thin plate limits the complete development of the cone failure surface, making it easier for the failure surface to be "cut off" by the free surface in advance, thus forming a smaller effective resistance volume; on the other hand, thin plates are usually accompanied by smaller edge distances and more compact connector arrangements, which makes it easier for the cone failure surface to intersect with the plate edge or overlap with the failure surface of adjacent connectors, resulting in a further reduction in bearing capacity relative to the single-unit condition. Considering that TCC floor slabs usually function as composite beams in structural systems, connectors are often arranged in rows along the beam length, and the group anchoring effect is particularly significant under thin plate conditions. If the spacing between connectors is insufficient, multiple cone failure surfaces will overlap, reducing the effective concrete resistance volume that each connector can "allocate", and the individual bearing capacity cannot be simply linearly superimposed. Accordingly, engineering design usually needs to introduce a reduction factor or use the group anchoring check method to correct the bearing capacity of a single connector in order to reflect the mutual influence and edge cutoff effect [15]. Furthermore, since the force direction of inclined bolts Steel rods is not purely tensile or purely shear, cone failure and pry-out failure may exhibit a competitive or coupled relationship under certain structural and load conditions, which means that independent verification of a single mode may not be sufficient to cover the actual control situation. For thin plate TCC, a more reasonable approach is to understand the potential failure of the concrete side as a brittle failure family "with anchorage depth and geometric boundaries as the core constraints", and to prioritize ensuring sufficient edge distance, reasonable connector spacing and local reinforcement scheme that matches the potential crack path in the structural design, so as to improve the resistance of the connection area to brittle failure and the predictability of failure.

3.3 Failure Modes on the Timber Side

Unlike concrete, which is mainly controlled by brittle cracking and spalling, the failure modes on the timber side are more often manifested as a progressive damage process of anisotropic materials under local pressure and crack propagation. For inclined connection with bolts (steel rods), typical failures that may occur on the timber side include dowel bearing failure, splitting along the grain, and block shear failure when multiple connectors are arranged in a row [16]. In the dowel bearing mechanism, the bolts Steel rods generates local compressive stress on the hole wall, and the timber undergoes indentation and plastic deformation under the constraint of the fiber structure. The bearing area gradually expands and is accompanied by local fiber buckling and crushing. This mechanism has ductile characteristics to a certain extent, but its development speed and ultimate bearing capacity depend significantly on the grain direction and moisture content.

The stress on timber by inclined bolts Steel rods is more complex because after the decomposition of the axial force and shear force of the bolts (steel rods), the timber will simultaneously bear stress components perpendicular to the grain and parallel to the grain. In order to deal with this complex stress state at the engineering level, the Hankinson formula is often used to estimate the equivalent bearing capacity of timber under different grain direction combinations. However, for connections with large tilt angles or significant axial components, stress concentration caused by wood anisotropy may lead to early microcracks at the hole edge. These microcracks may gradually penetrate and evolve into splitting failure along the grain under repeated loading, humidity changes, or stress redistribution. Such splitting failure often exhibits more obvious brittle characteristics and is highly sensitive to edge distance, end distance, pre-drilling quality, and wood moisture content changes. Therefore, it needs to be regarded as an important design control in the actual construction of thin-plate TCC [2]. In addition, when the connectors are arranged in rows along the beam length, hole edge cracks and shear cracks may be interconnected and form a block shear failure path, causing shear plug failure to occur at a small slip level. This will reduce the connection ductility and weaken the overall assembly efficiency [16]. Therefore, in the thin-plate TCC system, the wood side is not necessarily a "controllable ductile end". Its failure mode may also turn to brittle or quasi-brittle failure in advance due to geometric constraints, environmental effects, and arrangement density. This, together with the brittle mechanism of the concrete side, determines the controllable failure mode and structural safety boundary of the connection area.

**The Influence of the Clearance of Holes for Bolts (Steel Rods) on Installation Accuracy**

In actual engineering construction, to reduce installation difficulty and improve assembly efficiency, the pre-drilled hole diameter in the concrete slab is often moderately enlarged relative to the bolts Steel rods diameter. Simultaneously, factors such as drilling deviation, formwork positioning error, and duct deformation during pouring can also lead to unavoidable geometric deviations. The combined effect of these factors results in varying degrees of porosity between the bolts Steel rods and the hole wall, i. e., hole diameter margin. The geometric definition of the holes for Bolts (Steel Rods) clearance adopted in this study is illustrated in Figure 1 c. Extensive testing and field experience show that this seemingly subtle geometric difference not only affects construction convenience but also alters the stress initiation mode of the connection during small deformation stages, causing the interface shear force to shift from continuous transmission to staged contact transmission. This, in turn, significantly impacts the initial stiffness, energy dissipation characteristics, and failure mode of the TCC connection. To facilitate establishing a direct correspondence between porosity levels and mechanical consequences at the engineering level, this paper summarizes the initial response characteristics, stiffness and bearing capacity variation trends, and typical failure characteristics of different porosity types, as presented in Table 1, serving as a reference framework for subsequent discussion and parameter selection. For 70 mm thin plate TCC, the concrete cover and effective anchorage depth are already limited. Contact impact and local stress concentration caused by pores are more likely to trigger crushing or spalling near the concrete opening, making the pore effect more sensitive in thin plate systems.

4.1 Effects on Stiffness and Slip

The most direct consequence of pores is that they alter the stress initiation process of the connection, significantly affecting initial stiffness and slip evolution. When the pores are small or even close to a tight fit, the bolts Steel rods can form stable contact with the hole wall in the early stages of loading, the shear force transmission path is relatively continuous, and the load-slip relationship usually exhibits a clear linear elastic characteristic, thus maintaining a high equivalent slip modulus $K_{ser}$. Conversely, when the pores increase, the connection often experiences a stage where contact is not fully established in the early stages of loading. At this time, the interface shear force is mainly borne by friction and local point contact, and the bolts Steel rods will experience a certain degree of free movement within the hole until they fully conform to the hole wall and enter the bearing deformation stage. Because the stiffness in this stage is significantly lower than in subsequent stages, the overall load-slip curve will exhibit slip lag or a slip plateau, thus systematically reducing the equivalent stiffness of the initial segment. The patterns summarized in Table 1 show that from tight fit to Small clearance and then to Large clearance, the initial response gradually transitions from approximately linear elasticity to a more pronounced slip plateau characteristic, with the corresponding equivalent initial stiffness showing a decreasing trend. This phenomenon is usually further amplified in thin-plate TCCs.

From a structural response perspective, the deflection and vibration control of thin-plate TCCs are highly dependent on the initial stiffness of the connections. This is because the system often has not yet entered a significant plastic development stage under service load levels, and whether the combined effect is fully formed is largely determined by early slip. When porosity leads to amplified initial slip, the effective stiffness of the combined section will decrease at lower load levels, thereby amplifying mid-span deflection and floor vibration response. It also increases the dispersion between different specimens or different construction batches, making it more difficult to interpret test results consistently with actual engineering performance. Based on the classification results shown in Table 1, when performing SLS calculations and connecting the model, a more reasonable approach is to include the initiation stage corresponding to the pores as a component of the model, rather than using only a single linear stiffness to cover the entire process. This avoids systematic misjudgments of slippage and stiffness during small load stages.

4.2 Impact Effects and Stress Concentration

Pores not only affect stiffness, but more importantly, they alter the continuity of the contact process, introducing adverse effects such as impact and local stress concentration. When pores exist, the bearing contact between the bolts Steel rods and the hole wall is often not smoothly established from the loading start point, but rather occurs in a relatively abrupt manner after free movement ends. At this time, the stress in the local contact area will rapidly increase over a very small bearing area, equivalent to a contact impact, and induce local crushing and microcrack propagation near the concrete hole opening. For 70 mm thin TCC plates, the concrete slab thickness and protective layer are relatively thin. Once cracks initiate in the hole opening area, they are more likely to penetrate to the free surface and form spalling or local breakage, leading to further degradation of the bearing capacity and stiffness of the connection area. The typical failure characteristics in Table 1 also reflect this trend: as the pore size increases, the failure manifestations tend to shift from localized crushing to more significant splitting, prying out, or the associated risk of brittle spalling.

**Table 1** – Influence of holes for bolts (steel rods) clearance level on connection performance [17]

| Clearance level | Initial behavioural characteristics | Effect on Rigidity | Impact on load-bearing capacity | Typical Failure Characteristics |
|---|---|---|---|---|
| Tight-fit | Linear elastic response | High | High | Bolt yielding/wood compression failure |
| Small clearance (0,5–1 mm) | Minor slip hysteresis | Medium | Slightly reduced | Localised concrete crushing |
| Large clearance (>2 mm) | Significant slip plateau | Low | Significantly reduced | Impact-induced splitting/prying out |

Under long-term loads, repeated loads, or dynamic actions, the aforementioned impacts and stress concentrations exhibit stronger cumulative damage characteristics. The gradual propagation of pore wall crushing and microcracks continuously softens the contact surface, leading to sustained growth in slippage at the same load level. The equivalent stiffness and bearing capacity of the connection gradually decrease with the number of cycles. Especially when the pore size is large, the slippage platform is more pronounced, and repeated contact and release make localized damage more easily amplified, potentially resulting in a combined failure of splitting on the wood side and prying out or localized fragmentation on the concrete side. Consequently, the structural safety reserve is depleted more early. Given the correlation between porosity level and performance degradation summarized in Table 1, porosity should be considered as a key factor that changes the stress path of the connection in the structural design and construction control of thin plate TCC. Its adverse effects should be reduced by controlling the porosity accuracy, optimizing the installation process, and taking necessary local reinforcement and constraint measures. Sufficient attention should also be paid to the nonlinear starting behavior caused by porosity in the calculation model.

**Finite Element Numerical Simulation and Parametric Analysis**

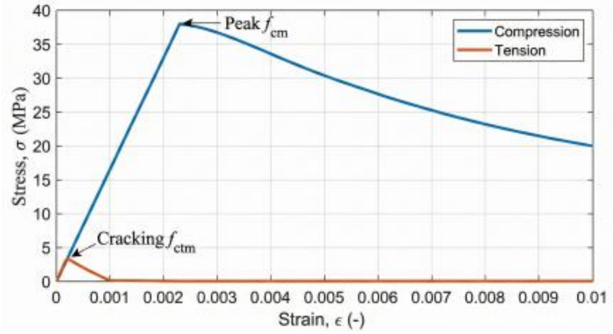
To overcome the limitations of experimental research in terms of cost, parameter coverage, and observability of internal responses, finite element analysis (FEA) has become an important tool for studying inclined connection with bolts (steel rods) in thin-plate TCC (Transient Cavity Cordless Concrete) systems. Unlike external characterizations that rely solely on bearing capacity or slip curves, numerical simulation can simultaneously track the evolution of the axial force and bending moment of the bolts (steel rods), stress concentration in the borehole bearing zone, the propagation of concrete cracks, and the formation of potential pry-out cones within a unified mechanical framework. This provides a more complete chain of evidence for identifying failure modes and sensitivity analysis of design parameters. Especially in cases where the concrete slab thickness is only about 70 mm, local failure often precedes overall yielding, and structural behavior is more dependent on subtle differences in detailed geometry and contact conditions. This makes it even more necessary to establish a high-precision model that reflects actual contact and damage evolution.

5.1 Material Constitutive and Contact Models

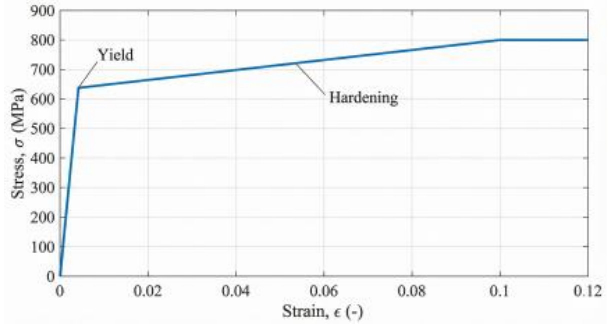
High-reliability FEA models are typically built upon the foundations of "interpretable material constitutive model" and "traceable contact definition". For wood, due to the significant differences in its mechanical properties along the grain, across the grain, and radial directions, and the obvious asymmetry in tensile and compressive strength and yield evolution, the orthogonal anisotropic elastoplastic model combined with the Hill yield criterion can more reasonably describe its strength envelope and yield initiation under multi-directional stress conditions [2]. In the borehole wall bearing problem of the connection zone, local indentation of wood is usually an important source of nonlinearity of the slip curve. Therefore, the constitutive model also needs to be able to reflect the gradual hardening or softening characteristics under compression, and to make the evolution of the borehole wall crushing zone consistent with the experimental phenomenon as shown in Figure 2c. If the model only uses linear elasticity or an oversimplified yield rule, it will often underestimate the initial stage of bearing deformation and overestimate the connection stiffness, thus affecting the reliability of subsequent parameterization conclusions.

The simulation of the concrete side is usually based on the concrete damage plasticity (CDP) model, because CDP can simultaneously characterize the stiffness degradation after tensile cracking and the hardening and softening process under compressive damage, and allows the influence of the crack propagation zone on the overall bearing capacity and stiffness to be characterized by damage variables [2]. For thin-plate TCC (Transformed Crush Capacitance), the key to the concrete side lies not in whether the overall compressive strength is sufficient, but in whether the model can stably capture local crushing, cracking cones, and pry-out wedges. Therefore, CDP (Contraction Power Determination) parameters typically need to be calibrated around the tensile softening segment, fracture energy, and the rationality of post-compression peak softening, ensuring that the crack morphology, crack propagation direction, and spalling tendency observed near the borehole in the model are consistent with thin-plate experimental observations. If tensile softening is ignored or an overly rigid post-compression peak behavior is used, the model may incorrectly transform the failure path, which should be controlled by brittle cracking, into ductile compressive yielding, thus masking the true controlling role of cone failure and pry-out failure.

The steel of the bolts (steel rods) typically employs an isotropic elastoplastic constitutive model with a bilinear response (Figure 2b), and the strain hardening, and the strain hardening process after yielding is described using the Von Mises yield criterion and strengthening laws. For inclined connections with bolts (steel rods), these bolts (steel rods) not only bear shear and bending but may also generate significant axial tensile force due to the rope effect. Therefore, the model needs to ensure consistency between the yield criterion and strengthening response of the steel under coupled axial tension and bending conditions. If the research objective involves the formation location of the yield hinge and the length of the plastic zone, a sufficiently fine mesh and a reasonable element type are usually required to avoid numerical sensitivity caused by plastic localization. The specific constitutive curves and stress responses defined for the three materials are summarized in Figure 2.




a)

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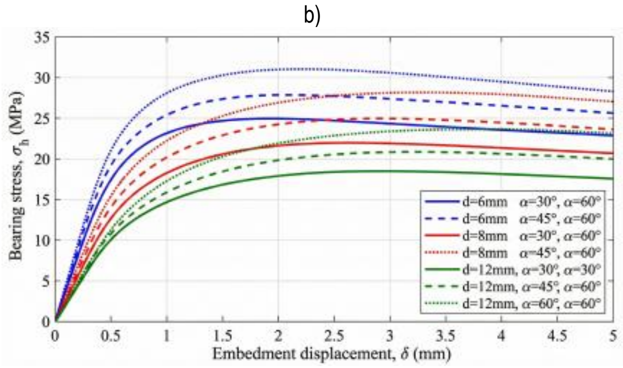



c)

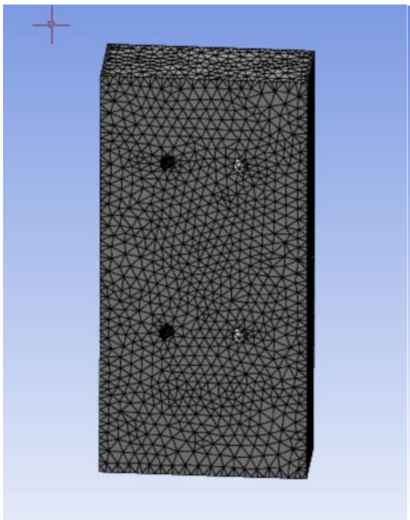
a) Concrete Damage Plasticity (CDP) model for compression and tension; b) Bilinear isotropic hardening model for bolt steel; c) Direction-dependent embedment stress-displacement curves for timber

**Figure 2** – Material constitutive models and stress-strain relationships adopted in the FEA

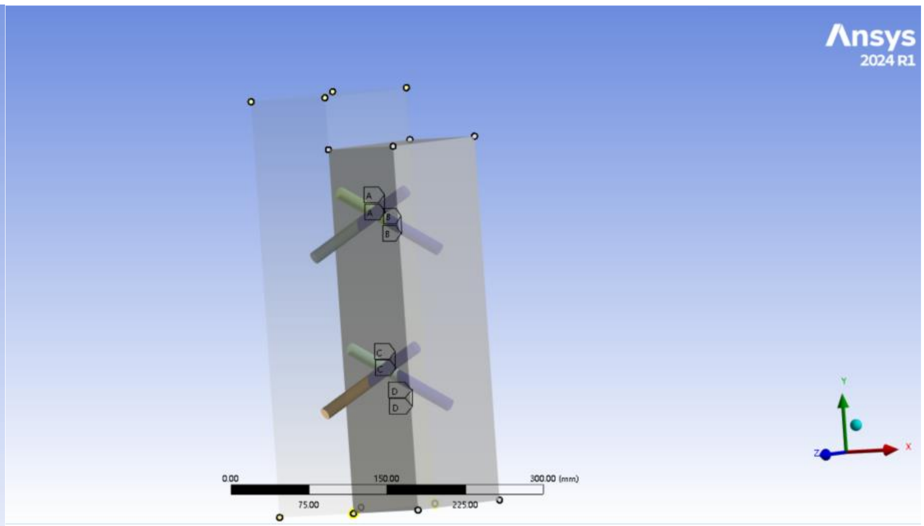
Contact simulation is one of the core aspects of the reliability of this type of FEA. The contact between the bolts (steel rods) and the wood hole wall, and between the bolts (steel rods) and the concrete hole wall, is generally defined as surface-to-surface contact as shown in Figure 3b. Hard contact is used in the normal direction to avoid penetration and ensure a reasonable contact pressure distribution during pressing. In the tangential direction, a penalty function friction model is often used, with the friction coefficient $\mu$ typically ranging from 0,3 to 0,6 to cover different interface roughness and construction conditions [4]. In thin plates, friction not only affects the initial slip but also changes the local damage evolution by increasing the interface normal pressure. Therefore, the value of the friction coefficient usually needs to be combined with experimental curves or literature recommendations for sensitivity testing to avoid mistaking the friction contribution as the material strength contribution. Meanwhile, porosity and installation deviations can cause the contact to not be continuously established in the early stages of loading. The initial clearance (gap) to be closed during loading is defined according to the detail shown in Figure 1c. If the initial gap is ignored in the model, the initial stiffness is often significantly overestimated and the slip plate length is underestimated. This is particularly important to be aware of in the SLS analysis of thin plate TCC. To more accurately reproduce the formation mechanism of pry-out failure, it is usually necessary to establish a solid model that includes the geometric details of the head of the bolts (steel rods), washer, and thread, rather than simply using equivalent beam elements, because pry-out failure is essentially driven by the local compression of the head of the bolts (steel rods) and its neighborhood, contact eccentricity, and lever rotation [18]. When the thickness of the thin plate is limited, the size of the local bearing zone near the head of the bolts (steel rods) is on the same order of magnitude as the thickness of the concrete cover, and the geometric details have a direct impact on the peak contact pressure and the crack initiation location. Accordingly, the model usually needs to use locally refined meshes at the orifice and anchorage area (Figure 3a), and through reasonable boundary constraints, and through reasonable boundary constraints and loading methods, make the stress path of the connection area as consistent as possible with the loading fixture conditions in the experiment, thereby improving the interpretability and comparability of the simulation results.

5.2 Parametric Analysis Results

After completing the reasonable calibration of the material and contact model, parametric analysis can systematically reveal the influence of key design parameters on the performance of thin plate TCC inclined connections with bolts (steel rods) at a lower cost. Based on a combination of multiple numerical studies and comparative conclusions, a relatively consistent trend judgment can be obtained, which explains the mutual constraint relationship between "stiffness improvement" and "brittleness risk" under thin plate conditions.



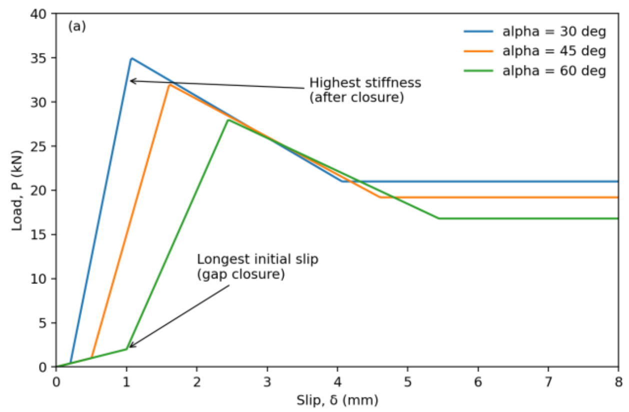
a)



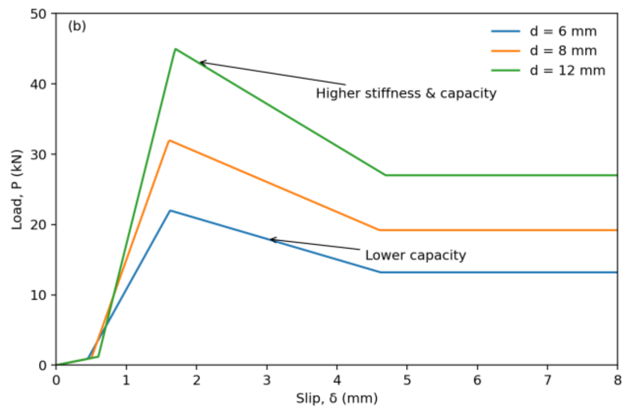

b)

a) Global mesh generation with local refinement; b) Definition of contact pairs at the head of the bolts (steel rods) interface

**Figure 3** – Finite element model establishment details, developed by the author of the article




a)




b)

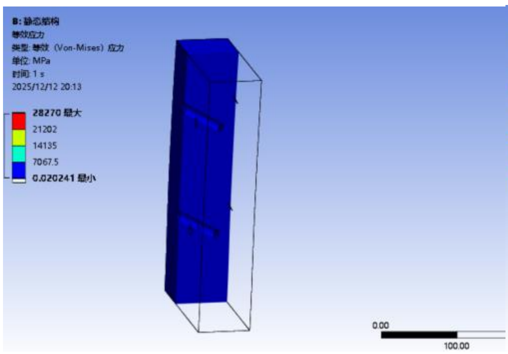
a) Effect of inclination angle ($\alpha$) on initial stiffness and gap closure mechanism; b) Effect of the diameter ($\mathrm{d}$) of the bolts (steel rods) on ultimate bearing capacity and stiffness

**Figure 4 –** Simulated load-slip response curves under different geometric parameters, received by the author of the article

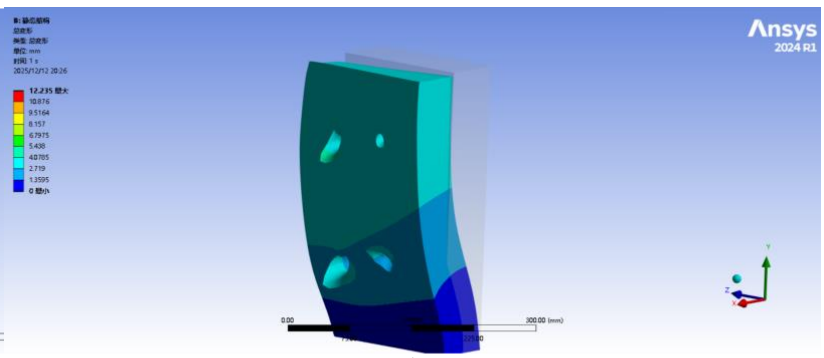
The tilt angle $\alpha$ is often one of the most decisive geometric parameters. As $\alpha$ gradually decreases from a vertical arrangement of 90° to around 45°, the initial stiffness and ultimate bearing capacity of the connection usually increase synchronously (Figure 4a). This is because the axial force component is easier to establish, the axial stiffness of the bolts (steel rods) and the interface friction effect are more fully mobilized, and the interface slip is more strongly constrained [3]. As shown in Figure 4 a, the 30° case exhibits the highest stiffness and effectively suppresses the initial slip plateau compared to the 60° case. In most studies, 45° is often considered to achieve a better balance between mechanical efficiency and construction convenience, because this angle can provide a significant axial contribution and avoid the construction perforation difficulties and insufficient anchorage length caused by too small an angle. If the angle is further reduced to the order of 30°, the effective anchorage depth that can be provided in the thin plate will be significantly reduced, and the concrete side is more likely to split or pry out before the axial tensile force of the bolts (steel rods) is fully developed, thus reducing the bearing capacity and possibly showing a stronger tendency for brittle failure [3]. This phenomenon suggests that angle optimization in thin plate TCC is not a monotonic problem, and the anchorage space and potential concrete failure surface must be taken into account.

The role of concrete strength $f_c{}'$ in thin plate systems is often more prominent than in thick plates, especially when the control failure mode is close to prying or cone failure, concrete strength almost directly determines the upper limit of brittleness of the joint. Numerical studies usually show that increasing $f_c{}'$ can significantly delay crushing and crack initiation near the orifice, slow down the propagation rate of the cone failure surface, and give the bolts steel rods a greater chance to enter the steel yield stage before reaching the concrete control limit, thereby improving the ductility and energy dissipation capacity of the joint [19]. In thin plates, due to the limitation of $h_{ef}$, it is often unrealistic to obtain higher load-bearing capacity simply by geometric enlargement. Therefore, the strength improvement and local constraint enhancement at the material level are more efficient within a certain range. However, it should be noted that strength improvement is not necessarily equivalent to toughness improvement. If the CDP parameter or fracture energy value is unreasonable, the model may show a "strong but brittle" response. Therefore, in the parameter analysis with $f_c{}'$ as the variable, it is usually necessary to check the crack propagation morphology and the post-peak softening rate at the same time to avoid mistaking the increase in bearing capacity as the disappearance of the risk of failure.

The bolts steel rods diameter $\mathrm{d}$ has a direct impact on the bearing capacity, because the increase in cross-section can increase the axial and shear bearing capacity reserves, and at the same time change the bearing area of the hole wall and the distribution of contact pressure. Most simulation results summarized in Figure 4 b show that increasing $\mathrm{d}$ can significantly increase the shear bearing capacity of the single unit and reduce the slip level required for steel yielding to a certain extent, but this gain is often accompanied by stricter end distance and edge distance requirements. The more critical problem in thin plates is that larger holes will weaken the effective cross-section of concrete and aggravate the stress concentration in the hole area (as visualized in Figure 5a), making the concrete plate more prone to splitting or spalling, especially when the connectors are densely arranged or close to the edge of the plate, this adverse effect will be further amplified [3]. Therefore, there is usually a more sensitive "diameter-thickness matching range" in thin plate TCC. If the diameter is too small, the steel yielding and friction effect will be difficult to develop fully, while if the diameter is too large, the failure mode may be pushed to the brittle control of concrete, making it difficult to exert the ductile advantage. The value of parametric analysis lies in its ability to clarify, by comparing the crack initiation location, the time of prying out cone formation (Figure 5a), and the evolution of the plastic zone of the bolts steel rods (Figure 5b) under different $d$, that the "optimal" is not determined solely by the peak bearing capacity, that the "optimal" is not determined solely by the peak bearing capacity, but is constrained by both bearing capacity and ductility.



a)




b)

a) Von Mises stress concentration indicating potential concrete pry-out failure ($d = 12$ mm); b) Large deformation and plastic hinge formation in the shank of the bolts steel rods ($d = 6$ mm)

**Figure 5** – Comparison of simulated failure modes under different diameters of the bolts steel rods

The presence of an interlayer is a common structural condition in actual TCC engineering. For example, OSB permanent formwork or sound insulation layers introduce additional thickness between the concrete slab and the wooden beam. Numerical simulations generally show that the interlayer increases the shear arm and introduces additional bending moment, making the bolts steel rods more prone to rotation, and the bearing zone of the hole wall also exhibits a more uneven stress distribution. Its direct consequences are usually manifested as a decrease in connection stiffness and a reduction in bearing capacity, with the reduction reaching approximately 30 % to 50 % in many studies [1]. For thin-plate TCC, this reduction is even more noteworthy, because thin plates rely on connection efficiency to form effective combined stiffness, and the stiffness reduction caused by the interlayer will quickly manifest as increased deflection and decreased vibration comfort during the service stage. Meanwhile, the intermediate layer may also alter the normal pressure path formed by the axial component of the bolts (steel rods) at the interface, making the friction contribution more unstable and thus exacerbating the nonlinearity and dispersion of the load-slip curve. Based on these mechanisms, engineering design typically requires explicit reduction of the intermediate layer effect, rather than treating it as a negligible construction ancillary condition. The numerical results in Figure 4a confirm that smaller inclination angles effectively mitigate the stiffness loss caused by hole clearance.

**Long-term performance and environmental factors**

The long-term service performance of thin-plate TCC structures is largely determined by the time-varying properties of the materials and the effects of the environment. Both wood and concrete exhibit significant creep behavior, and under long-term loads, the slippage of the joints increases over time, making the long-term deflection of the composite beam significantly greater than the short-term deflection [20]. Due to its larger specific surface area, thin-plate concrete develops drying shrinkage faster, and early shrinkage may introduce additional tensile or shear stresses near the interface, thereby changing the microcrack state and friction conditions in the joint area. In addition, wood is highly sensitive to changes in temperature and humidity; moisture absorption expansion and desiccation shrinkage will induce continuous stress redistribution in the bearing area of the borehole wall, leading to cumulative degradation of the joint stiffness. More importantly, in a cyclic humidity environment, a mechanical sorptive effect often occurs under moisture-drying cycles. This effect causes wood to produce additional deformations exceeding conventional creep predictions under the combined action of load and humidity changes, resulting in a gradual increase in residual slip and weakening the recoverability of the joint [20]. The difference between indoor and outdoor environments is often reflected in the humidity fluctuation range and cycle frequency. Therefore, the long-term slip growth rate of the same connection type may be significantly different in different environments. Related studies have pointed out that the creep coefficient of connections with bolts steel rods in outdoor environments can reach about 2,5 times that in indoor environments [20]. This means that if indoor parameters are directly used for long-term prediction of outdoor thin plate TCC, the risk of deflection growth and stiffness degradation may be significantly underestimated. Based on engineering usability considerations, long-term performance prediction should not directly use short-term $K_{ser}$. A more reasonable approach is to reduce the short-term stiffness to long-term stiffness through the effective modulus method and introduce the creep coefficient ϕ to characterize the time-varying effect. Its expression can be written as [21]

$$K_{eff} = K_{ser}/(1 + \phi). \quad (4)$$

In thin plate TCC, this reduction not only changes the deflection calculation results, but also affects the judgment of interface slip accumulation, because a lower $K_{eff}$ means a greater long-term slip demand. Meanwhile, the self-balancing stress caused by shrinkage and moisture expansion may alter the normal pressure level in the connection zone, thereby changing the friction contribution and slip threshold, resulting in stronger nonlinearity and path dependence in the long-term response of the connection. Therefore, in durability design, it is necessary to consider environmental level and humidity cycle characteristics as important bases for determining long-term stiffness values, and to verify the value of φ using experimental or long-term monitoring data to reduce systematic biases caused by environmental differences.

**Conclusions and Outlook Research**

Based on existing research, it can be concluded that inclined connections with bolts steel rods have clear mechanical advantages in thin-plate wood-concrete composite structures. In particular, the 45° cross arrangement can improve the initial stiffness and ultimate bearing capacity of the connection by introducing a stronger axial stiffness contribution and stimulating the rope effect, thus compensating to some extent for the insufficient flexural stiffness contribution of the thin concrete slab itself. At the same time, the geometric characteristics of the thin slab significantly compress the anchorage space and crack propagation path on the concrete side, making pry-out failure and cone failure more likely to become the controlling failure modes earlier, and triggering the upper limit of bearing capacity before the bolts steel rods have fully yielded. Given this paradoxical relationship, the key to thin-plate TCC (Transient Concrete Cavity Control) lies not in infinitely increasing the strength of the steel or the stiffness of the connection, but in ensuring that brittle fracture of the concrete side is not prematurely triggered while improving the efficiency of the combined action. To achieve this goal, the design phase needs to adopt stiffness models and load-bearing capacity assessment methods that better conform to the inclined connection mechanism, such as stiffness estimation based on the Tomasi model and explicit consideration of porosity effects. Simultaneously, the risk of brittle fracture of the concrete side should be reduced by reasonably controlling porosity, optimizing end and edge distances, and implementing necessary local structural reinforcement. Furthermore, the reduction in stiffness due to creep and humidity cycling effects should be incorporated into long-term predictions to make the performance assessment during service more closely reflect real-world service scenarios.

Looking to future research, several directions warrant further exploration. One direction is to develop more targeted structural details to address the anti-pry-out requirements under thin-plate conditions. For example, this could involve improving bolts Steel rods head and washer construction, introducing local reinforcing mesh or local thickening strips to reduce stress concentration at the orifice and delay the formation of cone and pry-out failures. Another direction is to establish a long-term slip prediction model that can reflect the coupling effect of humidity cycles, so that the damp-drying cycle and creep shrinkage can be consistently described within the same framework, thereby improving the prediction accuracy of long-term deflection and residual slip. Further research can be conducted on the applicability evaluation of new fasteners such as self-tapping screws in thinner concrete slabs, especially when the slab thickness is less than 50 mm. Anchoring mechanisms, crack propagation paths, and group anchoring effects may exhibit new controlling laws, requiring verification through both experiments and high-fidelity numerical simulations to promote the development of the TCC system towards lighter weight and higher efficiency.

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## MECHANICAL ENGINEERING

UDC 621.7

# INVESTIGATION OF THE OPERATIONAL CHARACTERISTICS OF PLASMA-CHEMICAL STRENGTHENING THIN-FILM SILICON-CONTAINING COATINGS, DEPOSITED FROM ARC PLASMA AT ATMOSPHERIC PRESSURE

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**Abstract**

The strengthening of metal surfaces by applying thin-film silicon-containing coatings deposited from arc plasma at atmospheric pressure allows them to be protected from wear and aggressive environments, and is ultimately determined by the performance characteristics of such coatings.

One of the basic operating performances of hardening protective thin-film coverages is their thickness. Definition of thickness of thin films by direct gauging represents an intractable technical problem.

In the paper, the use of an optical interference picture in the system of a substructure thin-film coverage for determining thickness is offered. The given approach allows determining and controlling the coating thickness not only on completed product but also during the coating process. An experimental study of the thickness of a thin-film silicon-containing coating using a scanning electron microscope showed that the film thickness is within 1,1–1,2 µm. Comparison of the calculated and experimental data on the thickness of the strengthening coating showed high convergence of the results (12–15 %). The ability to precisely control the thickness significantly expands the scope of application of thin-film strengthening silicon-containing coatings applied from argon arc plasma at atmospheric pressure.

Precise control over coating thickness significantly expands the range of applications for thin-film silicon containing strengthening coatings deposited from arc argon plasma at atmospheric pressure.

The results obtained during theoretical and laboratory studies were used in real production conditions at the largest enterprise of the Republic of Belarus, Open Society Mozyr Oil Refinery. In the conditions of repair and mechanical production, an author's installation for applying thin-film coatings and a technological process for applying corrosion-resistant thin-film silicon-containing coatings on parts operating under conditions of non-abrasive wear and in contact with aggressive environments were introduced.

**Keywords:** hardening, a thin-film siliceous coverage, arc plasma, thickness, an interference.

## ИССЛЕДОВАНИЕ ЭКСПЛУАТАЦИОННЫХ ХАРАКТЕРИСТИК ПЛАЗМОХИМИЧЕСКИХ УПРОЧНЯЮЩИХ ТОНКОПЛЕНОЧНЫХ КРЕМНИЙСОДЕРЖАЩИХ ПОКРЫТИЙ, ОСАЖДАЕМЫХ ИЗ ДУГОВОЙ ПЛАЗМЫ ПРИ АТМОСФЕРНОМ ДАВЛЕНИИ

**А. Л. Голозубов**

**Реферат**

Упрочнение металлических поверхностей нанесением тонкопленочных кремний содержащих покрытий, осаждаемых из дуговой плазмы при атмосферном давлении, позволяет защитить их от износа и действия агрессивных сред и в конечном счете определяется эксплуатационными характеристиками таких покрытий.

Одной из основных эксплуатационных характеристик упрочняющих защитных тонкопленочных покрытий является их толщина. Определение толщины тонких пленок непосредственным измерением представляет собой трудно разрешимую техническую задачу.

В статье предлагается использование оптической интерференционной картины в системе подложка – тонкопленочное покрытие для определения его толщины. Данный подход позволяет определять и контролировать толщину покрытия не только на готовом изделии, но и непосредственно во время нанесения. Экспериментальное исследование толщины тонкопленочного кремний содержащего покрытия с помощью растрового электронного микроскопа показали, что толщина пленки находится в пределах 1,1–1,2 мкм. Сопоставление расчетных и экспериментальных данных о толщине упрочняющего покрытия дали высокую сходимость результатов (12–15 %).

Возможность точного контроля толщины значительно расширяет область использования тонкопленочных, упрочняющих, кремнийсодержащих покрытий, наносимых из дуговой аргоновой плазмы при атмосферном давлении.

Полученные в ходе теоретических и лабораторных исследований результаты были использованы в условиях реального производства на крупнейшем предприятии Республики Беларусь ОАО «Мозырский нефтеперерабатывающий завод». В условиях ремонтно-механического производства была внедрена авторская установка для нанесения тонкопленочных покрытий и технологический процесс нанесения коррозионно-стойких, тонкопленочных, кремнийсодержащих покрытий на детали, работающих в условиях неабразивного изнашивания и в контакте с агрессивными средами.

**Ключевые слова:** упрочнение, тонкопленочное, кремнийсодержащее покрытие, дуговая плазма, толщина, интерференция.

### Introduction

Drawing of thin-film siliceous coverages from arc plasma at atmospheric pressure is new enough direction in a work-hardening range of details of cars [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13]. Working capacity of thin films is influenced by variety of factors – cohesive and adhesive properties of a coverage, and also property of a metal substructure [8, 14, 15, 16].

Hardening of metal surfaces by drawing thin-film silicium of containing coverages, besieged of arc plasma at atmospheric pressure allows to protect them from deterioration and operation of excited environments and eventually is defined by operating performances thin-film silicium of containing coverages. Definition of operating performances is necessary and a sufficient condition for an estimation working capacity and longevity of system «a substructure - a coverage». Those are: hardness (microhardness), adhesion, phase and a chemical compound, wear resistance. Important performance of a sheeting is also it thickness which can influence considerably on its operation features, defining including its longevity [17, 18].

### Definition of thickness thickness of a thin-film coverage

Samples from fragments thin-film silicium of containing coverages separated from a substructure were examined by the RSMA-ANALYSIS method on REM "Nanolab-7" with a spectrum of power variance EDS "Sistem 860".

As a result for films on the basis of a silicon oxide the following data on chemical element composition has been obtained: Si – 60,84 %, O – 39,02 %, C – 0,14 %. For films on the basis of silicium carbide: Si – 73,22 %, C – 26,7 %, O – 0,08 %. For films on the basis of silicium nitride: Si – 67,72 %, N – 32,2 %, O – 0,08 % [16, 18, 19].

Thus the conducted probes allow to make conclusion that received of the arc plasma containing products pyrolysis silicium of the organic, hardening siliceous thin-film silicium of containing coverages represents a difficult pseudo-alloy not stoichiometric composition, containing in the composition oxides, carbides and the silicium nitrides, not having a crystalline structure and representing uncrystalline (passer-by on the glass) structure. The obtained data will agree with results of probes [3, 8, 11, 20] also specifying in uncrystalline structure of the thin films received by sedimentation from ion bundles in vacuum.

Ratio change between components in thin-film silicium of containing coverages is possible at the expense of a variation of composition of arc plasma (a gas phase) a path the additional introductions of elements and joints in necessary densities, and also at the expense of process control in temperature the purposeful the job of its parametres [6, 8, 9, 21].

The picture observed in an optical microscope confirms an optical transparency hardening thin-film silicium of containing coverages (Figure 1).

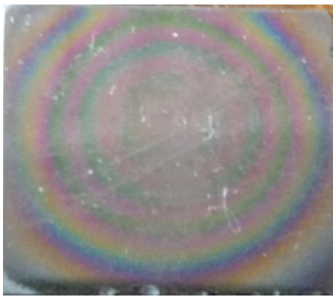

**Figure 1** – The Sample with plotted thin-film silicium of containing coverages. Material of substructure WC-Co, the polished surface

At small thickness of transparent films in an optical range, as the most exact and simple method of study of their shape and thickness serves visual observation changes of an interference picture on a surface of the substrate with simultaneous timekeeping [5, 18, 22].

For growth kinetics probe samples with the polished a surface for deriving of an accurate optical picture were used at when applying thin-film silicium of containing coverages [7, 18, 23, 26].

In the course of drawing plasma of the chemical coverages at stationary position plasma the generator (plasmatron) on the processed surfaces series of the optical phenomena is observed. In the beginning handlings, the polished surface of the sample starts to lose gradually a reflecting capacity, acquiring dark colour. Further handling leads to colour change on dark blue then in the hcentre of a plasma spot start to appear sequentially the expanding circles of the colours making a spectrum of a natural light. Circles grow to certain magnitude (diameter of 6–10 mm) then in the centre the monochrome a circle there is a growing circle of following colour. In result on a surface the picture of the concentric colour rings similar to rings of Newton is observed.

By results of the experiment, shown in table 1 the graph of dependence of thickness of a besieged coverage from duration of handling of a substructure which is presented in Figure 2 is constructed.

On a curve there are some characteristic sites, the corresponding to different stages of formation and coverage growth.

**Table 1** – Dependence of occurrence of maxima on duration of handling by a plasma stream

| Appearance a colour picture | Experiment number (time in seconds) | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| Dark-blue | 16 | 17 | 16 | 12 | 14 |
| 1 red | 26 | 33 | 30 | 29 | 31 |
| 2 red | 41 | 48 | 40 | 48 | 46 |
| 3 red | 63 | 72 | 62 | 75 | 64 |
| 4 red | 92 | 95 | 90 | 91 | 94 |
| 5 red | 120 | 115 | 117 | 122 | 116 |

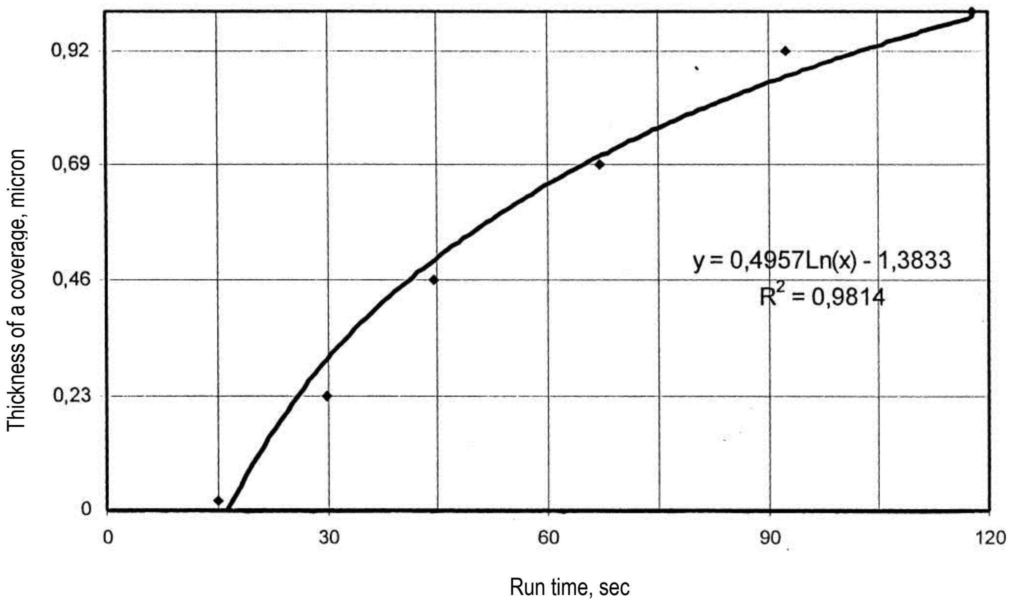


**Figure 2** – Growth kinetics thin-film silicium of containing coverages

Experiments by coating separation from a substructure have displayed that the coverage is optically transparent, and its thickness decreases from the centre to periphery, according to radial distribution of temperatures in plasma the jet [22, 24]. Such in the image, the observable optical picture grows out interference of light in system a thin lens-metal a substructure. In this case, from geometrical reasons (Figure 3), we have

$$r_k^2 = R^2 - (R - h_k)^2 . \quad (1)$$

where $r_k$ – radius of k-rings, R – radius of curvature of a lens, $h_k$ – height of a lens from a surface of a coverage to a plain of k-rings.

After transformations with the account that $h_k^2 \to 0$, we have

$$r_k^2 = 2 \cdot R \cdot h_k \, , \tag{2}$$

accordingly

$$r_{max}^2 = 2 \cdot R \cdot d \, , \tag{3}$$

where $r_{max}$ – radius of the maximum ring.

R – radius of curvature of a lens, $h_k$ – height of a lens from a surface of a coverage to a plain of k-rings, d – thickness of a lens (film) on the centre.

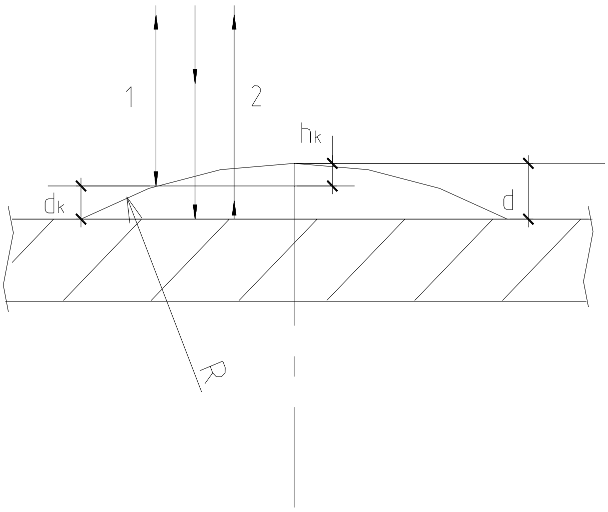


**Figure 3** – The Settlement circuit of definition of thickness thin-film silicium of containing coverages

Considering that both rays are reflected from optically more tight environments (in the first case from a lens material, in the second from a surface metal) with phase loss on half of wavelength in each case, condition a maximum will be recorded in an aspect

$$d = 2 \cdot d_k \cdot n = k \cdot \lambda, \tag{4}$$

where n – an index of refraction of a lens (film), (k = 0,1, 2...).

From here

$$d_k = \frac{k \cdot \lambda}{2 \cdot n}. \tag{5}$$

Considering that $d_k = R - h_k$, we will receive

$$h_k = R - \frac{k \cdot \lambda}{2 \cdot n}. \tag{6}$$

Substituting (2) in (1) it is had

$$r_k^2 = 2 \cdot R^2 - \frac{(R \cdot \lambda \cdot k)}{n}. \tag{7}$$

From here, having expressed a lens radius of curvature through radius of i and k rings and taking into account (1) we receive expression for definition thicknesss coverages

$$d = \frac{r_{max}^2 \cdot (i-k) \cdot \lambda}{2 \cdot (r_i^2 - r_k^2) \cdot n}. \tag{8}$$

As a result of gaugings next sizes of radiuses of rings have been defined: $r_{max}$ = 9,1 mm, $r_i$ = 7,0 mm, $r_k$ = 5,5 mm. The index refractions for thin-film silicium of containing coverages composition $SiO_2$ is equal n = 1,458 ± 0,002 [25]. The wavelength of light corresponding to red colour is accepted equal 672 nanometers. Thus, after evaluations under the formula (8) it is had maximum thickness lenses

$$d = 1,017 \pm 0,092 \; \mu m.$$

Thickness change coverages, leading to changeover of a colour gamma, it is possible to define thickness change from the output before regularities. Distance (thickness of a film) between the next maxima on a surface (rings of one colour) in conformity about figure 1 are defined on ratio

$$h_k - h_i = \frac{i \cdot \lambda}{2 \cdot n} - \frac{k \cdot \lambda}{2 \cdot n} \tag{9}$$

$$\Delta h = \frac{\lambda}{2 \cdot n} = \frac{672 \cdot 10^{-9}}{2 \cdot 1,4584} \approx 0,23 \; \mu m.$$

Thus, occurrence of a following ring of identical colour in process processing testifies to increase in thickness of a film at 0,23 microns.

It allows operatively and to watch precisely enough thickness of a plotted coverage in the course of handling that is important parametre of technique. Besides, the test coating on substructures allows to establish univalent connection with simultaneous timekeeping between thickness of a coverage and a run time for the given mode of behaviour of installation. It does possible to realise exact control of thickness thin-film silicium of containing coverages in places where direct observation of an interference picture, for example, in holes of small diameter through passage, including, die holes is impossible. Feature of drawing thin-film silicium of containing coverages from arc plasma at atmospheric pressure (as transport response), is ability of drawing of coverages in holes of small diameter through passage, and also under any edges to a shaft of a plasma stream, thus exact control of thickness of plotted coverage thin-film silicium of containing coverages allows to harden such difficult details with a thickness quality assurance that cannot achieve with use of traditional techniques.

For experimental definition of thickness thin-film silicium of containing coverages it was used REM "Nanolab-7" and a fragment of the coverage separated from a substructure. Gaugings on a back of the sample have displayed that thickness of a film is in within the limits of 1,1–1,2 microns [14, 18]. Thus, for the first time compared settlement and experimental data about thickness hardening thin-film silicium of containing coverages, received by sedimentation from arc plasma, have given high convergence of results (12–15 %). Toe-outs in values most likely are linked with an aberration of curvilinear external surface thin-film silicium of containing coverages from a theoretical surface of a thin lens with fixed radius.

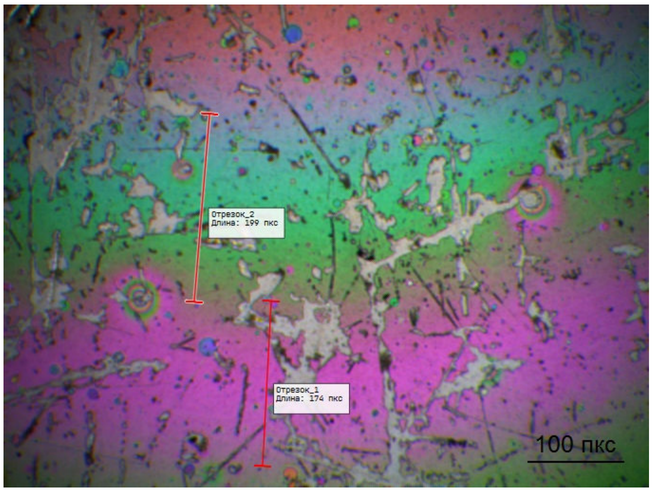


**Figure 4** – Color gamma on surface thin-film silicium of containing coverages. An optical microscope «Altami» with a digital camera. 1 pixel = 3,2 × 3,2 a micron

Exact values of thickness allow to delineate area of use coverages, in particular, obviously that the coating thick to 0,3 microns gets to a zone of the tolerance for all qualifications exactitude and consequently process on a coating can be finishing (not demanding aftertreatment).

The maximum thickness besieged thin-film silicium of containing coverages has made 2 microns. Receiving such thicknesss it has appeared possible only at use special the measures preventing overheating of a substructure. Thus processing it was carried on by cycles till 15–20 seconds, with an interval 20–30 seconds, and with insignificant lowering


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(on 20–30 %) densities of metalloorganic joint in plasma after application coverages thickness more than 1 microns. However, spent tribological trials have displayed that in the best performances possess thin-film silicium of containing coverages thickness from 0,7 microns to 1,0 microns.

Thus, having possibility of exact control of thickness of a coverage, we can essentially expand area of use of technique. Control of thickness of a coverage on a colour gamma allows to plot thin-film silicium of containing coverages the set thickness on surfaces of any configuration and shapes. And there is possible drawing thin-film silicium of containing coverages of the set thickness on local sites, i.e. for example strips of the set thickness and length. Figure 4 also there is possible drawing thin-film silicium of containing coverages of identical thickness, including on a surface of a difficult configuration that is almost impossible with use of traditional methods of drawing of protective hardening coverages. It is necessary to mark that occurrence of an interference picture in a place of drawing thin-film silicium of containing coverages takes place not only for the polished surfaces, but also for surfaces after a coarse finishing, for example polishings, millings, turning. In this case the picture interference rings becomes more diffusion and not having clear boundary, but nevertheless allowing to define thickness with enough split-hair accuracy (to 20 %).

The observable picture of interference rings (Figure 1) is characteristic only for a fixed plasma stream, i.e. at exhibiting plasmatron over one point. The longitudinal travel plasmatron allows to plot thin-film silicium of containing coverages in the form of strips of the set thickness (Figure 5).

In the conditions of real manufacture most often there are situations when it is necessary to harden surface of revolutions (shafts, axis). In this case shaft rotation is carried out in accommodating, and the coating on extended sites occurs for the movement score plasmatron along a shaft shaft therefore the coverage is plotted on extended sites.

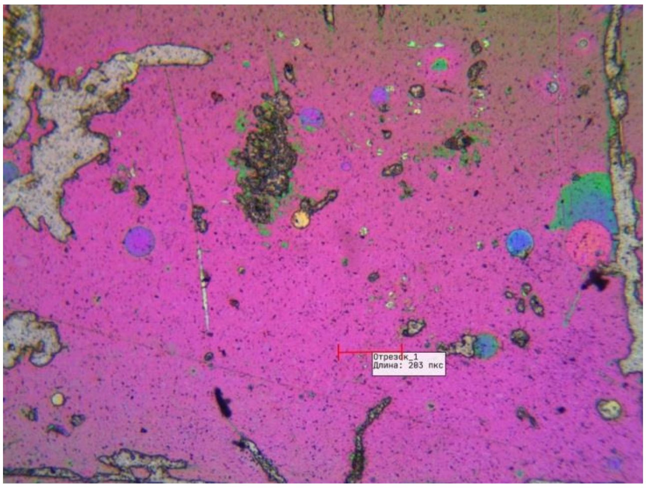

**Figure 5** – A site of a surface with identical thickness thin-film silicium of containing coverages

Received during theoretical and laboratory probes results have been used in the conditions of real manufacture at the largest operation of republic of Belarus Open Society Mozyr Oil Refinery. In the conditions of mechanical-repair manufacture author's installation for drawing of thin-film coverages and a master schedule of drawing of noncorrosive thin-film siliceous coverages on a detail, working in the conditions of not abrasive wear process and in contact to excited environments has been introduced. Surfaces of shafts of pumps of centrifugal type PC (a material-steel 40X, 290 HB) intended for pumping the oil, the liquefied hydrocarbon gases and oil products were hardened at temperature of a pumped over fluid from 193 K (–80° C) to 673 K (+400° C) with viscosity from $0{,}5 \cdot 10^{-4}$ $m^2$/sec to $8{,}5 \cdot 10^{-4}$ $m^2$/sec.

Principal causes of outage of shafts of pumps were: excess of supposed escape through shaft seals and deterioration of mounting surfaces to pinion point under bearings and he impeller. The given problem has been solved for the score plasmochemical drawings of its – thin-film sheetings saving resources the technique allowing safely to protect metals from staining and deterioration by drawing on their surface of chemically steady siliceous joints, having high physicomechanical properties («Anticorrosive guard of details of the nasosno-compressor equipment» certificate of registration № 2003536, «Working out of a master schedule of hardening and a corrosion prevention of seats of bearings and face seals» certificate of registration № 20023233).

Thus thin-film silicium of containing coverages it was used not only in the form of a noncorrosive coverage, but also as a barrier coverage for separation of contacting mounting surfaces to pinion point under bearings and impeller, at joint assembly-demolition that has led to change of conditions of deterioration yo-to reduction or complete an exception microcutting at the expense of surface hardness increase. In this case the optimum condition-elastic interaction of conjugated surfaces is ensured.

Operational trials of shafts of pumps of centrifugal type PC (cantilever) for pumping oil products in the conditions of real manufacture have displayed that the period of their use was augmented in 2,5–3 times at the expense of an exception of effect of the active corrosion environment and deterioration by mounting surfaces to pinion point of shafts that has allowed to cut expenditures on reconditioning of the equipment and to raise its reliability.

**Conclusion**

The method of definition used in operation on an interference picture of thickness of the protective hardening thin-film siliceous coverages besieged from arc plasma at atmospheric pressure, has displayed split-hair accuracy with simultaneous possibility not only definitive, but also intermediate and a process control inspection.

Reliability of the received theoretical dependences is confirmed by experimental researches of the separated fragments of a coverage methods of scanning electron microscopy.

The obtained data about thickness thin-film silicium of containing coverages allows to define and specify areas of use of such coverages in various areas of engineering.

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# THIN-LAYER NANOCOMPOSITE COATINGS FOR CONSTRUCTION EQUIPMENT

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**Abstract**

Fluorine-containing coatings are promising materials for increasing the service life of equipment used in construction. The range of these compounds is quite wide, and the thickness of the coatings can vary from tens of nanometers to tens of millimeters. Interest in these coatings is due to high performance. Thin-layer coatings of fluorine-containing compounds formed from solutions were studied. These connections can be widely used in various friction assemblies of construction equipment to increase the service life. The article discusses issues related to the change in the physical and mechanical characteristics of fluorine-containing coatings, known under the trade name "Foleox." The morphology and microhardness of coatings were studied depending on the technological parameters used to create these protective layers. As surfactant, fluorine-containing oligomers of the trade name "Foleox" were used, the structural formula of which is RF – COOH (F1); RF = CONHR1 (F-AK1); RF – RF (F14) (where RF – fluorine-containing radical), RF – CONHR2 (F-AK2), B1 – water-soluble foleox. The coatings were applied by dipping the substrate in a 1–2 % solution of fluorine-containing oligomer in chladone 113 followed by air drying. A HWMMT-X7 microhardness meter was used to measure the microhardness of coatings formed on metals. The morphology was studied using an NT-206 atomic force microscope. It has been found that fluorine-containing oligomers strengthen the surface layers of the substrate if chemical (chemisorption) bonds such as salts of higher acids are formed between the film of the fluorine-containing oligomer and the metal (substrate). If the formation of a chemisorption interaction between the oligomer molecules and the substrate does not occur, plasticization of the surface layers of polycrystals occurs. Energy treatment intensifies the processes of crystal formation in thin films, as a result, the microhardness of the thin-layer composite coating increases. These coatings can be recommended for friction assemblies of construction equipment operated in severe conditions.

**Keywords:** nanocomposite coatings, morphology, microhardness, fluorine-containing compounds, oligomer, crystal, construction machinery.

## ТОНКОСЛОЙНЫЕ НАНОКОМПОЗИТНЫЕ ПОКРЫТИЯ ДЛЯ СТРОИТЕЛЬНОЙ ТЕХНИКИ

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**Реферат**

Фторсодержащие покрытия являются перспективными материалами для увеличения срока службы техники, применяемой в строительстве. Ассортимент данных соединений достаточно широк, а толщина покрытий может варьироваться от десятков нанометров до десятков миллиметров. Интерес к данным покрытиям обусловлен высокими эксплуатационными характеристиками. В работе исследованы тонкослойные покрытия фторсодержащих соединений, формируемых из растворов. Данные соединения возможно широко применять в различных узлах трения строительной техники для увеличения срока эксплуатации. В статье рассмотрены вопросы, связанные с изменением физико-механических характеристик фторсодержащих покрытий, известных под торговым названием «Фолеокс». Изучена морфология и микротвердость покрытий в зависимости от технологических параметров, применявшихся при создании данных защитных слоев. В качестве ПАВ использовали фторсодержащие олигомеры с торговым названием «Фолеокс», структурная формула которых имеет вид RF – COOH (Ф1); RF – CONHR1 (Ф-АК1); RF – RF (Ф14) (где RF – фторсодержащий радикал), RF – CONHR2 (Ф-АК2), В1 – водорастворимый фолеокс. Покрытия наносили путем окунания подложки в 1–2 % раствор фторсодержащего олигомера в хладоне 113 с последующей сушкой на воздухе. Для измерения микротвердости покрытий, сформированных на металлах, использовали микротвердомер HWMMT-X7. Морфологию изучали с применением атомно-силового микроскопа NT-206. Установлено, что фторсодержащие олигомеры упрочняют поверхностные слои подложки, в случае если происходит образование химических (хемосорбционных) связей типа солей высших кислот между пленкой фторсодержащего олигомера и металла (подложкой). В случае если не происходит образование хемосорбционного взаимодействия между молекулами олигомера и подложкой происходит пластифицирование поверхностных слоев поликристаллов. Энергетическая обработка интенсифицирует процессы кристаллообразования в тонких пленках, в результате повышается микротвердость тонкослойного композиционного покрытия. Данные покрытия могут быть рекомендованы для узлов трения строительной техники, эксплуатируемой в тяжелых условиях.

**Ключевые слова:** нанокомпозиционные покрытия, морфология, микротвердость, фторсодержащие соединения, олигомер, кристалл, строительная техника.

### Introduction

Fluorine-containing coatings are a promising material for increasing the service life of construction equipment. These materials consist of layers ranging in thickness from nanometers to several millimeters, consisting of fluorinated polymers, oligomers, or polymer-oligomer compounds. The most common representative of this class of materials polyvinylidene fluoride

(PVDF). These coatings are known for their high performance characteristics: high chemical resistance, resistance to ultraviolet radiation, high Mechanical strength, hydrophobicity, and heat resistance. Another fluorinated material widely used in the construction industry is polytetrafluoroethylene. It has unique anti-adhesive properties. It is often used not as a decorative but as a functional coating for friction units (bearings, sliding surfaces) to reduce the adhesion of soil, clay, and concrete [1–3]. The use of coatings based on this chemical compound can significantly increase the durability and appearance of the product, provide protection against corrosion, increase resistance to mechanical damage, and reduce the adhesion of various types of contaminants to the surface of construction equipment, which improves environmental friendliness and reduces fuel consumption. Typically, the thickness of these coatings is 100 µm or more. Another area is the use of thin-film coatings with a thickness of about 0,5 µm to 10 µm. These coatings are formed on the surface of solids from solutions and using vacuum methods. Formation from solutions is carried out by applying surfactants to a pre-cleaned substrate [1–4].

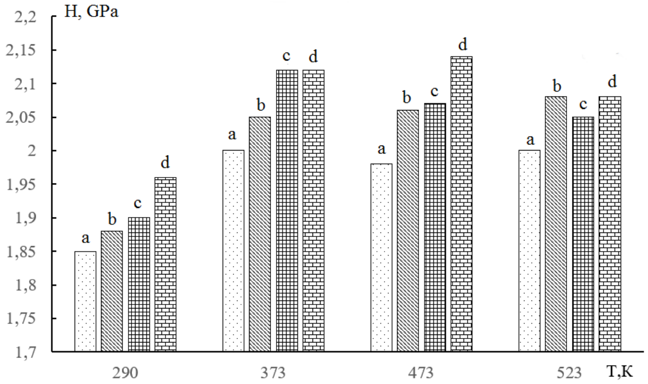
According to modern concepts, the application of surfactants to the surface of a polycrystal leads to a decrease in strength. This strength-reducing effect (meaning the external adsorption effect, when volume diffusion and corrosion phenomena do not occur) is caused by the facilitation of dislocation emergence at the surface of the deformation crystal as a result of a decrease in the surface energy of the solid during surfactant adsorption [4–6]. This effect is widely used in the plastic deformation of metals. However, in a number of cases, when treating crystals with surfactants based on fluorine-containing oligomers, an increase in the microhardness and strength of metals is observed [4, 6, 7].

The aim of the work was to study the strength properties of polycrystals modified with surfactants based on fluorine-containing oligomers, including when exposed to energy factors.

**Study methodology and some results**

The following metals were used as a substrate: copper (M1); steel 45; aluminum (Al 99); titanium nitride. Fluorine-containing oligomers with the trade name "Foleox" were used as surfactants; their structural formula is $R_F$ – COOH (F1); $R_F$ – CONHR $_1$ (F-AK1); $R_F$ – $R_F$ (F14) (where $R_F$ is a fluorine-containing radical), $R_F$ – CONHR $_2$ (F-AK2), B 1 – water-soluble foleox. The coatings were applied by dipping the substrate in a 1–2 % solution of fluorine-containing oligomer in freon 113, followed by drying in air. Heat treatment of metals with a FSO coating was carried out in air for 1 hour at T = 373 K; 473 K; 573 K. Irradiation was carried out on a URS – 1,0 setup at a voltage of 40 kV and a current of 20 $\mu$A on a molybdenum anode (wavelength K $_\alpha$ = 0,7 (A)). The irradiation time was varied from 0 to 60 min. The morphology of the FSO film was examined on an NT 206 atomic force microscope. Microhardness was measured on. The structure of the boundary layers was studied by IR spectroscopy (AFR).

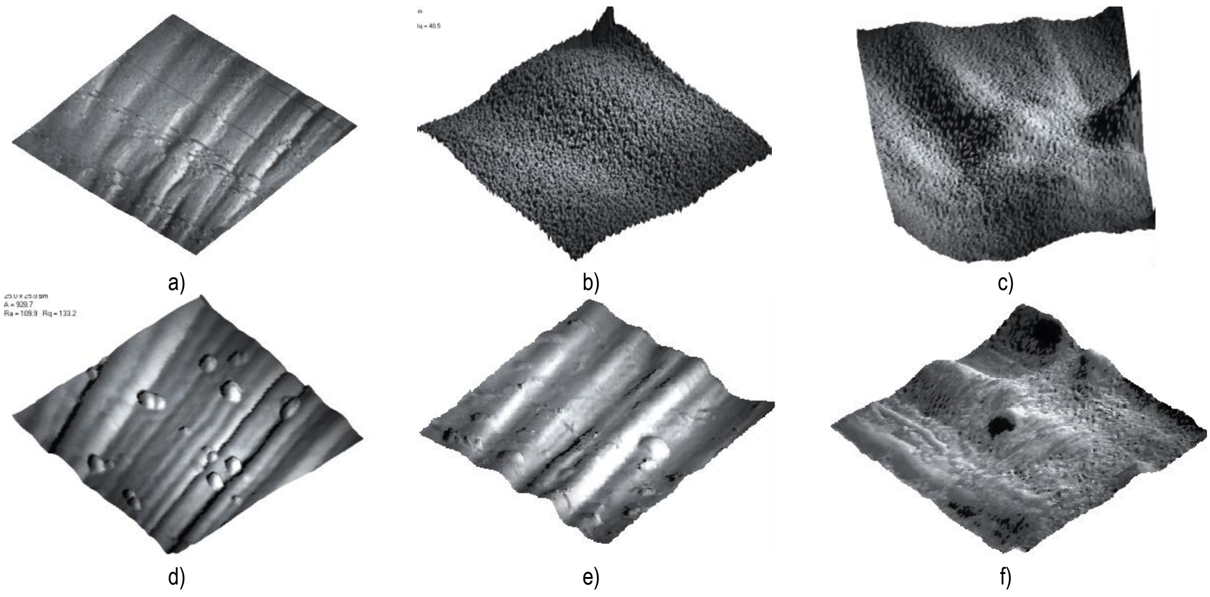
Figure 1 shows the dependence of the microhardness of a steel substrate treated with different grades of fluorine-containing oligomers on the heat treatment mode. The application of fluorine-containing oligomers in all cases leads to an increase in the microhardness values. This can be explained by the process of chemisorption of polar molecules on the surface of the steel substrate, which results in the healing of microdefects in the surface layers of polycrystals and an increase in the free energy of the surface layers of the metal, which hinders the emergence of dislocations on the surface [6]. Chemisorption of these grades of foleoxes on the metal surface is confirmed by the appearance of an absorption band in the IR spectrum in the region of 1610–1690 cm$^{-1}$, which is identified as the absorption band belonging to the metal salts $(COO)_2$ Me, Me $(NH_2)$, Me $(NH_3)$ [7].




a – steel 45; b – steel 45 + B1; c – steel 45 + FAK-2; d – steel 45 + F14

**Figure 1** – Dependence of the microhardness of steel treated with fluorine-containing oligomers on the heat treatment mode

The optical density of the absorption band depends on the grade of foleox used, i. e., on its structure. Heat treatment leads to a further increase in microhardness values. As a result of energy exposure, crystallization processes occur in thin-layer composite coatings (Figure 2), which may explain the effect of increased microhardness values [8–11].




a – original steel substrate; b – steel substrate + Folekos F1; c – steel substrate + Folekos F1, heat treatment at 473 K for 1 hour;
d – steel substrate + Folekos F1, heat treatment at 573 K for 1 hour; e – steel substrate + Folekos F1, X – ray irradiation for 15 minutes;
f – steel substrate + Folekos F1, X – ray irradiation for 60 minutes (scanning area 12 × 12 µm)

**Figure 2** – Morphology of oligomer films on metals depending on the energy treatment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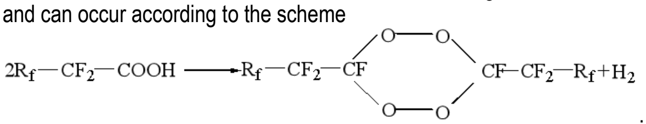
Foleoxes F1 and F14 are fluorine-containing compounds containing chemically active groups: COOH (F1) and CF2 = CF (F14). Exposure of FSO to radiation results in noticeable changes in both the ATR and external reflectance spectra, with the difference that the changes in the ATR spectra are more significant. This indicates that, although the process affects the entire volume of the FSO, it is diffusion-controlled and is apparently related to the action of atmospheric oxygen [12–14].

Qualitatively, the spectral changes are expressed in a decrease in the optical density of the absorption bands at 980 and 1280 $cm^{-1}$, an increase in the optical density at 1340 $cm^{-1}$, and the appearance of additional peaks in the region of wavenumbers of 1600-1900 $cm^{-1}$. In the F1 spectra, there is a decrease in the optical density of the 1640 $cm^{-1}$ band with the simultaneous appearance of absorption bands at about 1720 and 1780 $cm^{-1}$, which can be attributed to C = O bonds in organofluorine compounds.

Irradiation of Foleox F1 on an aluminum substrate leads to the appearance of absorption bands in the ATR and BO spectra in the region of 1700–1800, 1870–1900 $cm^{-1}$, which can be attributed to peroxide and hydroperoxide groups [15–17].

Transformations of this kind are characteristic of organofluorine acids and can occur according to the scheme




Based on the properties of fluorinated acids, oxidation under the influence of oxygen promotes the formation of free radicals, which leads to the formation of peroxy acids $R_F$ – COOH ® RCOOOH.

Another possible process under these conditions may be decarboxylation with the formation of unsaturated compounds:

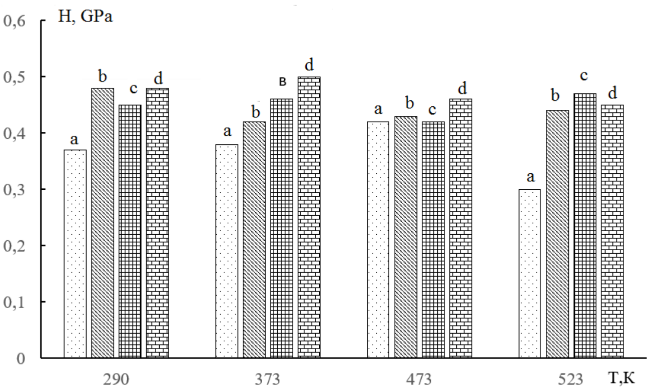
$$R_F\text{–COOH ® } R_f\text{– CF}_2\text{H + CO}_2$$
$$R_f\text{–CF}_2\text{H ® } R_f\text{– CF +HF}$$
$$R_f\text{–CF + } R_2\text{– CF ® } R_f\text{– CF = CF – } R_2.$$

Unsaturated compounds are capable of reacting with peroxyacids to form cross-linked structures. The appearance of absorption bands at 1700–1800 $cm^{-1}$ in the spectra is consistent with the proposed mechanism.

It is obvious that transformations of this kind must be carried out with the participation of the substrate as a catalyst. It is known that copper and iron are capable of forming carboxyl binuclear complexes with metal-metal bonds, which are catalysts for many transformations. The absorption bands at 1540–1670 $cm^{-1}$ correspond to the absorptions of the carboxyl groups COO – in complex compounds with Al, Cu and Fe.

Irradiation of F1 deposited on a copper substrate leads to a decrease in the intensity of the absorption band at 1660 $cm^{-1}$ with a simultaneous increase in absorption in the region of 1520–1600 $cm^{-1}$ [18, 19].

Irradiation of FSO grade F1 film on an iron sample leads to increased unsaturation and, with longer exposure times, to oxidative processes. The orientation of CF and CF2 bonds is perpendicular to the substrate plane, while the C–C bonds are parallel to the substrate. The C–O bonds formed as a result of irradiation are oriented perpendicular to the substrate. With increasing irradiation time, the orientation increases for both F1 and F14 [20].

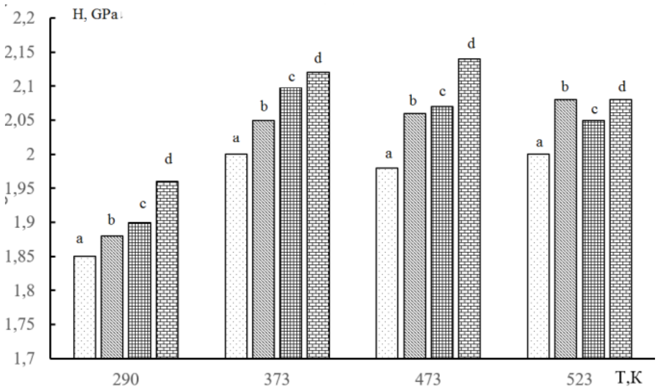



a – aluminum + FAK-2; b – aluminum + F14; c – aluminum; d – aluminum + B1

**Figure 3** – Dependence of the microhardness of aluminum treated with fluorine-containing oligomers on the heat treatment mode

At temperatures above 523 K, ~destructive processes occur in fluorine-containing oligomer films, resulting in film desorption from the metal surface and a consequent reduction in microhardness. Applying fluorine-containing oligomers to an aluminum substrate sometimes leads to a decrease in microhardness (Figure 3).

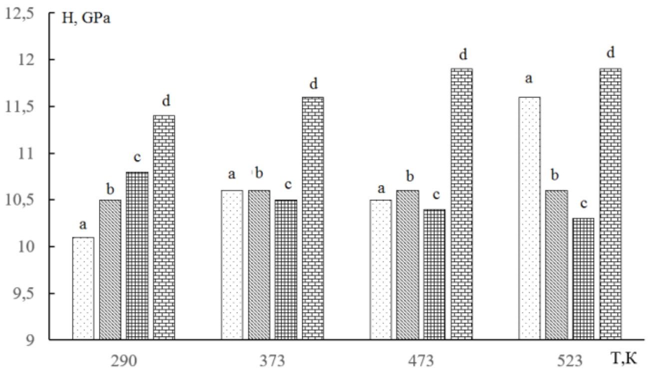
IR spectroscopy studies of the structure of fluorine-containing oligomer films revealed that chemisorption bonds do not form upon application of fluorine-containing oligomers, resulting in the Rehbinder effect. Heat treatment induces crystallization processes in thin fluorine-containing oligomer films. Figures 4 and 5 show the microhardness curves for copper and titanium nitride substrates treated with various grades of fluorine-containing oligomers. As in the previous cases, an increase in microhardness is observed when chemisorption bonds form between fluorine-containing oligomer molecules and the substrate. If this process does not occur, plasticization of the polycrystal is observed. Heat treatment virtually always leads to an increase in microhardness.




a – copper, b – copper+FAK2; 3 – copper+F1; 4 – copper+B1

**Figure 4** – Dependence of the microhardness of copper treated with fluorine-containing oligomers on the heat treatment mode

Another mechanism explaining the increased microhardness of polycrystals may be that oligomer molecules "flow" into the indentation after the indenter is removed from the test material. This results in a decrease in the indentation diagonal and, consequently, an increase in microhardness. Studies have shown that this effect has virtually no effect on microhardness measurements.




a – titanium nitride + fluoroplastic; b – titanium nitride + FAK2; b – titanium nitride + F14; g – titanium nitride + FAK1, titanium nitride + F1

**Figure 5** – Dependence of the microhardness of titanium nitride treated with fluorine-containing oligomers on the heat treatment mode

According to classical concepts, the application of surfactants to metal surfaces should lead to the implementation of the Rehbinder effect [9].

Typically, two types of the Rehbinder effect are distinguished: 1) external and 2) internal. The external Rehbinder effect consists in the fact that upon adsorption of surface-active substances (surfactants), the free energy of solids decreases. This reduces the resistance of the surface layer of the solid to plastic deformation, facilitates plastic flow in grains and the emergence of dislocations to the surface [9]. The upper layer of the metal may have lower microhardness than the underlying layers saturated with dislocations. The internal Rehbinder effect (adsorption-wedging) is realized during the adsorption of molecules on the surfaces of cracks occurring in the surface layer of the solid. The active centers of the molecules reach an area whose size is less than two sizes of the molecules, the latter, attracted by the crack walls and experiencing the pressure of neighboring molecules, tend to wedge it. This phenomenon contributes to the destruction of the modified surface layer. However, in the works [10–13] it was shown that the application of surfactants such as fluorine-containing oligomers to metal substrates in a number of cases leads to strengthening of the surface layers of the material and the Rebinder effect does not appear.

The application of fluorine-containing oligomers to metals results in the formation of nanophase composite materials that exhibit an electret state, as evidenced by the presence of conduction current values ranging from |1–5| pA under normal experimental conditions. It was found that increasing the thickness of the fluorine-containing oligomer coating leads to a decrease in conduction current values, which is explained by the shielding effect of the fluorine-containing oligomer coating on the charge mosaic of solid surfaces. However, exceeding the thickness of the fluorine-containing coating on a metal surface above 1,0–1,2 µm reduces the shielding effect due to disordering in the boundary layers of the coating. The charge activity of the metal substrate significantly influences the activity of the resulting fluorine-containing coating. The presence of picoampere currents in coatings formed from non-polar fluorine-containing oligomers was established, with these currents exceeding those generated in coatings formed from polar oligomers. This effect can be explained by the fact that chemisorption of polar fluorine-containing oligomers most likely occurs primarily at the active (charge) centers of the metal surface. Changes in thermally stimulated currents in coatings formed from non-polar oligomers on a metal substrate are virtually independent of the coating thickness when the metal surface is treated with fluorine-containing oligomers more than twice. Coatings formed from a combination of polar and non-polar oligomers produce protective layers that combine high chemical adsorption activity provided by the polar oligomer with a surface layer formed from a non-polar oligomer with low shear strength. These coatings exhibit a high shielding effect on the charge surface of the solid.

**Conclusions**

Fluorinated oligomers strengthen the surface layers of the substrate if chemical (chemisorption) bonds, such as salts of higher acids, are formed between the film. A fluorine-containing oligomer and a metal (substrate) are combined. If chemisorption interactions between the oligomer molecules and the substrate do not occur, plasticization of the surface layers of the polycrystals occurs. Energy treatment intensifies crystal formation processes in thin films, resulting in increased microhardness of the thin-film composite coating. These coatings are recommended for friction units of construction equipment operating in harsh conditions.

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# DEVELOPMENT OF LEAD-FREE PIEZOCERAMICS WITH APPLICATION OF ULTRASONIC VIBRATIONS

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**Abstract**

The development of lead-free ferroelectric materials is an important task due to the restrictions on the use of lead in industry enacted in a number of European countries, the United States, and Japan (Directive 2011/65/EU of the European Parliament). In the Republic of Belarus, a technical regulation TR EAEU 037/2016 has been in effect since 2018, established by the EAEU member states. This technical regulation sets down requirements for the restriction of the use of hazardous substances in electrotechnical and radio-electronic products.

The bismuth sodium titanate solid solution system Na0.5Bi0.5TiO3 (NBT) is considered one of the promising materials for practical application, despite its characteristics being inferior to those of the classical PZT-system. The application of ultrasonic vibrations during the synthesis of PZT-ceramics suggests that ultrasound at different stages of the production of NBT-based piezoceramics could also enhance its physical and mechanical properties.

This work presents the results on the influence of ultrasonic vibrations during mechanoactivation and pressing on the properties of lead-free piezoceramics of the NBT type. It has been shown that applying ultrasonic vibrations during mechanoactivation and pressing leads to the grinding of the initial powder, allowing the obtaining of denser homogeneous ceramics, preventing the formation of microcracks during sintering, reducing the sintering temperature by ~60° C, increasing the Curie temperature by 50–60° C, and increasing the dielectric constant. Ceramics produced with ultrasound is characterized by high electromechanical anisotropy (d33/d31), which is important for practical applications when it is necessary to excite certain vibration modes. The obtained results will serve as a basis for further development of the scientific field of ultrasonic mechanoactivation and pressing of piezoceramic powders.

**Keywords:** piezoceramics, ultrasound, ultrasonic mechanoactivation, sodium bismuth titanate, ultrasonic pressing.

## ПОЛУЧЕНИЕ БЕССВИНЦОВОЙ ПЬЕЗОКЕРАМИКИ С ПРИМЕНЕНИЕМ УЛЬТРАЗВУКОВЫХ КОЛЕБАНИЙ

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**Реферат**

Разработка сегнетоэлектрических материалов, не содержащих свинец, является актуальной задачей, что обусловлено ограничениями по использованию свинца в промышленности, принятыми в ряде Европейских стран, США и Японии (директива Европарламента 2011/65/EU). В Республике Беларусь с 2018 г. действует технический регламент ТР ЕАЭС 037/2016, разработанный странами, входящими в Таможенный союз, который запрещает использование токсичных элементов в радиоэлектронной промышленности.

Система твердых растворов титаната-натрия-висмута Na0.5Bi0.5TiO3 (NBT) считается одной из перспективных в плане практического применения несмотря на то, что по своим характеристикам она уступает классической PZT-системе. Результаты применения ультразвуковых колебаний в процессе синтеза PZT-керамики позволяют предположить, что применение ультразвука на различных этапах производства пьезокерамики на основе NBT способно также улучшить ее физико-механические свойства.

В данной работе показано влияние ультразвуковых колебаний на этапах механоактивации и прессования на свойства бессвинцовой пьезокерамики типа NBT. Установлено, что ультразвуковая механоактивация и прессование с наложением ультразвуковых колебаний приводит к измельчению исходного порошка, что позволяет получать более плотную однородную керамику, предотвратить образование микротрещин при спекании, снизить температуру спекания на ~60 °С и повысить температуру Кюри на 50–60 °С, увеличить диэлектрическую проницаемость. Для керамики, полученной с применением ультразвука, характерна высокая электромеханическая анизотропия (d33/d31), что важно для практического применения, когда необходимо возбуждать определенные моды колебаний. Полученные результаты послужат основой для дальнейшего развития научного направления ультразвуковой механоактивации и прессования пьезокерамических порошков.

**Ключевые слова:** пьезокерамика, ультразвук, ультразвуковая механоактивация, титанат натрия висмута, прессование с ультразвуком.

**Introduction**

A study [1] on the compaction of structural zirconia ceramics using ultrasonic compaction demonstrated the possibility of obtaining products with high strength characteristics, which are established at the stage of producing press blanks from ultrafine powders. This significantly reduces the influence of powder characteristics such as bulk density, flowability, formability, and compactibility without the use of lubricants and binding additives. Studies on the ultrasonic pressing of ferroelectric and


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piezoelectric ceramic powders [2–6] also demonstrated that the finished products have higher density and improved physical and mechanical properties compared to those obtained using traditional technology.

The traditional method of compacting powdered parts in a metal mold [7] involves loading the powder into a die and compacting it by applying high static pressure. A disadvantage of this method is the highly uneven distribution of mechanical stresses throughout the volume, which can lead to subsequent failure of the pressed or sintered part. To increase static pressure on powders of hard and brittle materials causes high elastic stresses at the contact points between particles and brittle fracture in these areas when the pressure is released that makes it impossible to form large parts with complex geometric shapes. The use of plasticizers does not completely solve the problem due to the formation of a significant number of pores when the powder burns out during sintering.

One effective method for modifying the properties of ceramic materials is the use of powerful ultrasonic vibrations at different stages of their production: ultrasonic mechanoactivation of powder, pressing, and synthesis. Ultrasonic mechanoactivation is based on the phenomenon of acoustic cavitation – formation and collapse of cavities in a liquid medium being subjected to ultrasonic waves. In this process, particles and their powder aggregates are crushed as a result of repeated exposure to pulsed loads caused by the collapse of cavitation bubbles. Furthermore, grinding is possible due to the collision of powder particles during their random movement under the influence of ultrasonic vibrations. Due to mechanoactivation the sintering temperature of the processed powder decreases, the mechanical properties improve (reduced porosity, increased strength, improved plastic properties), and reactivity increases [8–11].

In ultrasonic powder pressing, high-power ultrasound is typically applied to the powder using a punch or a die via the entire compaction cycle or by applying a certain pressure from the beginning of the process. The principle of ultrasonic pressing is that through the periodic application of ultrasonic vibrations with an amplitude comparable to the size of particles or their agglomerates, the overall stress in the deformed powder material is uniformly redistributed and relaxes within the compact due to the uniform distribution of powder particles. When pressing with ultrasonic vibrations, the pressure distribution within the compact becomes more uniform due to both reduced wall friction and reduced interparticle friction, resulting in denser particle packing and an increased density of the pressed blank. Furthermore, the use of ultrasound during pressing results in the healing of small pores and a reduction in the number and size of large pores [12].

Thus, a major advantage of using ultrasound in the process of pressing is to produce compacts without a mechanical stress gradient, as otherwise, subsequent operations will result in product failure due to the formation of delamination cracks. Reducing pressing pressure is generally not considered the primary advantage of using ultrasonic vibrations. Firstly, the application of ultrasonic vibrations requires additional energy consumption. Secondly, higher compact density can be achieved, and is much easier, by increasing pressure. However, pressure can be increased up to a certain optimal value. For example, for barium titanate, this value is 30÷70 MPa [12]. Exceeding the optimal pressure causes cracking. This is because, as pressing pressure increases, the elastic force causing cracking increase proportionally to the pressure, while the strength of the compact increases only slightly. As a result, when pressing pressure reaches a certain value, the destructive elastic strength exceeds the strength of the compacts, and cracks appear in the pressed product.

Based on the described physical laws of the pressing process, it is proposed [13] to initially press to the optimal pressure value without applying ultrasonic vibrations. Then, to relieve uneven mechanical stress in the sample, apply ultrasonic vibrations to the compacted mass in a static state under the optimal fixed pressure.

Applying ultrasonic vibrations to the pressed powder for less than one second is ineffective, since the energy of ultrasonic vibrations in this case is insufficient to relieve the uneven distribution of mechanical stress that arises during the pressing process. The application of ultrasound for 2–5 s leads to complete equalization of stresses throughout the entire volume of the pressed product. Increasing the ultrasonic exposure time beyond 5 s does not improve the quality of the pressed product and reduces the service life of the press mold [13].

Employing rotational movements in the press tooling (matrix and punch) can enhance the quality of press blanks. The analysis of the dependence of powder density on pressing pressure for barium titanate showed that the application of ultrasonic vibrations increases the density of samples obtained at the same pressure. This difference is particularly significant at low pressure.

Studies of the compaction process of $BaTiO_3$ powder using holographic interferometry methods revealed that at the initial stage of pressing without ultrasonic vibrations, compaction occurs in a limited area near the upper punch and then extends to the middle and lower parts of the compact. As the compaction density increases, particle motion becomes more orderly, and slippage decreases. When pressing with ultrasound, the powder undergoes the same compaction stages as without ultrasound vibrations and, when it reaches a state of density, behaves as a monolithic body. However, when pressing with ultrasound at lower pressures, the powder reaches a state where the particles begin to move in a regulated manner, reducing contact friction forces between the powder particles and between the powder and the die walls, providing the desired density with lower static stress [14].

The aim of this work is to study the influence of ultrasonic vibrations on the physical and mechanical properties NBT – NBT-BT based piezoceramics.

**Experimental procedure**

Ultrasonic mechanoactivation of powder can be achieved using an immersible sonotrode or by exciting vibrations in a container (cup) where the powder is loaded (Figure 3). Powder processing can be performed dry, i.e., without pouring it into a liquid medium, or by placing the powder in a liquid in which ultrasonic vibrations are excited. In the first case, the physics of the process are similar to powder processing in planetary mills. In the second case, mechanoactivation and crushing of powder agglomerates occur through ultrasonic dispersion in a liquid medium due to cavitation and ultrasonic flows. Moreover, the efficiency of ultrasonic processing is significantly increased if the process is carried out under excess hydrostatic pressure (Figure 2). Excess hydrostatic pressure in a process medium was created using a compressor.

Two acoustic schemes were used for pressing the synthesized powder with the application of ultrasonic vibrations: the half-wave and quarter-wave reflectors (Figure 4). The first scheme (Figure 4a) is convenient because the amplitude of displacements at the end of the half-wave reflector can be seen to estimate the amplitude of vibrations in the powder deformation (compacting) zone. A laboratory setup was designed and built for these schemes using a UZDN-2T generator with a power of 0.4 kW, a frequency of ~22 kHz, and a manual hydraulic press with a force of 35 kPa. This setup was used to test the compaction tests.

The charge was prepared from $Na_2CO_3$, $TiO_2$ and $Bi_2O_3$ powders. Mixing was performed in a jasper mortar using alcohol. The powder was then pressed into briquettes of 20 mm in diameter and 10 mm in height for subsequent synthesis. The synthesis temperature was 800–850 °C, and the synthesis time was 5 hours: a 3-hour temperature rise and a 2-hour hold. To minimize deviations from the calculated stoichiometric composition due to evaporation of volatile oxides, the synthesis was carried out in a closed crucible with a backfill of powder of the same composition. Samples of composition (1-x) NBT – xBT, where x = 0,1; 0,12, were obtained using a similar technology.

The X-ray diffraction pattern of the obtained compound (Figure 1) showed a typical perovskite structure [15], as a confirmation of a successful synthesis.

The synthesized briquettes were ground using a mortar. The stoichiometric mixtures of the initial NBT and NBT – BT powders obtained after synthesis were then subjected to ultrasonic mechanoactivation using a 2 kW ultrasonic generator operating at a frequency of ~22 kHz in distilled water for 30 minutes (Figures 2, 3).

For ultrasonic pressing of the synthesized powder we used a 0,4-kW generator with a frequency of ~22 kHz and a manual hydraulic press (Figures 4, 5). The pressing force was 35 kPa.

The obtained press blanks were sintered in a closed crucible at 1150 °C for 5 hours. Then the end surfaces of the samples were ground to ensure flatness and parallelism for subsequent application of conductive coatings and dielectric measurements. Electrodes were applied by firing silver paste using a standard method at 800 °C. The dielectric measurements were carried out using an E7-20 immittance meter at a frequency of 1 kHz.

The study of granulometric composition of powders was analyzed using the Malvern Mastersizer 2000 laser analyzer (Malvern Instruments Ltd., Malvern, UK) in the range of 0,02–2000 μm according to the standard method.

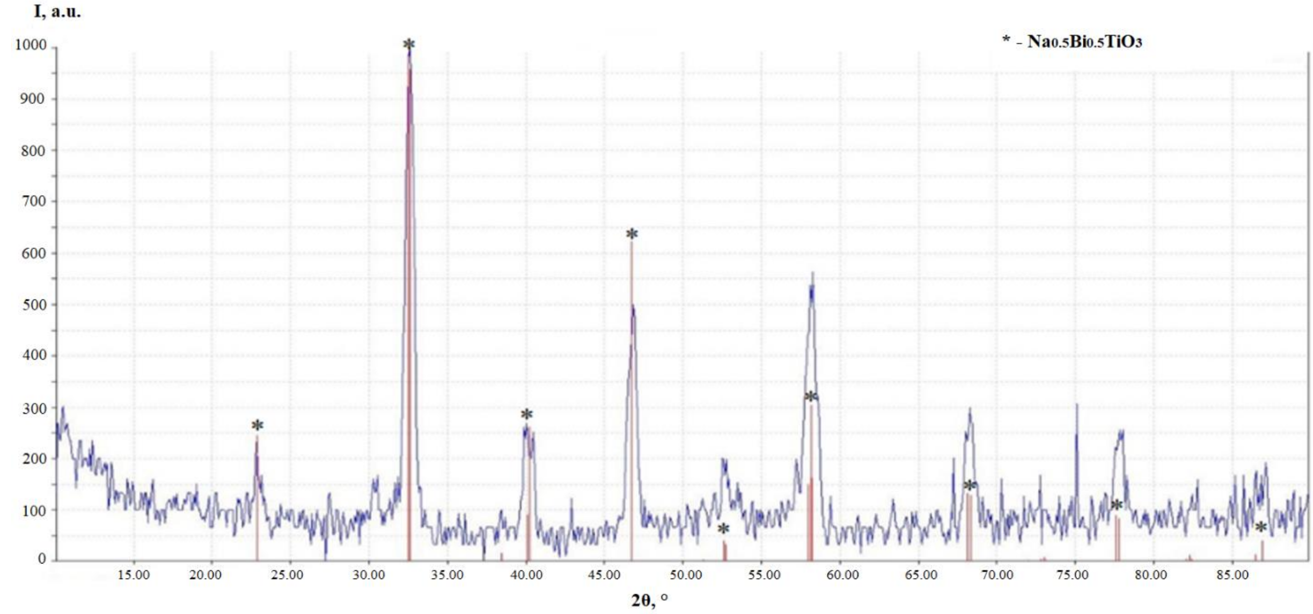
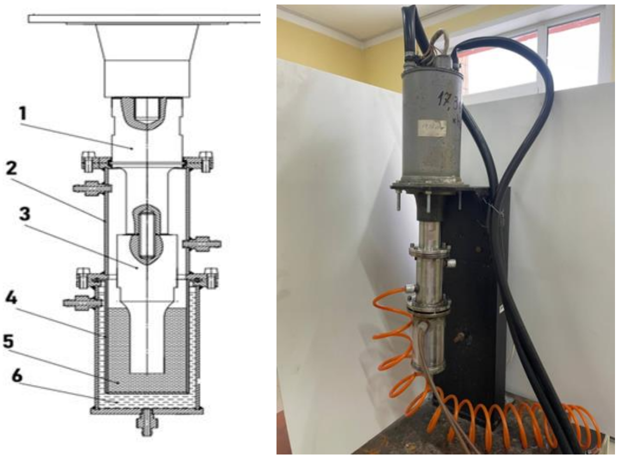
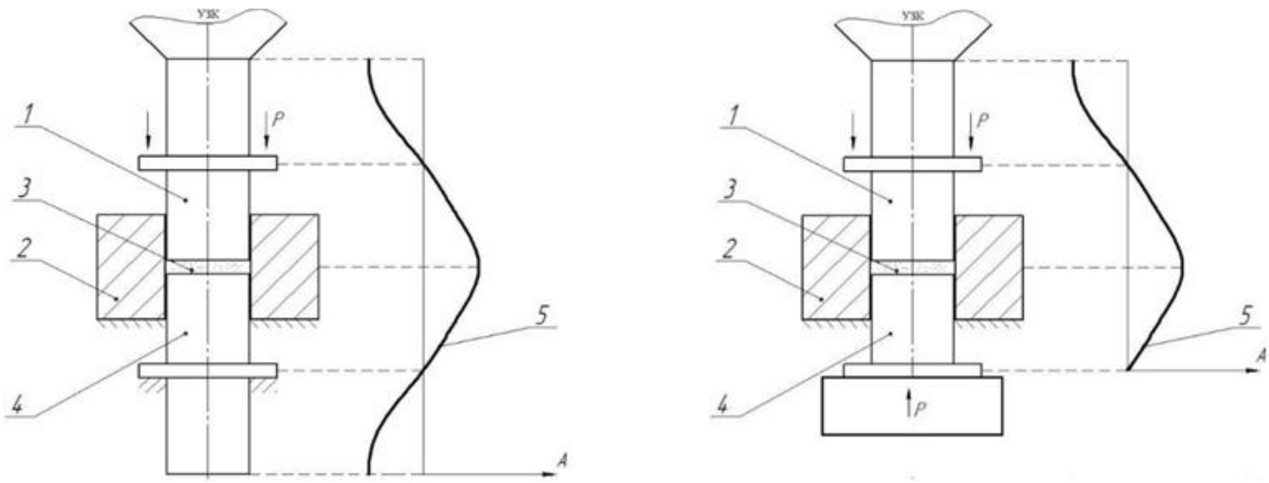



**Figure 1** – X-ray diffraction pattern of the studied NBT (*– peaks of the standard substance from the database)




1 – booster; 2 – reactor chamber body; 3 – waveguide; 4 – glass;
5 – processed medium; 6 – cooling liquid
**Figure 2** – Scheme and acoustic unit for ultrasonic mechanoactivation of powders:

**Figure 3** – Laboratory setup for ultrasonic mechanoactivation




a) b)

1 – half-wave waveguide-punch; 2 – matrix; 3 – powder; 4 – reflector; 5 – diagram of mechanical displacements
**Figure 4** – Schematic diagram of an acoustic unit with a half-wave (a) and quarter-wave-reflector (b) for ultrasonic pressing of powder

**Figure 5** – Experimental setup for ultrasonic powder pressing

**Results and discussion**

The results of particle size analysis (Figures 6 and 7) showed that the ultrasonically treated powder reduced particle agglomeration and improved particle size. Thus, while the average particle size of the original powder was 67,5 μm, the average particle size after ultrasonic treatment was 5,7 μm.

Figure 8 shows pictures of powder before and after ultrasonic mechanoactivation.

At the next stage we studied the microstructure of sintered press blanks obtained both without the application of ultrasonic vibrations and with ultrasonic vibrations.

The ultrasonic-assisted pressing process leads to a reduction in the number of large pores and a more uniform structure of the press blank (Figure 9). Usually, the grain-size, grain orientation and porosity, can strongly affect the domain structure and polarization switching behavior [16–18].

Measurement of the permittivity showed that the application of ultrasonic vibrations at different stages of the synthesis of NBT-based piezoceramics leads to an increase in the permittivity (Figure 10). Curves are strongly frequency-dependent, which is characteristic of a relaxor-like behavior [19], potentially arising from disordered polar regions [20].

The permittivity increased for samples of each composition obtained using ultrasonic vibrations. The maximum increase in permittivity was observed for the composition with x = 0,12. The increase in the dielectric loss tangent values for the samples subjected to ultrasonic vibrations was observed compared to those for the samples obtained using a standard technology. However, in the temperature range from 370 to 400 °C, the tangent values for the composition with x = 0,12 obtained using ultrasonic vibrations were lower than those for the samples of the same composition obtained using a standard technology (Figure 11).

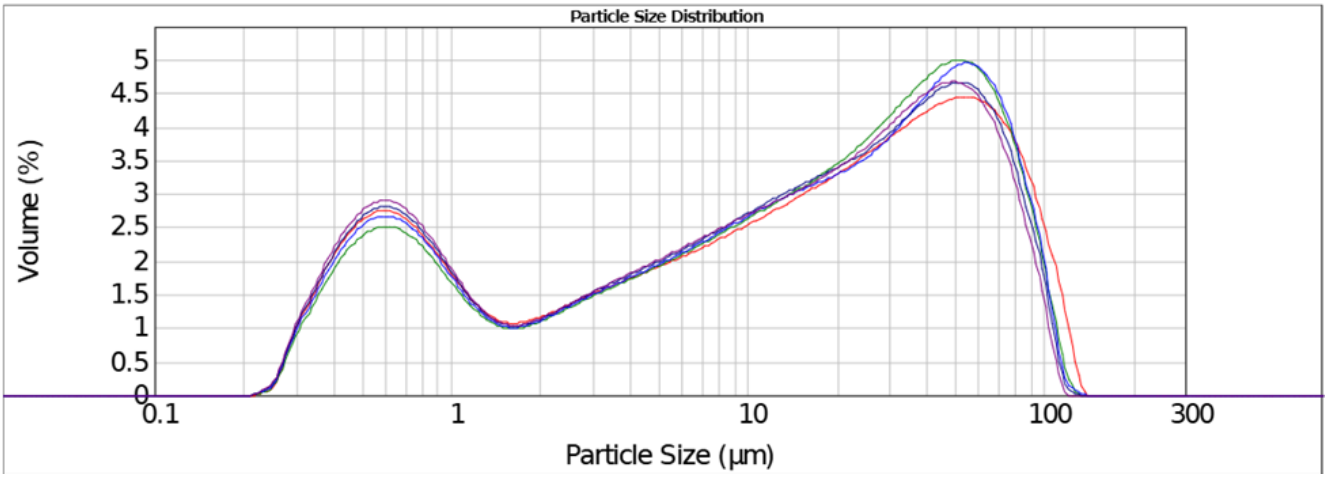



**Figure 6** – Particle size distribution of the initial powder

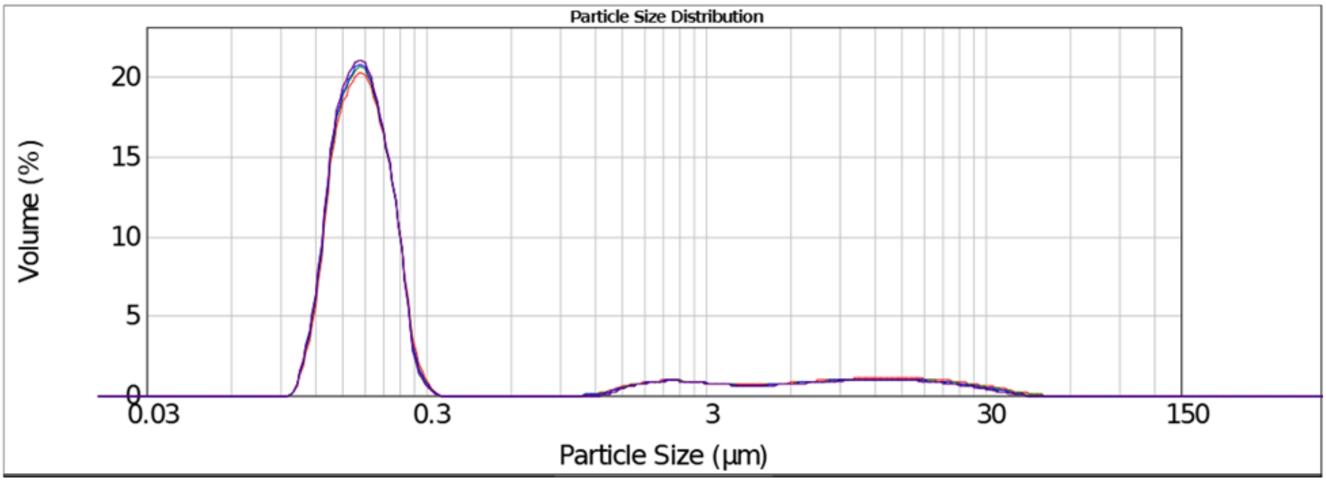
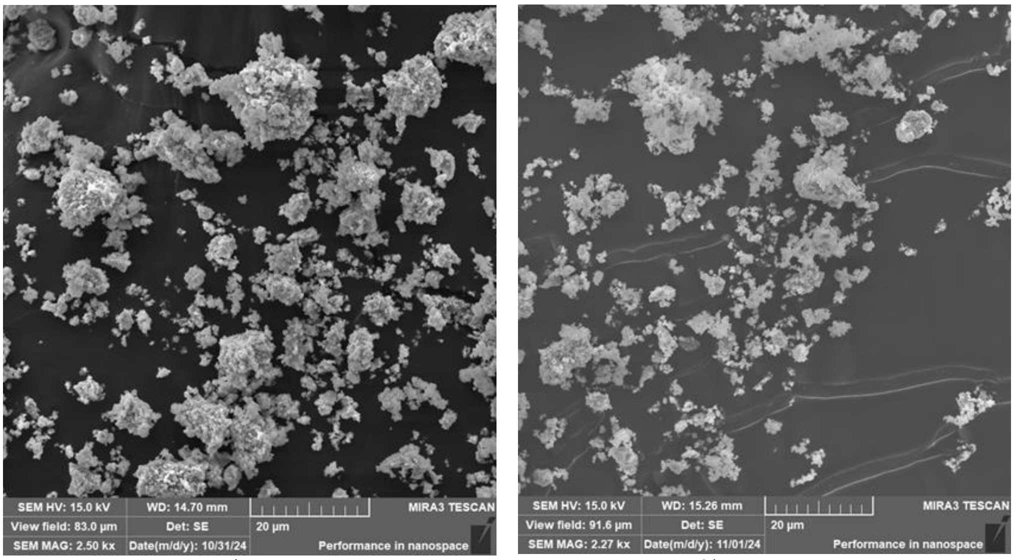
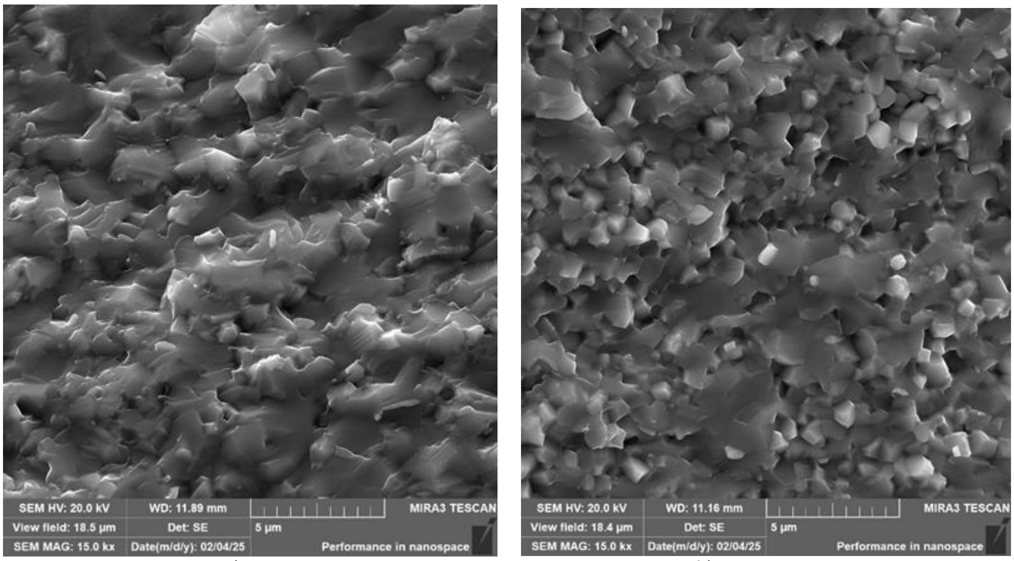



**Figure 7** – Particle size distribution of powder after ultrasonic mechanoactivation

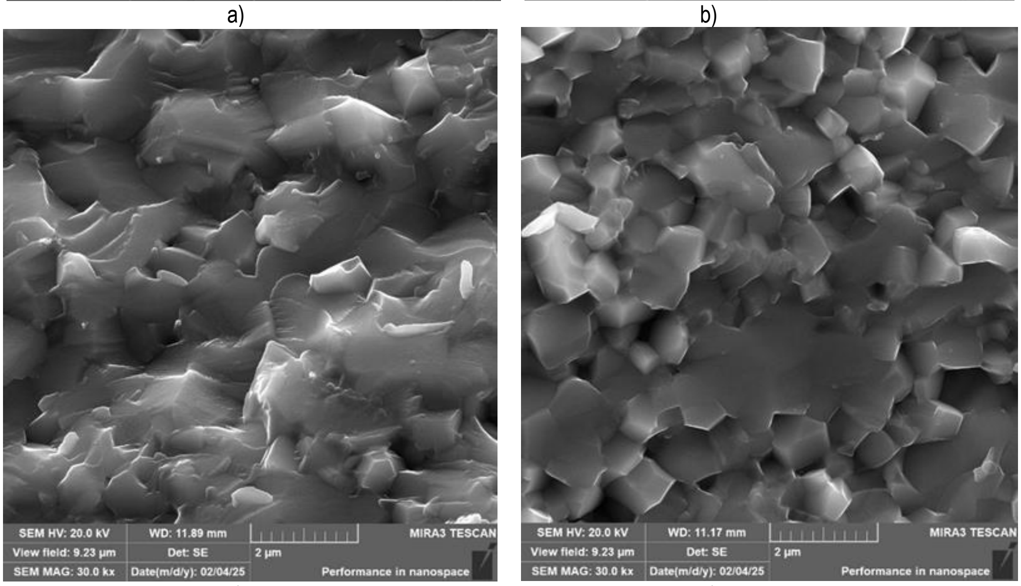



a) b)

**Figure 8** – Pictures of the initial powder (a) and after ultrasonic mechanoactivation (b)




a) b)




c) d)

**Figure 9** – Microstructure of the sintered press blank obtained without the application of ultrasound (a, c) and obtained using ultrasound (b, d)

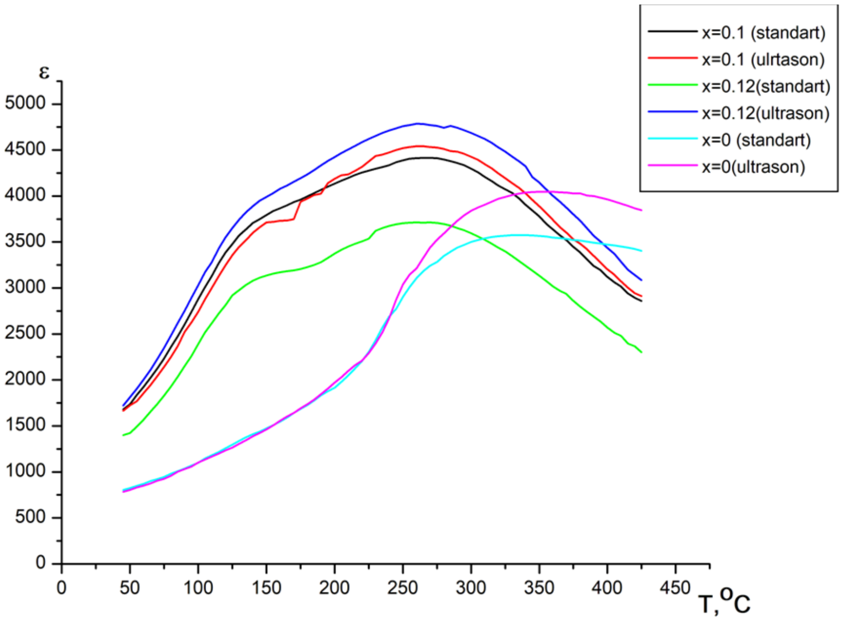



**Figure 10** – Temperature dependence of dielectric constant ε

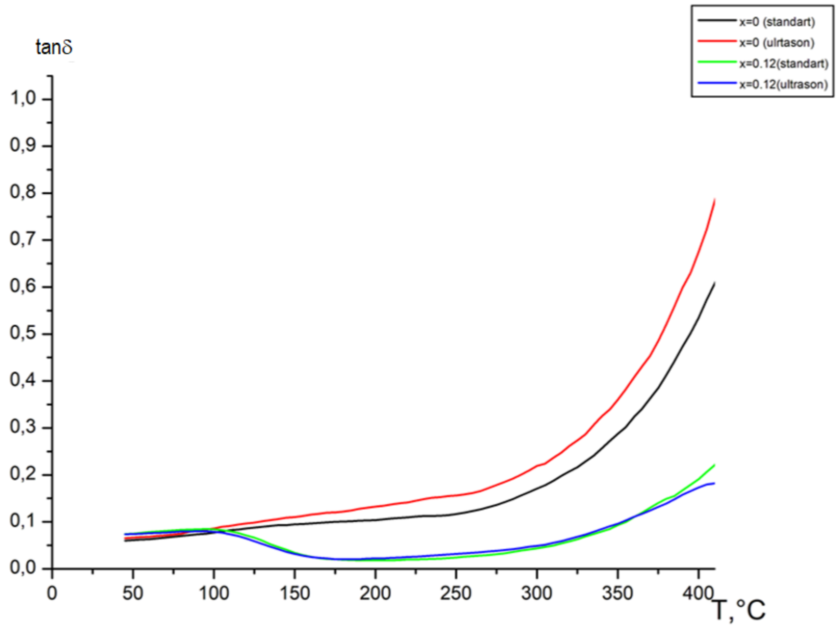



**Figure 11** – Temperature dependence of the dielectric loss tangent

**Conclusion**

The application of ultrasonic vibrations during mechanoactivation and pressing of the synthesized powder of NBT-based piezoceramics provides the obtaining of denser homogeneous ceramics, preventing the formation of microcracks during sintering, reducing the sintering temperature by ~60 °C, increasing the Curie temperature by 50–60 °C, and increasing the dielectric constant. Ceramics produced with ultrasound is characterized by high electromechanical anisotropy (d33/d31), which is important for practical applications when it is necessary to excite certain vibration modes. The obtained results will serve as a basis for further development of the scientific field of ultrasonic mechanoactivation and pressing of piezoceramic powders.

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**GEOECOLOGY**

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# ELEMENTAL COMPOSITION OF INDIVIDUAL PHOSPHOGYPSUM FRACTIONS AFTER DRYING IN A FLASH DRYER

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**Abstract**

This paper demonstrates for the first time that individual fractions of phosphogypsum dried in a flash-drying system to a residual sorption moisture content of 0.01–0.03% have different contents of individual elements. Drying waste phosphogypsum in the described drying system produces highly dispersed products, eliminating the costly milling of the phosphogypsum after drying. The particle size of the dried product corresponds to the size of the phosphogypsum crystals formed in the baths during phosphoric acid extraction. Fractions with the required impurity content can be separated from the powder obtained after drying the waste phosphogypsum using a mechanical sieve analyzer. Thus, fractions of 0.050–0.045 mm (0.045 sieve residue), 0.140–0.090 mm (0.100 and 0.090 sieve residue), as well as dried material from the cyclone, bag filters, and the original waste phosphogypsum, were analyzed for the content of individual elements using X-ray fluorescence analysis. It was found that the content of certain rare earth elements and strontium in the finely dispersed product (obtained from the filters) increased by more than twofold compared to the original waste phosphogypsum, while the content of elements such as cerium, lanthanum, and lutetium increased by up to fourfold. The results of the studies showed that the 0.140–0.090 mm fraction (residue on 0.100+0.090 sieves) has significantly reduced amounts of individual elements compared to both the original waste phosphogypsum and the dried product collected from the cyclone. Specifically, the 0.140–0.090 mm fraction has reduced the content of the following elements (in terms of their oxides): barium (more than 17 times), iron (up to 10 times), titanium (up to 7 times), etc. The 0.140–0.090 mm fraction also lacks the following elements: potassium, nickel, silicon, germanium, selenium, palladium, indium, erbium, lutetium, hafnium, tantalum, and mercury. This suggests that the 0.140–0.090 mm fraction does not contain elemental compounds that limit its use in building materials and can be used as a substitute for natural gypsum. Furthermore, the increased REE content allows the filter product to be considered a REE concentrate, with the potential to utilize numerous developed "wet" technologies for their extraction.

**Keywords:** phosphogypsum, phosphogypsum fractions, chemical composition, elemental oxides, X-ray fluorescence analysis, microscopy.

## ЭЛЕМЕНТНЫЙ СОСТАВ ОТДЕЛЬНЫХ ФРАКЦИЙ ФОСФОГИПСА ПОСЛЕ СУШКИ НА ФЛЭШ-СУШИЛКЕ

**О. Г. Горовых, А. В. Волосач**

**Реферат**

Впервые показано, что отдельные фракции фосфогипса, высушенного в сушильном комплексе с флэш-сушилкой до остаточной сорбционной влажности 0,01–0,03 %, имеют различное содержание отдельных элементов. Сушка отвального фосфогипса на описываемом сушильном комплексе обеспечивает получение высокодисперсных продуктов, использование которых позволяет исключить дорогостоящую операцию помола фосфогипса после сушки. Величина частиц в высушенном продукте соответствует величине кристаллов фосфогипса, формирующихся в ваннах при экстракции фосфорной кислоты. Из порошка, полученного после сушки отвального фосфогипса, можно выделить с применением ситового механического анализатора фракции с требуемым содержанием примесей. Так фракции 0,050–0,045 мм (остаток на сите 0,045), 0,140–0,090 мм (остаток на ситах 0,100 и 0,090), а также высушенный материал из циклона, рукавных фильтров и исходный отвальный фосфогипс проанализировали методом ренгенофлоуресцентного анализа на содержание отдельных элементов. Было обнаружено, что содержание некоторых редкоземельных элементов и стронция в мелкодисперсном продукте (полученном из фильтров) повысилось, по сравнению с исходным отвальным фосфогипсом более чем в два раза, а содержание таких элементов, как церий, лантан и лютеций до четырех раз. Результаты исследований показали, что во фракции 0,140–0,090 мм (остаток на ситах 0,100+0,090) значительно снижено количество отдельных элементов по сравнению как с исходными отвальным фосфогипсом, так и высушенным продуктом, отбираемым из циклона. А именно, во фракции 0,140–0,090 мм уменьшилось содержание таких элементов (в пересчете на их оксиды), как барий более 17 раз, железа – до 10 раз, титана – до 7 раз и т. д. Также во фракции 0,140–0,090 мм отсутствуют такие элементы, как калий, никель, кремний, германий, селен, палладий, индий, эрбий, лютеций, гафний, тантал и ртуть. Это даёт основание говорить о том, что фракция 0,140–0,090 мм не содержит соединений элементов, ограничивающих её использование в строительных материалах, и может применяться как заменитель природного гипсового камня. Кроме того, повышение содержания РЗЭ уже позволяет считать продукт из фильтров концентратом РЗЭ с возможностью применения многочисленных разработанных «мокрых» технологий для их извлечения.

**Ключевые слова:** фосфогипс, фракции фосфогипса, химический состав, оксиды элементов, ренгенофлоуресцентный анализ, микроскопия.

### Introduction

One of the largest waste streams, the third largest in Belarus, is waste from the production of wet-process phosphoric acid from apatite concentrate at the Khibiny deposit. Over the 50 years of operation of the Gomel Chemical Plant, over 18 million tons of phosphogypsum waste have accumulated, contaminating soils, surface water, and groundwater, covering an area of over 70 hectares. Numerous studies have been devoted to the use of phosphogypsum (PG) in various industrial fields, most of which concerned the production of artificial gypsum [1–6] using autoclave or thermal treatment methods (firing PG at 900–1000 °C), sulfate-slag binders, as an additive to agricultural soils, as raw material for the production of gypsum bricks, stone walls, binders for road bases, etc. However, all the considered areas of PG use have not found widespread application due to the high content of various impurities [7] present in waste PG (WPG). Impurities negatively affect the quality of the resulting building materials [8–14], and operations to reduce the amount of impurities in PG (neutralization, enrichment, drying, thermal treatment) increase the cost of gypsum binders and reduce its competitiveness in comparison with natural gypsum rock. A reserve for increasing the efficiency of FG processing is the elimination of heat treatment, grinding, and, in the future, filtration of the product, since these stages consume about 45 % of capital, about 50 % of current, and more than 60 % of heat and energy costs.

The chemical composition of the FG of the Gomel Chemical Plant OJSC was carried out by researchers many times, as a result of which it was established that the FG of the Gomel plant contains from 95 % to 97 % of dihydrate and hemihydrate of calcium sulfate, and impurities [15], including compounds of the elements Cd, Zn, Pb, Hg, Zr, Cu, Ba, REE, Y, Th, U. However, the determination of REE and other elements was carried out in the total mass of the FG, even if it was subjected to heat treatment, then after grinding the sintered agglomerates, averaged samples selected from the total mass of the dried material were again examined.

As a result of the presence of difficult-to-remove impurities (with the exception of a small volume of secondary processing from 4 to 10 %), the predominant storage of FG occurs in the form of waste heaps, the formation and maintenance of which requires significant costs (the rate of environmental tax for the storage of 1 ton of FG in 2024 was 1.04 Belarusian rubles [16]).

**Study of individual fractions of phosphogypsum dried in a flash dryer**

**The purpose of the study**: to establish the elemental composition of individual fractions of PhG, with the determination of the possibility of using individual fractions in the production of building materials or other areas.

**1 Research methods**

To study the elemental composition of the Gomel plant's fluorinated gas, representative samples from the Gomel chemical plant's waste heaps with five- and ten-year storage periods were analyzed.

The elemental composition of the samples was determined by X-ray fluorescence analysis using an Epsilon 1 PANalytical energy-dispersive spectrometer equipped with an X-ray tube with a silver anode, six filters, and a high-resolution silicon detector. Automatic data processing was performed using Epsilon 3 software. Results were also automatically corrected for ambient temperature and pressure.

The sorption moisture content of the samples was monitored using an Elvis-2S moisture analyzer at 55 °C (exceeding this temperature resulted in the onset of loss of crystallization water).

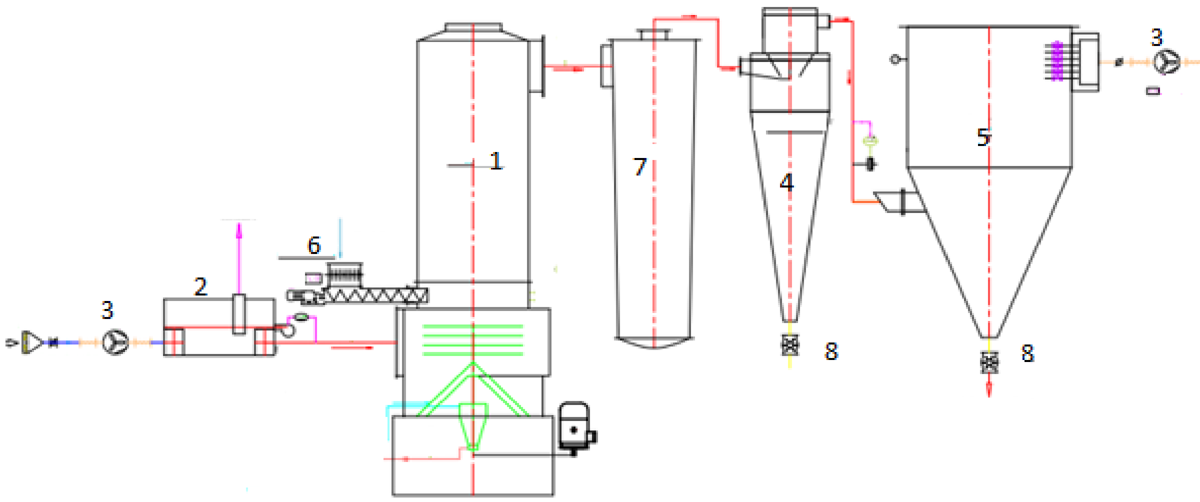
Micrographs were taken using a Phenom Pro scanning microscope (Thermo Fisher Scientific, USA). Separation into fractions was carried out on a sieve mechanical analyzer "Vibroprivod VP 30 T" No. 4938, on metal sieves with mesh cell sizes, mm: 1.000; 0.140; 0.100; 0.090; 0.080; 0.071; 0.050; 0.045; 0.040.

**2 Obtaining phosphogypsum fractions**

The phosphoric acid produced at any plant worldwide during the production of wet-process phosphoric acid has an adsorption moisture content of 30–40 %. This high adsorption moisture content causes it to easily clump, forming lumps of varying sizes (Figure 1).

**Figure 1** – Type of phosphogypsum collected from waste heaps

To remove adsorbed moisture from FG, dryers such as drum, belt, shaft, and IR dryers are used. Drying this material in these dryers results in the formation of solid lumps of varying sizes that do not disintegrate spontaneously and require subsequent grinding of the dried product. To eliminate the need for grinding, FG was dried in an industrial complex (Figure 2) comprising a flash dryer, a fuel furnace, a cyclone, bag filters, a feed auger, a final drying unit, and unloading devices. The flash dryer is a combination of a suspended bed dryer and a cyclone vortex dryer with a cocurrent flow of incoming drying gas.




1 – flash dryer, 2 – indirect fuel furnace, 3 – air blower, 4 – cyclone, 5 – bag filters, 6 – feed auger, 7 – final drying device, 8 – unloading devices

**Figure 2** – Schematic diagram of the complex for drying waste phosphogypsum

The FG was dried to a residual sorption moisture content of no more than 0.03 %. This drying method allowed us to obtain products with a dispersion similar to that of the FG precipitate in baths used for phosphoric acid extraction.

The drying temperature regime for obtaining a product (dried FG) with a sorption moisture content of no more than 0.03 % was set as follows: the coolant temperature at the dryer inlet was 180–200 °C, and at the dryer outlet, 85–95 °C.

Increasing the temperature above 200 °C at the dryer inlet resulted in the formation of calcium sulfate hemihydrate. Being a strong desiccant, calcium sulfate begins to adsorb water from the surrounding air, leading to a subsequent change in the overall moisture content of the product within 1 hour (an unstable product). When the dryer inlet temperature exceeded 205 °C, reactions began to occur, leading to the release of chemically bound (crystallization) water from the crystal lattice. Depending on the conditions under which these reactions occur, the dehydration products of calcium sulfate dihydrate can be represented in various ways:

$CaSO_4 \cdot 2H_2O$ = a $CaSO_4 \cdot 0{,}5H_2O$+1,5$H_2O$ (п) – 83,17 kJ/mol;

$CaSO_4 \cdot 2H_2O$ = a $CaSO_4 \cdot 0{,}5H_2O$+1,5$H_2O$ (ж) – 17,9 kJ/mol;

$CaSO_4 \cdot 2H_2O$ = b $CaSO_4 \cdot 0{,}5H_2O$+1,5$H_2O$ (п) – 85,3 kJ/mol;

$CaSO_4 \cdot 2H_2O$ = b $CaSO_4 \cdot 0{,}5H_2O$+1,5$H_2O$ (ж) – 19,3 kJ/mol;

$CaSO_4 \cdot 2H_2O$ = $CaSO_4$ + 2$H_2O$ (ж) – 16,9 kJ/mol;

$CaSO_4 \cdot 2H_2O$ = $CaSO_4$ + 2$H_2O$ (п) – 95 kJ/mol.

The dried product obtained using the flash dryer was essentially only the dihydrate form of calcium sulfate, as confirmed by the X-ray diffraction pattern shown in Figure 3.

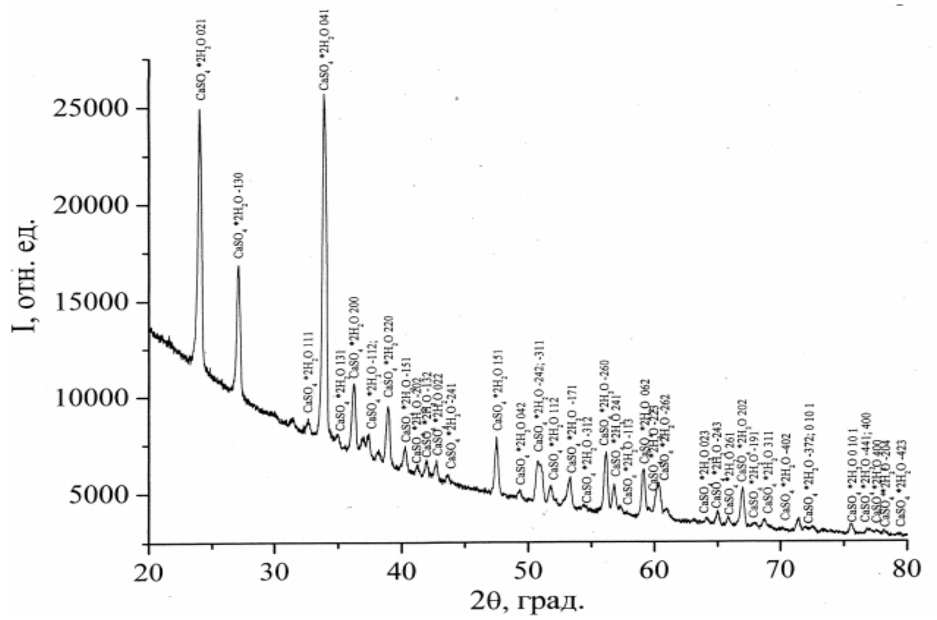



**Figure 3** – Radiograph of dried OFG

Heating to 75–80 °C is sufficient for the slow release of sorption moisture from the FG, but lowering the dryer inlet temperature to 75–80 °C resulted in increased sorption moisture content at the dryer outlet.

Two thermocouples were used to monitor the drying process, with information being output to a secondary device mounted on the control panel. Some of the results of the studies on selecting the operating temperature parameters for the flash dryer system are presented in Table 1.

**Table 1** – Flash dryer operating modes and residual sorption moisture content in the final product

| Feed rate, kg/hour | Temperature in the dryer, ºC | | Humidity of the obtained product, % |
|---|---|---|---|
| | at the entrance | at the exit | |
| 1000 | 200 | 65 | 10 |
| 1000 | 250 | 70 | 4 |
| 500 | 180 | 70 | 3 |
| 500 | 200 | 85 | 1 |
| 350 | 180 | 95 | 0,04 |
| 350 | 200 | 85 | 0,01 |
| 200 | 180 | 75 | 0,01* |

* strongly absorbs water from the air.

The moisture content of the OFG fed to the drying chamber depends on the season and transport conditions and varies by up to 10 %. This affects the final moisture content of the dried product and requires adjustment of the dryer temperature.

The finished dried material consists of two products: a coarse product (from the cyclone) and a fine product (from the bag filters). The particle size distribution of the products obtained after drying the OFG is presented in Table 2. Figure 4 shows a micrograph of the dried FG.

**Table 2** – Granulometric composition of fractions obtained at the drying complex

| Fraction | Sieve size, µm [GOST 6613-86] | | | | | |
|---|---|---|---|---|---|---|
| | <45 | 45 | 50 | 80 | 100 | 1000 |
| | Content, % | | | | | |
| Finely dispersed (from bag filters) | 64,5–71,5 | 25–30 | 3–5 | 0,5–0,6 | – | – |
| Coarse (from cyclone) | 15–18 | 5–10 | 45–50 | 10–12 | 3–10 | – |

**Figure 4** – Micrograph of the coarse fraction (from the cyclone) of dried PhG. Magnification 1000x

**3 Elemental composition of dried phosphogypsum fractions**

The fine and coarse products obtained from drying the OFG in the drying complex were analyzed using X-ray fluorescence analysis. The content of individual elements, including rare earth elements, in these products is listed in Table 3.

The data in Table 3 show that the strontium content in the filter product increased more than twofold compared to the original FGZ, the total REE increased threefold, while the content of almost all elements, including the total REE, decreased in the coarsely dispersed product. This can only be explained by the relationship between the crystal size and the amount of elements sorbed by the surface or coprecipitated during crystallization. However, since the area-to-volume ratio of large crystals is smaller than that of small ones, their sorption surface is also smaller, which is evident from the results presented. The process of impurity element coprecipitation is also not the same for particles of different sizes, since this change in the REE content cannot be explained by the area-to-volume ratio of a particle alone. It is known from [17] that the distribution of rare earth elements (REE) among apatite processing products is as follows: up to 80 % of the REE present in the ore is transferred to the FGZ, and 20 % is transferred to the extraction phosphoric acid. In [18] it is stated that coprecipitation of REE with calcium and sodium sulfate occurs at temperatures above 85 ºC, presumably with calcium sulfate hemihydrate. In [19] it is shown that REE – La, Ce, Nd are present in PG in the form of solid solutions of the compounds NaLn(SO4)2·H2O, KLn(SO4)2·H2O and the hemihydrate CaSO4·0.5 H2O, PG also contains REE in the form of the compounds NaLn(SO4)2·H2O, KLn(SO4)2·H2O, which are not included in the crystal structure of the monoclinic cell of CaSO4·2H2O and do not form solid solutions with CaSO4·2H2O. In [20] it is stated that the presence of REE leads to a decrease in the size of calcium sulfate crystals.

Based on these data, it can be assumed that large crystals of calcium sulfate dihydrate have a small amount of adsorbed or co-precipitated REE sulfates, while small particles will contain a larger amount of impurity elements, including REE.

**Table 3** – Content of some elements in fractions of dried FG

| Element | Content, % | | |
|---|---|---|---|
| | OFG (original) | Fine fraction (from filters) | Coarse fraction (from cyclone) |
| Cerium (Ce) | 0,529±0,015 | 1,746±0,032 | 0,695±0,285 |
| Lanthanum (La) | 0,293±0,003 | 1,264±0,023 | 0,298±0,065 |
| Neodymium (Nd) | 0,121±0,001 | 0,431±0,023 | 0,109±0,020 |
| Yttrium (Y) | 0,029±0,004 | 0,048±0,001 | 0,017±0,005 |
| Dysprosium (Dy) | 0,022±0,002 | 0,025±0,002 | 0,005±0,001 |
| Scandium (Sc) | 0,014±0,001 | 0,019±0,002 | 0,003±0,001 |
| Tellurium (Te) | 0,022±0,001 | 0,020±0,005 | 0,015±0,004 |
| Lutetium (Lu) | 0,002±0,001 | 0,006±0,001 | 0,003±0,001 |
| *Total Rare Earth Elements* | *1,031±0,021* | *3,555±0,086* | *1,145±0,382* |
| Strontium (Sr) | 4,908±0,073 | 14,800±1,160 | 4,065±0,09 |
| Titanium (Ti) | 0,365±0,033 | 0,442±0,190 | 0,368±0,018 |
| Mercury (Hg) | 0,002±0,001 | 0,004±0,002 | 0,002±0,001 |
| Iron (Fe) | 0,233±0,052 | 0,635±0,119 | 0,200±0,007 |

In the next stage of the study, the product from the cyclone was separated into fractions using a mechanical analyzer. The fractions of 0.140–0.090 mm (a combined sample of residues from 0.100 and 0.09 sieves) and 0.050–0.045 mm (residue on a 0.045 sieve) were also analyzed using X-ray fluorescence analysis. The results of the analysis of both the product collected from the cyclone and the individual fractions of particle sizes 0.140–0.090 mm and 0.050–0.045 mm are presented in Table 4.

**Table 4** – Content of element oxides in various fractions

| Oxides | Fractions, mm | | |
|---|---|---|---|
| | 0,900–< 0,045 | 0,140–0,090 | 0,050–0,045 |
| | Content, % | | |
| Cerium oxide ($CeO_2$) | 0,854±0,35 | 0,318±0,013 | 1,337±0,025 |
| Lanthanum oxide ($La_2O_3$) | 0,699±0,153 | 0,152±0,024 | 0,911±0,037 |
| Neodymium oxide ($Nd_2O_3$) | 0,254±0,047 | 0,077±0,011 | 0,274±0,04 |
| Yttrium oxide ($Y_2O_3$) | 0,043±0,013 | 0,014±0,006 | 0,025±0,009 |
| Dysprosium oxide ($Dy_2O_3$) | 0,012±0,003 | 0,001±0,001 | 0,014±0,005 |
| Scandium oxide ($Sc_2O_3$) | 0,009±0,003 | 0,062±0,016 | 0,047±0,011 |
| Tellurium oxide ($TeO_2$) | 0,019±0,005 | 0,005±0,001 | 0,006±0,002 |
| Lutetium oxide ($Lu_2O_3$) | 0,007±0,002 | 0,001±0,001 | 0,001±0,001 |
| *Total rare earth oxides* | *1,896±0,575* | *0,629±0,072* | *2,616±0,131* |
| Silicon oxide ($SiO_2$) | 1,881±0,069 | 0,001±0,001 | 2,358±0,101 |
| Strontium oxide (SrO) | 4,808±0,107 | 1,994±0,305 | 10,954±1,568 |
| Titanium oxide ($TiO_2$) | 0,613±0,03 | 0,088±0,017 | 0,521±0,075 |
| Mercuric oxide (HgO) | 0,002±0,001 | 0 | 0,003±0,001 |
| Barium oxide (BaO) | 0,291±0,103 | 0,016±0,003 | 0,113±0,012 |
| Iron oxide ($Fe_2O3$) | 0,629±0,021 | 0,065±0,006 | 0,510±0,094 |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An analysis of the presented results shows that the fraction with a particle size of 0.140–0.090 mm, compared to the product coming from the cyclone, has a 17-fold decrease in the amount of barium, approximately 10-fold decrease in iron, and 7-fold decrease in titanium. It also contains less strontium, yttrium, cerium, and other elements. Furthermore, the 0.140–0.090 mm fraction is free of oxides of potassium, nickel, silicon, germanium, selenium, palladium, indium, erbium, lutetium, hafnium, tantalum, and mercury. The calcium sulfate content has increased due to a decrease in the total amount of other components. The fraction with a particle size of 0.050–0.045 mm has increased contents of strontium, silicon, and zirconium, which once again confirms the theory of a relationship between the particle size of the PG and the adsorbed and coprecipitated elements. It should be noted that chlorine and bromine were absent from both analyzed fractions, which can be explained by the volatilization of these elements and their compounds during passage through the drying system. This means that during the flash dryer drying of the OFG, not only the sorption moisture is lost, but also volatile components such as fluorine compounds and some phosphorus compounds.

The hydrogen ion activity (pH) of the 0.140–0.090 mm fraction solutions is 7.2; and the pH of the cyclone product is 6.79, which also indicates different contents of some compounds in these products. Comparing the values of individual indicators of the 0.140–0.090 fraction with the requirements of TU 400069905.047–2019 [21] for artificial gypsum stone, its full compliance is revealed (Table 5).

If we compare it with natural gypsum stone [22], all indicators correspond to grade 1 (Table 6).

**Table 5** – Comparison of the 0.140–0.090 mm fraction with the requirements for artificial gypsum stone

| Name of the indicator | Meaning, according to [21] | Fraction 0.140–0.090 mm |
|---|---|---|
| Content of the main substance - calcium sulfate dihydrate ($CaSO_4$ $2H_2O$), %, | Not less than 90 | 95 |
| Total content of phosphates in terms of $P_2O_5$, %, | Not more than 0.8 | 0,77 |
| including the content of water-soluble phosphates | Not allowed | Absent |
| Total content of fluorine, % | Not more than 0.40 | Absent |
| including the content of water-soluble fluorine (fluorine ion), % | Not more than 0.005 | Absent |
| Hydrogen ion activity (pH) | 7.0–8.0 | 7,2 |

**Table 6** – Content of main components in the 0.140–0.090 mm fraction and the requirements of GOST 4013–2019 [22]

| Contents | Gypsum ($CaSO_4 \cdot 2H_2O$), % | Water of crystallization, % | Sulfur(VI) oxide ($SO_3$), % |
|---|---|---|---|
| Gypsum stone grade 1 | Not less than 95 | Not less than 19.9 | Absent |
| Gypsum-anhydrite stone grade 1 | Not less than 95 | Absent | Not less than 44.2 |
| Fraction of dried PhG (0.100+0.090) mm | 95,8 | Absent | 49.7 |

**Conclusion**

1. Using a drying system with a flash dryer enables the production of phosphorus hydrate (FG) as a fine powder, primarily in the form of calcium sulfate dihydrate, with an adsorbed moisture content of no more than 0.03%, without loss of crystal water and, consequently, without crystal breakage or reduction in size. The particle size of the dried FG corresponds to the size of crystals formed in extraction baths during the production of phosphoric acid from apatite concentrate. Producing a fine powder eliminates the need for FG milling before further use, reducing its cost. Furthermore, the fine particle size of the dried FG allows it to be separated into individual fractions using mechanical classifiers.

2. The chemical composition of the fractions with particle sizes of 0.140–0.090 mm and 0.140–0.090 mm differs in impurity element content from their content in the OFG and from the product obtained from the cyclone. This can only be explained by the relationship between the crystal size and the amount of elements sorbed on the surface or coprecipitated during crystallization.

3. The fraction with particle sizes of 0.140–0.090 mm contains an amount of impurities that will not affect the quality of products manufactured from it compared to the use of artificial gypsum (calcium sulfate hemihydrate) and complies with the requirements of GOST 4013–2019 and TU BY 400069905.047–2019.

4. The presented data provide grounds for talking about the possibility of using a reagent-free, non-thermal method (firing FG at 900–1000 °C) to reduce impurities in FG and the prospects for using various fractions obtained from OFG dried in a flash dryer as raw material for the production of artificial gypsum applicable for building materials or other applications.

5. The data presented in the article indicate that further, finer separation of the dried FG into narrow fractions is possible, which will contain varying amounts of impurities, and this content will enable the targeted use of this fraction without the labor-intensive processes of precipitation of impurities with strong acids, separation of precipitate, etc. The product obtained from the filters can be used to obtain REE, since the concentration in this product is several times higher than in the original FG, and the yield of finely dispersed product is significantly less than the initial amount of OFG.

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# TECHNICAL SOLUTION FOR APPLYING LIQUID FERTILIZERS WITH IRRIGATION WATER

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**Abstract**

Applying liquid fertilizers (mineral and/or livestock-derived) with a precise irrigation technology is an important agricultural practice aimed at utilizing the nutrients contained in fertilizers to enhance soil fertility and crop yields. However, this method requires adherence to certain regulations to prevent negative environmental impacts.

This article presents an effective method for applying fertilizers while simultaneously irrigating agricultural land. For this purpose, a special device is used to inject liquid fertilizers into a pressure irrigation pipeline. Transportation through the pipeline is accomplished automatically using the potential energy of the water, using an ejector and a pressure differential between the ejector's inlet and outlet. The device comprises a pressure pipeline, a liquid fertilizer tank, and a dosing pump. The pump has working chambers with a piston kinetically coupled to a hydraulic motor via a drain line, distributor, and connecting fittings. The end of the discharge pipeline is equipped with a nozzle designed as a vacuum chamber. The bottom of the chamber is connected to feed and discharge pipes. The chamber contains an ejector unit, feed pipes, and a nozzle facing the annular bell.

Use of this device will improve the efficiency of mixing liquid fertilizers, enhance operational reliability, and regulate the fertilizer flow rate. Experimental studies were conducted to determine the effects of pipeline pressure, suction energy, and water supply to the power cylinders, which are associated with installing the ejector unit on a main clean water pipeline.

**Keywords:** pipeline, fertilizer, irrigation water, fertilizer mixing device, characteristics, operation.

## ТЕХНИЧЕСКОЕ РЕШЕНИЕ ДЛЯ ВНЕСЕНИЯ ЖИДКИХ УДОБРЕНИЙ С ПОЛИВНОЙ ВОДОЙ

**Ю. А. Мажайский, М. И. Голубенко, С. М. Курчевский, А. В. Стрелюхин**

**Реферат**

Применение жидких удобрений (минеральных и (или) животноводческих) с выверенной технологией дождевания является важной практикой в сельском хозяйстве, направленной на использование питательных веществ, содержащихся в удобрениях для повышения плодородия почвы и урожайности сельскохозяйственных культур. Вместе с тем, данное мероприятие требует соблюдения определенных правил для предотвращения негативного воздействия на окружающую среду.

В статье представлен эффективный способ внесения удобрений с одновременным орошением сельскохозяйственных угодий. Для этой цели используется специальное устройство для внесения жидких удобрений в напорный трубопровод оросительной воды. Транспортировка по трубопроводу осуществляется с использованием потенциальной энергии воды в автоматическом режиме, в котором устроен эжектор и перепад напоров между входом и выходом эжектора. Устройство содержит напорный трубопровод, емкость для жидких удобрений, насос-дозатор. Насос имеет рабочие полости с поршнем, кинетически связанным с гидродвигателем, сообщенным через сливную линию, распределитель и соединительную арматуру. Конец напорного трубопровода снабжен насадкой, выполненной в виде камеры разрежения. Дно камеры подключено к питающим и сбросной трубкам. Камера содержит блок эжектора, питающие трубки и сопло в сторону кольцевого раструба.

Использование данного устройства позволит улучшить эффективность смешивания жидких удобрений, повысить надежность работы, а также регулировать расход подачи удобрений. Проведены экспериментальные исследования по определению влияния напора в трубопроводах, энергии всасывания и подачи воды в силовые цилиндры, что связано с установкой узла эжектора на магистральном трубопроводе чистой воды.

**Ключевые слова:** трубопровод, удобрения, оросительная вода, устройство по смешиванию удобрений, характеристика, функционирование (работа).

## Introduction

Environmental requirements for irrigation systems prioritize reducing the negative impact of irrigation on the environment. One of the main directions of scientific and technological progress in land reclamation is the improvement of techniques and technologies for delivering liquid fertilizers to irrigated fields, as well as their efficient application to the soil [1–2].

Another crucial factor in increasing the efficiency of agricultural production on irrigated lands is creating a gross level of plant nutrient supply. Complete and timely supply of fertilizers to irrigated crops allows for maximizing their productive capacity, avoiding nutrient losses, ensuring economical water consumption, and accelerating the payback of funds invested in irrigation infrastructure.

Irrigated farming creates prerequisites for obtaining high and stable yields of agricultural crops. Realizing the existing potential is primarily associated with the rational interaction of irrigation and chemicalization. This is confirmed by experience gained in the process of cultivating crops.

Applying fertilizers in conjunction with timely irrigation is a powerful agronomic technique aimed at improving crop quality and optimizing irrigation costs. This process is associated with the improvement of the water and nutrient regimes of plants, the intensification of their growth and the metabolic activity of the root system, the enhancement of biological processes, and changes in the intensity of metabolism and the formation of generative organs.

Yield increase can also be achieved through phosphorus top dressing during the flowering and fruiting periods. Such top dressings can also be used to accelerate fruit ripening and improve product quality. Top dressing can satisfy the changing nutrient requirements of plants during different growth periods and yield better results.


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The timing and methods of fertilizer application should ensure high labor productivity and contribute to reducing the financial and energy costs of these operations [3–14]. Furthermore, fertilizer application should be coordinated with other agrotechnical measures.

Currently, due to the improvement of irrigation techniques and technology, much attention has been paid to methods of applying liquid fertilizers with irrigation water during sprinkling.

Fertilizer application with irrigation water can be carried out both before crop sowing and with vegetative irrigations. The timing and doses of nutrient supply under regular irrigation should be established depending on the biological characteristics of the crops, soil conditions, and fit into the irrigation schedule.

Recently, ejectors have found the widest application in fertigation systems for low-intensity irrigation. Operation is based on the principle of a jet pump. When delivering liquid fertilizers to the place of use and distribution over the area of the site, main irrigation pipelines are used, where, due to the maximum kinetic flow rates formed in the central part of the pipeline, the injected fertilizer solution is absorbed. Unlike known types and designs of pumps, jet pumps lack any rotating or moving elements, which determines their high operational reliability [15–16]. Furthermore, the hydraulic method involves pre-mixing water and fertilizers for irrigation using irrigation systems, including both localized networks and sprinkler irrigation [5].

**Materials and Methods**

The aim of the work was to develop the structural and technological parameters of a device for applying liquid fertilizers with irrigation water.

As an example, consider the proposed technological scheme of a system for introducing liquid fertilizers into the pressure pipeline of irrigation water with the subsequent possibility of transportation through the pipeline using the potential energy of water in an automatic mode, facilitated by an ejector and the pressure differential between its inlet and outlet [17–19].

The mode of application of concentrated fertilizers with irrigation water must correspond to the device's operating design. The concentration of fertilizers in the irrigation water at an irrigation rate of more than 500 m³/ha should not exceed 0,2…0,3 % during dry and hot periods. During rainy and cool periods, this limit can be increased to 0,5 %. For example, with a rate of 300 m³/ha, the water concentration usually should not exceed 0,01…0,1 %, or 0,1…1,0 g/l, and with an irrigation rate of 600...900 m³/ha – 0,2…0,3 % or 2…3 g/l.

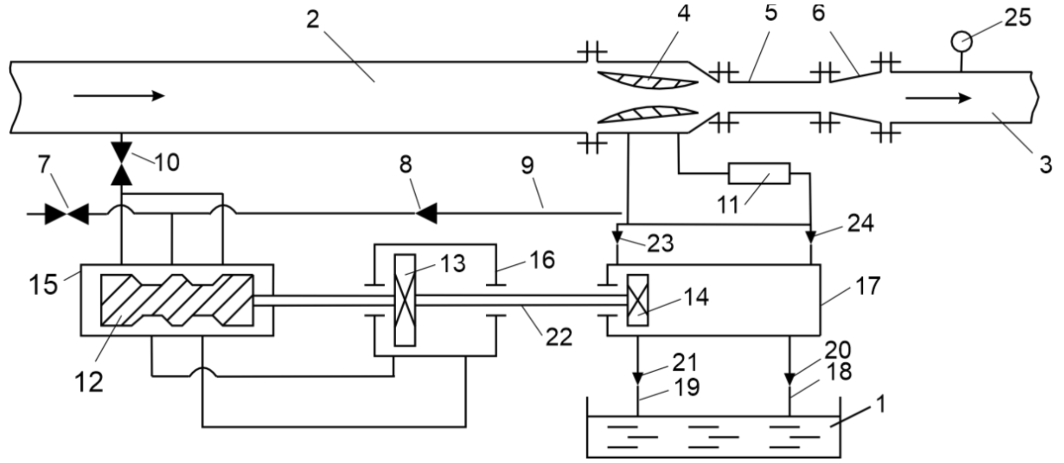
When applying liquid concentrated fertilizers with water after harvest under fall plowing, a solution concentration of up to 2…3 % is allowed.

A mandatory condition for the use of fertilizing irrigation is the prevention of gravitational discharge of solutions outside the irrigated area – into drainage collectors, pipelines, and water bodies.

We base our parameters on objects where the following data are used: for example, irrigation water is supplied at a rate of 400 m³/ha to the irrigation fields through an 800 mm diameter pipeline, and before its distribution by sprinkler machines (units), nutrient solutions are added in the required quantity directly into the pipeline. The permissible pressure drop after the mixing unit is up to 75 m, and the pressure increase before the mixing unit is up to 85 m. The mixing unit must ensure the supply of nutrient solutions into the pipeline up to 25 l/s. Liquid fertilizers are stored in designated holding ponds, the depth of which does not exceed three meters.

**Research Results**

In this study, a scaled-down model setup at a ratio of 1:8.5, resembling the actual equipment (Froude number modeling), was constructed. It incorporates two double-acting power cylinders with pistons 13 and 14 (Figure 1) and two single-acting pressure-suction cylinders.




1 – tank for liquid fertilizers; 2 – inlet pressure pipeline; 3 – outlet pressure pipeline; 4 – ejector; 5 – acceleration pipe;6 – diffuser; 7 – gate valve; 8 – check valve; 9 – bypass pipe;10 – gate valve; 11 – flow meter; 12 – spool distributor; 13, 14 – piston; 15 – water distribution chamber; 16 – power cylinder; 17 – discharge cylinder; 18, 19 – suction pipelines; 20, 21, 23, 24 – check valves; 22 – rod; 25 – pressure gauge

**Figure 1** – Schematic diagram of the automatic device for fertilizer application into a closed network

The working process begins with opening valve 10. Water from the supply pressure pipeline 2 flows through the open valve 10 into the spool valve-water distributor 12 (hydraulic distributor) and then into one side (e. g., the left side) of the double-acting power cylinder 16. Under the influence of water pressure, piston 13 of cylinder 16 moves to the left, and correspondingly, moves piston 14 of the discharge cylinder 17, which is mechanically connected to it. Simultaneously, the working chamber of cylinder 17 fills with fertilizer solution from the liquid fertilizer tank 1 through the suction pipeline 18 with check valve 20. The solution then passes through pipeline 24 with check valve 24 into the ejector 4 and through the accelerating pipe 5, into the discharge pressure pipeline 3. Water from the supply pressure pipeline 2 now enters the double-acting power cylinder from the other side, moving the piston to the right. The piston 13 of the cylinder pushes the used water into the settling tank. That is, all the above-described rightward movement operations are repeated. The cycle is completed by the actuation of the spring synchronizer-pusher, which moves the rod of the spool valve-water distributor 12 to its extreme right position. The cycles then repeat automatically. The gate valve 10 regulates the flow rate of the nutrient solution. Stopping (turning off) the device is also accomplished by closing the gate valve 10.

Taking into account the modeling scale, the following were determined: pressure, pipe diameter, cylinder diameters, ejector nozzle diameter, main pipeline flow rate, liquid fertilizer flow rate, total mixture flow rate, and accordingly, the areas of pipelines, cylinders, ejector nozzle, mixing chamber, piston stroke, and cylinder working volumes.

The optimal ratio of the power cylinder diameter to the discharge cylinder diameter was achieved at a ratio of 1:1.83, where the power cylinder diameter was 55 mm (467 mm full-scale), and the discharge cylinder diameter was 30 mm (255 mm full-scale).

Ejector research was conducted to clarify the magnitude of pressure reduction in the mixer and the flow capacity of its nozzle at given inlet and outlet pressures, as well as in the absence of fertilizer supply to the mixer.

Experiments were conducted for two ejector nozzle diameters: 23 mm (195,5 mm full-scale) and 20 mm (200 mm full-scale) at fixed outlet pressures – 64 m, 68 m, 72 m, 76 m, and 80 m of water column (full-scale).


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Table 1 presents the results of hydraulic studies of the device for introducing liquid (mineral) fertilizers into the pressure pipeline (converted to full-scale).

Figure 2 shows the nature of the change in the ejector's flow capacity.

In the operational technological mode, the device ensures the supply of fertilizer into the pressure main pipeline.

Figure 3 shows a schematic diagram of the ejector assembly.

This system is universal and applicable for both liquid fertilizer delivery and transporting the finished mixture via pipeline to the irrigation site. As established during the study, the throughput of the system for fertilizer tank 1 (see Figure 1) is limited by the maximum lifting height of the pump given the existing elevation difference and pressure in the pipelines. With a correct calculation, the mixing unit will meet all technological requirements under these conditions.

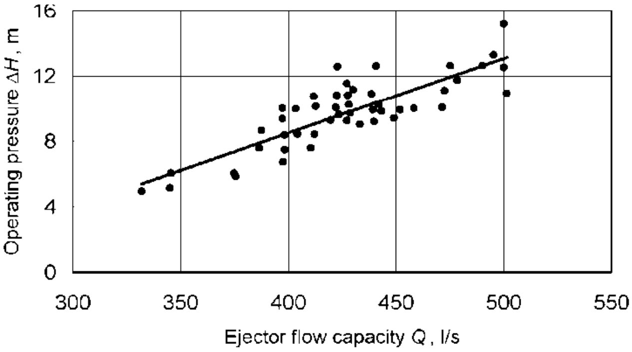
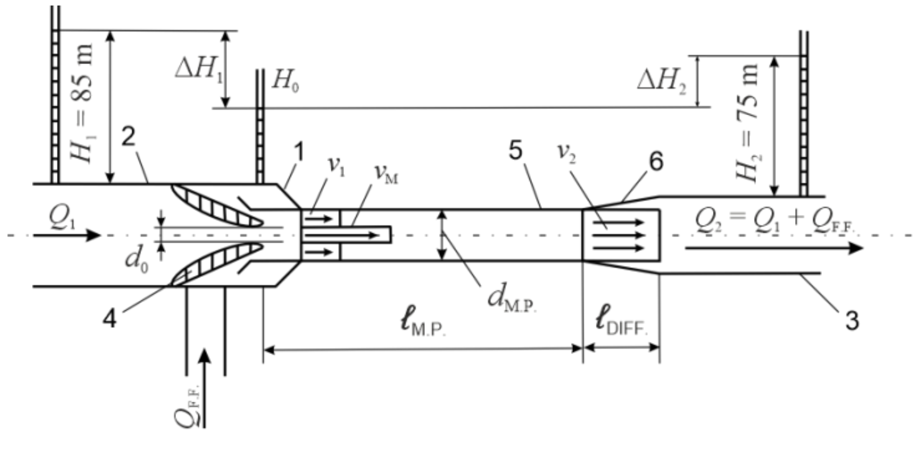



**Figure 2** – Ejector flow capacity (*Q, l/s*) depending on the operating pressure (*ΔH, m*)

**Table 1** – Results of hydraulic studies (converted to full-scale)

| Inlet Pressure, $H_{in}$, m | Nozzle Pressure, $H_o$, m | Outlet Pressure, $H_{out}$, m | Pressure differential, $H_n$, m | Flow in pipeline before ejector, $Q_1$, l/s | Cycle Duration, $T_c$., s | Liquid fertilizer flow rate, l/s | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | 1st feed cylinder, $Q_{f1}$ | 2nd discharge cylinder, $Q_{f2}$ | Total $Q_f$ |
| 83,3 | 67,2 | 68,0 | 15,3 | 400 | 6,23 | 4,00 | 4,36 | 8,36 |
| 80,7 | 67,2 | 68,0 | 12,7 | 400 | 6,29 | 2,34 | 3,53 | 5,87 |
| 79,9 | 69,7 | 70,6 | 9,3 | 400 | 7,89 | 2,41 | 3,54 | 5,95 |
| 84,1 | 69,7 | 71,4 | 12,7 | 420 | 7,42 | 2,61 | 4,13 | 6,74 |
| 82,4 | 69,7 | 70,6 | 11,8 | 473 | 9,49 | 1,13 | 1,77 | 2,90 |
| 81,6 | 69,7 | 71,4 | 10,2 | 414 | 6,02 | 1,77 | 3,86 | 5,63 |
| 80,7 | 67,2 | 68,0 | 12,7 | 400 | 6,37 | 3,91 | 5,94 | 8,85 |
| 80,7 | 66,3 | 67,2 | 13,5 | 408 | 6,23 | 6,06 | 11,85 | 17,91 |
| 79,9 | 66,3 | 67,2 | 13,6 | 414 | 6,23 | 3,09 | 4,76 | 7,85 |
| 81,6 | 70,6 | 71,4 | 12,7 | 400 | 7,40 | 4,61 | 6,17 | 10,78 |




1 – vacuum chamber; 2 – inlet pressure pipeline; 3 – outlet pressure pipeline; 4 – ejector; 5 – acceleration pipe; 6 – diffuser

**Figure 3** – Calculation scheme of the ejector unit

When determining the area of the ejector nozzle, the given flow rate of the main pipeline and the flow coefficient of the ejector nozzle are used

$$\omega = \frac{Q}{\mu\sqrt{2gH_0}}, \tag{1}$$

where *ω* – area of the ejector nozzle, m²; *Q* – water flow rate in the pipeline, m³/s;

*μ* – flow coefficient of the nozzle, taken as 0,9; *g* = 9.81 m/s² – acceleration due to gravity; $H_0$ – pressure in the ejector, m.

The diameter of the ejector nozzle can be determined by the formula $d_0 = \sqrt{4\omega/\pi}$.

For the proposed scheme (Figure 3), during research, the pressure $H_1$ and flow rate $Q_1$ in the inlet pipeline, as well as the pressure $H_2$ and flow rate $Q_2$ in the outlet pipeline, were set. Then the value of the pressure at the device inlet and the fertilizer application rate at pressure $H_1$ are refined using the formulas

$$H_1 = \frac{H_0(1-\delta K)}{\delta \cdot K}, \tag{2}$$

$$\delta = \frac{2\varphi(\lambda+1)^2}{m^2}, \tag{3}$$

where *φ* – coefficient of velocity of outflow from the nozzle, equal to 0,93; $\lambda = Q_{F.F.}/Q_1$ – required degree of dilution of fertilizers with irrigation water; *m* – ratio of the diameter of the acceleration mixing pipe to the nozzle diameter depends on *λ*

$$m = \frac{d_{a.p.}}{d_0}, \tag{4}$$

The coefficient $K$ is determined by the formula

$$K \leq \frac{m(m-1+\lambda)}{(\lambda+1)^2 \cdot (m-1)} - 0,5(1+\xi_{\text{diff.}}), \quad (5)$$

where $\xi_{diff.}$ – loss coefficient in the diffuser (0.08…0.15).

The pressure $H_0$ before the nozzle is determined from formula (2)

$$H_0 = \frac{H_1(\delta \cdot K - H_2)}{(1-\delta \cdot K)}. \quad (6)$$

It should be noted that if adjustment of pressure $H_0$ is necessary, the diameter of the acceleration mixing pipe is changed and $H_0$ is refined using formulas (4–6).

Based on the obtained value of the ejector nozzle pressure, other design parameters of the ejector are determined: nozzle length, length of the acceleration mixing pipe, diffuser length, and, accordingly, the geometric parameters of the horizontal diaphragm with a hole, which is located below the body at the bottom of the chamber. The diffuser length $\ell_{diff.}$ is determined by the formula

$$l_{diff.} = \frac{\left(D_{pip.} - l_{m.p.} \cdot \frac{ctg\beta}{2}\right)}{2}, \quad (7)$$

where $D_{pip}$ – diameter of the outlet reclamation pipeline, m; $\beta$ – cone angle of the diffuser; $\ell_{m.p.}$ – length of the mixing pipe, m.

Considering the above conditions, the ratio of the diameter of the power cylinder to the discharge cylinder can be taken in the range from 1,8 to 2,0. The piston stroke of the fertilizer feed pump is taken from one to two diameters of the power cylinder. The optimal cycle duration for the injection devices is from 2,0 to 2,5 seconds and depends on the diameter of the discharge cylinder, piston stroke, and the flow rate of fertilizers supplied to the irrigator; they are related by the ratio

$$Q_{\text{F.F.}} = \frac{d_{\text{D.C.,}} \cdot \ell_{\text{P.S.}}}{T_{C.}}, \quad (8)$$

where $Q_{F.F.}$ – flow rate of liquid fertilizers, cm³/s; $d_{D.C.}$ – diameter of the discharge cylinder, cm; $\ell_{P.S.}$ – piston stroke of the discharge cylinder, cm; $T_C$ – cycle duration, sec.

The ratio of the power cylinder diameter to the outlet pipeline diameter ranges from 2,7 to 3,0.

The speed of movement of the hydraulic cylinder rod depends on the direction of fluid supply, which can be found from the expression

$$V_M = \frac{4 \cdot Q \cdot \eta_0}{\pi \cdot D_{CYL}^2}, \quad (9)$$

where $D_{CYL}$ – internal diameter of the hydraulic cylinder; $\eta_0$ – volumetric efficiency.

Hence, the ratio of the rod movement speeds in the indicated directions depends on the ratio of the hydraulic cylinder diameters. The force developed by the hydraulic cylinder when supplying fluid to the piston cavity is determined by

$$\mathrm{P}_P = \frac{\pi \cdot D_{CYL}^2}{4} \eta_0 \cdot \mathrm{P}. \quad (10)$$

It should be noted that the piston stroke of the hydraulic cylinder is linked to the design of the spool distributor, which prevents the piston from striking the covers in the hydraulic cylinders.

The results obtained during the research show that the calculation of the flow areas of spool hydraulic distributors is performed according to the formula

$$F_m = q \cdot h = \frac{Q}{V}, \quad (11)$$

where $F_m$ – flow area of the spool gap; $q$ – perimeter of the gap; $h$ – gap opening value; $Q$ – flow rate through the gap; $V$ – permissible fluid velocity through the gap.

Laboratory studies of the model showed the feasibility of the device, which ensures the injection of liquid fertilizer into the pressure pipeline using the potential energy of the water in the same pipeline, and also allowed for the refinement of the calculated ratios of structural parameters and the technical characteristics of the device. All this allows for the reduction of construction costs for production and mitigates the negative impact of liquid fertilizers during irrigation on the environment.

This device ensures a high degree of mechanization and automation of the fertilizer application process with irrigation water and does not require additional energy costs for supplying liquid fertilizers into the irrigation water flow. This factor improves the uniformity of nutrient application to the irrigated field, increasing crop yield while saving on fertilizer.

**Conclusion**

The developed technical design for a system for mixing various liquid fertilizers, as well as a pump equipped with an ejector unit for collecting and transporting the resulting mixture, minimizes environmental risks associated with the use of these fertilizers in irrigation. The proposed solution provides design organizations with an opportunity to modernize traditional technological schemes for supplying fertilizers, aimed at eliminating the shortcomings inherent in existing technologies. When substantiating the structural parameters of the technology for applying liquid fertilizers with irrigation water noted in the article, we have formed the main technical requirements for the device:

– the device provides an improved layout of distribution fittings, promoting uniformity of fertilizers applied with irrigation water across the reclamation system;

– the elements of the device are unified in manufacturing for closed reclamation systems by assembling from parts produced industrially at relevant factories;

– the device provides a high degree of automation of the process of applying fertilizers with irrigation water; does not require additional energy costs for supplying the fertilizer solution into the flow of irrigation water; improves the uniformity of nutrient application in the field; allows for top dressing at any time and during any plant development phase; improves nutrient uptake, increases crop yields while saving fertilizers.

A new technical solution, protected by patents, has been developed, ensuring the implementation of key research directions related to the technology of applying liquid fertilizers with irrigation water.

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# RESEARCH AND RENOVATION OF PEAT BOGS IN THE CENTER OF RUSSIA AND THE BELARUSIAN POLESIE

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**Abstract**

Under conditions of aridization in humid zone of Russia and Belarus there is a practical need to restore part of previously drained marsh landscapes for the ecological sustainability of the territory and the restoration of biotopes, improving fire safety and reducing greenhouse gas emissions. Rational nature management in peat bogs should be based on a scientific approach, with an assessment of the dynamics of modern natural processes in peat bog systems, both in their natural state and under anthropogenic impact. It is necessary to consider the totality of all wetland complexes used for various purposes and unused. In order to carry out works on reclamation arrangement of bogs and their use in agricultural production, it is necessary to develop rational methods for assessing the safety of peat soil and its durability. The article presents theoretical aspects of protection and rational use of peat bogs based on their ecological restoration. The issue of restoration of depleted peat bogs and scientifically substantiated prospects for studying peat bogs in national economic and ecological aspects in modern conditions are also considered. The rational use of peat bogs should be based on the type of water supply of the bogs, determining the nature of the peat deposit, types and methods of nature conservation and reclamation measures. The water regime is determined by the conditions of surface and groundwater runoff of watershed landscapes. In this regard, the direction of their use in industrial, agricultural and nature conservation areas is determined.

**Keywords:** peat bogs, reclamation, rational use, nature protection measures, renovation.

## ИССЛЕДОВАНИЯ И РЕНОВАЦИЯ ТОРФЯНЫХ БОЛОТ ЦЕНТРА РОССИИ И БЕЛОРУССКОГО ПОЛЕСЬЯ

**Ю. А. Мажайский, Л. Н. Гертман**

**Реферат**

В условиях аридизации гумидной зоны России и Беларуси возникает практическая необходимость восстановления части ранее осушенных болотных ландшафтов для обеспечения экологической устойчивости территории и восстановления биотопов, повышения пожарной безопасности и снижения выбросов парниковых газов. Рациональное природопользование на таких территориях должно базироваться на научном подходе, который связан с оценкой динамики современных природных процессов в торфяных болотных системах как в естественном состоянии, так и в условиях антропогенного воздействия. Необходимо рассматривать совокупность всех водно-болотных комплексов, используемых в различных целях, а также неиспользуемых. Для проведения работ по мелиоративному обустройству болот и возможному дальнейшему использованию их для различных целей, в том числе в сельскохозяйственном производстве, необходима разработка рациональных методов оценки сохранности торфяной почвы и ее долговечности. В статье изложены теоретические аспекты охраны и рационального использования торфяных болот на основе их экологической реабилитации. Рассмотрены вопросы восстановления выработанных торфяных болот и научно обоснованные перспективы изучения и использования торфяных болот в различных секторах экономики, с учетом экологических аспектов, в современных условиях, а также с учетом возможной трансформации территории в условиях изменяющегося климата. Рациональное использование торфяных болот должно учитывать тип водного питания болот, определяющем характер торфяной залежи, виды и методы проводимых природоохранных и мелиоративных мероприятий. Водный режим определяется условиями поверхностного и грунтового стока водораздельных ландшафтов, в связи с чем определяется направление их использования в промышленных, сельскохозяйственных и природоохранных целях.

**Ключевые слова:** торфяные болота, мелиорация, рациональное использование, природоохранные мероприятия, восстановление.

### Introduction

Peat bogs are natural formations that play an important role in the Earth's biosphere, preserving large reserves of fresh water and thereby determining the hydrological regime of the territory.

In Belarus, the goals and directions of swamp rehabilitation are regulated by such fundamental documents as the Strategy for the Conservation and Rational (Sustainable) Use of Peatlands [1] and the Scheme for the Distribution of Peatlands by Target Designation for the Period up to 2030 [2]. According to these documents, by 2030 it is planned to restore approximately 75,000 hectares of disturbed peatlands – depleted areas of peat deposits, degraded lands with peat soils, and swamps that have not been effectively drained by forest reclamation.

In the last 10 years with the support of international organizations such as the UN Development Programme (UNDP), Belarus has been restored to a water regime of 60,000 hectares of disturbed and inefficiently drained swamps [3]. There are a number of approaches for the effective rehabilitation of such territories [4–8]. For example, Belarus is testing methods for controlled winter burning of dry vegetation as well as sowing of swamp plants. The ecological rehabilitation of disturbed upper marshes is being successfully implemented through the construction of hydraulic engineering structures (jumpers, dams, locks) in order to control the groundwater level of drained peatlands.

To determine the most effective watering scheme (project) rationally use mathematical (numerical) modeling of the flood processes of drained wetlands during spring floods, which are the main sources of watershed water supply (70–90 % of total discharge) [9, 10].

### Purpose and methodology of the research

The purpose of the work is to provide scientific foundations for the protection and rational use of natural resources of bogs. The methodological basis is a systems approach, analysis, and synthesis of current regulatory documents [11–13], the authors' practices [14–18], and scientific


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research [19–20]. Today the main Belarussion ruls for rehabilitation of disturbed peatlands are seted out in TKP 17.12-02-2008 "Procedure and Rules for Conducting Work on the Environmental Rehabilitation of Depleted Peat Deposits and Other Disturbed Bogs and the Prevention of Disturbances to the Hydrological Regime of Natural Ecosystems During Reclamation Work" [13]. In accordance with the requirements of this regulatory document, a scientific justification for the environmental rehabilitation of the site and an environmental impact assessment are initially conducted, and only then are the necessary design and survey work carried out. This workflow does not allow for a full assessment of the feasibility, appropriateness, and results of the measures. On examples of some projects developed for sites in Russia, the possibility and necessity of using an integrated approach to planning the rehabilitation of depleted peat deposits is demonstrated, based on surveys and modeling of the existing and potential changes to the site's hydrological regime [14, 18].

**Materials and methods**

What is the difference between ecological restoration and traditional recultivation or so-called "flooding" measures as fire prevention measures or recultivation.

The main goal of ecological restoration is to restore the original ecosystem, which will be maintained by natural processes. Methods of ecological restoration are not only the restoration of the ecosystem structure, but also the main processes in ecosystems and ecosystem functions. The result of the work at the initial stage is not the final ecosystem, but the conditions for its formation later. Optimal ecological (abiotic and biotic) parameters must be set, they can then lead to the target ecosystem due to natural processes. In modern practice of nature management in many countries, this direction is often called – "working with nature" or "green engineering".

Methodology of ecological restoration of drained peat bogs is in the Table 1.

A natural ecosystem can be the object of recultivation in the Russian Federation and in the Republic of Belarus, for example, for greenhouse gas emissions. In this case, recultivation can be aimed at implementing climate-efficient solutions. Traditionally, this is planting forests on dry lands. In the case of drained bogs, afforestation leads to an increase in greenhouse gas emissions. The only possible approach in the case of peat bogs is the cultivation of crops on waterlogged lands or dual regulation systems of the hydrological regime. For example, a voluntary carbon market, or an ecosystem services market, or part of a business's social environmental or corporate responsibility program.

Like most projects, ecological restoration projects involve the steps shown in the figure, which are also part of the adaptive management cycle, since the results of the monitoring-based assessment may lead to further project adjustments. The adaptive management cycle has not been fully integrated into domestic nature management practices yet. The main stages of ecological and reclamation restoration of swamps recultivation project ends with an acceptance certificate, and at best, specific recommendations are given for maintaining the site for several years. Adaptive management does not exclude changes to the original project based on the results of monitoring data analysis.

The main stages of ecological restoration of swamps are shown in Figure 1.

Ecological restoration is based on comprehensive information about the current situation in three areas at each stage: information about the state of ecosystems – ecological and biotic parameters; information about the socio-economic situation; information about the legal basis for the implementation of the project.

The Table 2 provides an approximate list of information for each of the three blocks that is required at each stage.

**Table 1** – Methodology of ecological restoration of drained peat bogs

| | Ecological restoration | Recultivation, including climate-efficient technologies | Fire prevention measures |
|---|---|---|---|
| Purpose | Restoration of the natural ecosystem | Creation of an artificial ecosystem with specified economic and ecological characteristics[2] | Creation of conditions for reducing fire risk and/or fire suppression infrastructure |
| Indicators | Complex indicators/parameters of ecological processes or functions of a natural bogs ecosystem | Structural and functional characteristics of agricultural land, forest area or water body | Frequency of fires |
| Maintaining the state of the ecosystem | Mainly due to natural processes | Management during usage | Continuous target management |
| Costs of maintaining sites | No regular costs, limited costs possible when succession scenario changes, or for monitoring if the site is part of a special program that includes regular reporting[3] | The costs are mostly covered by the price of the produced products | High annual costs |
| Principles of technical solutions | The use of natural materials, technical solutions are based on modeling and forecasting of processes to achieve target indicators of abiotic and biotic characteristics | Traditional methods of recultivation to create conditions for the growth of forest or agricultural crops, including fish farming, functioning of a water body | Construction work on the creation of dual control systems, fire reservoirs and roads, creation of an artificial ecosystem |

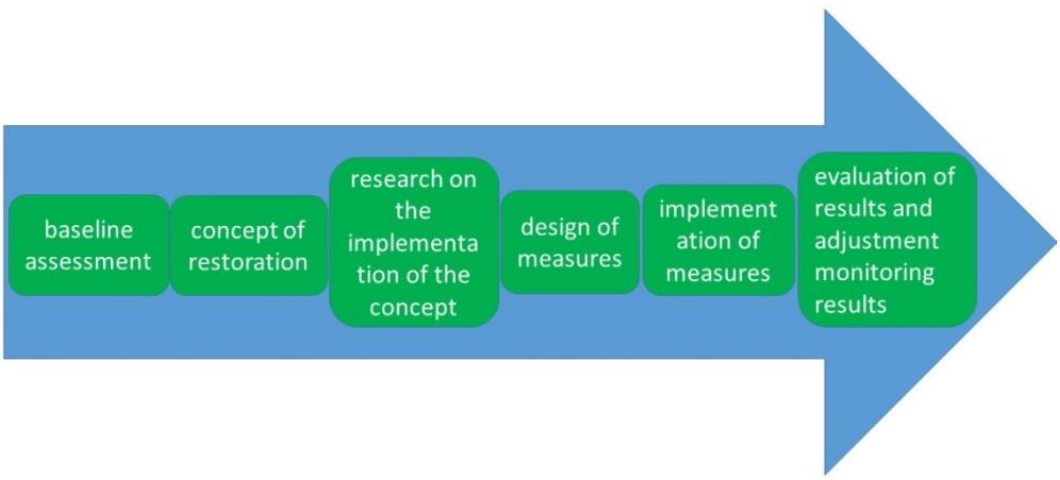


**Figure 1** – The main stages of ecological restoration of swamps

**Table 2** – Information for the stages of wetland restoration

| Stages of work/result | Tasks and content of stages | | |
|---|---|---|---|
| | Ecological block | Social and economic block | Legal block |
| Baseline Study / Baseline Study Report | Data on the state of abiotic and biotic ecosystem characteristics of the disturbed and background area. Definition of target parameters of the ecosystem<br>Additionally – data on the types of disturbances and their impact on the main characteristics | Estimation of ecosystem service losses in the disturbed area compared to the background one. Therole of the site in the economy and social life. The attitude of different groups to restoration | Information about the lands of the site. Land category, owner, user, nature of the relationship between the user and the owner, existing encumbrances and easements, rules for the use of natural resources based on the land category, encumbrances, easements, conditions of the owner and user |
| Concept (Project Concept) or pre-project solutions | Forecasting and modeling processes to achieve ecosystem targets Identifying structural parameters that will facilitate these processes | Forecasting the attitude of the population to various scenarios, the potential of the territory for the socio-economic situation | Checking proposed solutions for compliance with regulations and legislation |
| Engineering survey / Survey report | Identification of conditions for technical implementation of pre-design solutions | Study of the possibility of involving the population in the performance of work as volunteer assistance, prevention of counteraction, development of measures to support the conduct of research | Assistance in concluding contracts |
| Design (Development of engineering design)/project (Desing) | Alignment of models and technical solutions. Step-by-step planning and budgeting of works. Writing a project based on the concept and research, including a description of the monitoring scheme | Informing the public about design solutions, public hearings together with events to support design solutions | Checking proposed solutions for compliance with regulations and legislation. Assistance in concluding contracts |
| Project implementation / Work execution protocol and acceptance certificate | Supervision of implementation. Record-keeping | Involving the population in the implementation of the project – planting trees, etc. | Supervision of compliance with standards. Legal basis for further management of the territory<br>Preparation of acceptance and/or transfer acts |
| Monitoring the state of ecosystems | Defining parameters for monitoring, implementing a monitoring scheme | Involvement of the population in monitoring, publication of monitoring data | Legal status of information, degree of openness, authorship, legal possibility of wide distribution |
| Evaluation of project results | Evaluation of the progress of processes and the degree of achievement of target indicators, identification of deviations from processes | Evaluation of the population's attitude to the implemented project | Evaluation of the legality of the measures and grounds for further work |
| Recommendations for project adjustments | If necessary, set new intermediate target parameters | Taking into account the opinions of different population groups | Checking proposed solutions for compliance with regulations and legislation |

**Theoretical research results**

The work on the development of swamps has begun in the 50s of the last century with the aim of using waterlogged lands in agriculture. The following areas have been defined: drainage network parameters have been developed; peat soil drainage modes have been studied; a system of farming on drained peat soil has been developed; peat sedimentation and depletion processes have been studied; the effect of bogs drainage on the adjacent territory has been studied.

The reclamation condition of drained peat lands has significantly worsened due to the lack of proper maintenance of the drainage network and its repair. Work on the reconstruction of drainage systems has also been completely stopped, which has led to the abandonment of previously used peat soil in agricultural production.

The rational use of peat bogs should be based on the type of water supply of the bogs, determining the nature of the peat deposit, types and methods of nature conservation and reclamation measures. The water regime is determined by the conditions of surface and groundwater runoff of watershed landscapes. In this regard, the direction of their use in industrial, agricultural and nature conservation areas is determined. It is necessary to develop: recommendations for the formation and implementation of agroecological monitoring of reclaimed agricultural landscapes; new technical and technological solutions aimed at rational measures to preserve the fertility of residual peat soil; measures for the environmental protection of peat bogs from the intensive production load of their use; hydrological and agro-meliorative measures for the recultivation of exhausted and depleted peat lands or the return of the bog ecosystem to its original state (their restoration).

Restoration of exhausted and depleted bogs of the Meshcherskaya lowland and Belarusian Polesie. Restoration of bogs is carried out in stages. There are the following stages of restoration: **initial situation** (bog after use of peat extraction or in agriculture); **over-watering** (restoration of the hydrological regime – 10 years); **renaturalization** (restoration of natural vegetation – 10–100 years) and **regeneration** (the process of peat accumulation over 100 years).

The process of waterlogging is considered as the primary stage of bogs restoration, which is characterized by an increase in the water level almost at the surface for 3–5 years until it stabilizes.

The second stage (renaturalization) consists of the restoration of the natural bog vegetation cover and is defined as a technically controlled measure, after which the regeneration of the peat bog begins. In general, bog regeneration is understood as a set of natural processes and artificial technical measures that affect the renewal of bog formation and peat accumulation processes.

It should be noted that the regenerated bog develops thanks to special measures much faster than natural development.

The stage of over-wetting is the most critical moment in the restoration of the bog, since the increase in the water level to the surface of the developed peat will increase the level of groundwater in the adjacent territories. In this regard, it is necessary to study the impact of bog flooding on the ecology of the adjacent territories.

**Conclusion**

It is necessary to conduct a patent search for technologies and technological solutions that can be used in modern conditions, a comprehensive reconnaissance survey of all bogs, their quantity, area, efficiency of use, types of bogs, water-physical and agrochemical properties of peat and mineral adjacent soil, and also to evaluate the work of reclamation systems.

Nature restoration work to return to the environment must be carried out according to specially developed projects, taking into account the recommendations and methodology outlined in this article. This will make it possible to resume peat accumulation and habitat for the animal and plant world of wetlands. This is shown by the existing experience in the center of Russia and the Belarusian Polesie.

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# DIGITAL PROCESS REGULATIONS FOR ENVIRONMENTALLY SAFE DIVERSION AND TREATMENT OF WASTE WATER FROM WOOD PROCESSING PLANTS

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**Abstract**

The environmental hazard from formaldehyde-containing wastewater from wood processing enterprises was analyzed, including their extremely negative impact on active sludge from biological treatment facilities. The disadvantages of using technological regulations at production plants were assessed, which made it possible to substantiate the main tasks in improving the efficiency of technical regulation of water use. Schemes of digital technological regulations for wastewater diversion and treatment have been substantiated and developed, which has a structural similarity with digital twins in terms of the implementation of operational monitoring. The use of fuzzy neural networks, which provide the generation of production rules, in this case, which are the basis of intellectual knowledge bases, has been proposed and tested for modeling preliminary chemical cleaning. A structural diagram of the corresponding digital technological regulation was substantiated and created, consisting of two methodological and algorithmic blocks: monitoring of processes that have static boundary values of technological parameters and a single intellectual knowledge base of processes that determine environmental safety according to the parameters "Concentration of formaldehyde," "Chemical oxygen consumption" and "pH." An algorithm for the implementation and regular operation of such a software and hardware complex has been developed. The main advantages of the proposed digital technological regulations for the disposal and treatment of formaldehyde containing wastewater from wood processing enterprises have been identified.

**Keywords:** formaldehyde containing wastewater, technological regulations, wastewater diversion, local treatment facilities, fuzzy neural networks, intellectual knowledge base.

## ЦИФРОВОЙ ТЕХНОЛОГИЧЕСКИЙ РЕГЛАМЕНТ ЭКОЛОГИЧЕСКИ БЕЗОПАСНОГО ОТВЕДЕНИЯ И ОЧИСТКИ СТОЧНЫХ ВОД ДЕРЕВОПЕРЕРАБАТЫВАЮЩИХ ПРЕДПРИЯТИЙ

**В. Н. Штепа, А. В. Дубина, О. Н. Прокопеня**

**Реферат**

Проанализирована экологическая опасность от формальдегидсодержащих сточных вод деревоперерабатывающих предприятий, включая их крайне негативное воздействие на активный ил биологических очистных сооружений. Оценены недостатки применения на производствах технологических регламентов, что позволило обосновать основные задачи при усовершенствовании эффективности технического регулирования водопользования. Обоснованы и разработаны схемы цифрового технологического регламента отведения и очистки сточных вод, который имеет структурное подобие с цифровыми двойниками в части реализации оперативного мониторинга. Предложено и проверено для моделирования предварительной химической очистки применение нечетких нейронных сетей, которые обеспечивают генерацию продукционных правил, в данном случае, являющихся базисом интеллектуальных баз знаний. Обоснована и создана структурная схема соответствующего цифрового технологического регламента, состоящего из двух методико-алгоритмических блоков: мониторинга процессов, имеющих статические краевые значения технологических параметров и единую интеллектуальную базу знаний процессов, определяющих экологическую безопасность по параметрам «Концентрация формальдегида», «Химическое потребление кислорода» и «рН». Разработан алгоритм внедрения и штатной эксплуатации такого программно-аппаратного комплекса. Определены основные преимущества предложенного цифрового технологического регламента отведения и очистки формальдегид содержащих сточных вод деревоперерабатывающих предприятий.

**Ключевые слова:** формальдегидсодержащие сточные воды, технологический регламент, водоотведение, локальные очистные сооружения, нечеткие нейронные сети, интеллектуальная база знаний.

### Introduction

Wood processing waste water is an environmental hazard due to the content of formaldehyde, which is a highly toxic, carcinogenic substance of the first hazard class [1, 2]. It can cause cancer, genetic mutations and pollute natural water reservoirs, catastrophically reducing their suitability for life [3]. To prevent harm, cleaning methods are used, including physicochemical (ozonation, flotation) and biological (use of microorganisms), as well as modern technologies of the class of advanced oxidative processes [4].

Negative environmental consequences of exposure to formaldehyde [5, 6]:

– toxicity: is a poisonous substance that negatively affects the health of humans and animals, affecting their airways and central nervous system;

– carcinogenicity and mutagenicity: the substance has properties that promote cancer and genetic changes, which makes it extremely dangerous for living organisms in the long term;

– pollution of water resources: getting into water reservoirs, formaldehyde pollutes water, making it unsafe for drinking and life of aquatic life, as well as reducing the general ecological state of the environment.

Accordingly, it is necessary to ensure effective treatment of waste water discharged into natural reservoirs by wood processing enterprises [7]. At the same time, in cases of diversion of waste water in municipal sewage systems, environmental risks remain to a greater extent: formaldehyde, even in insignificant concentrations, causes the death (or suppression) of the active sludge of biological treatment facilities, which in turn leads to the ingress of biogenic elements into geo-eco-systems and their degradation.

Technological control of the processes of reducing pollutants is complicated by the multifactorial nature of the processes: the parameters in real time stochastically, non-stationary, non-linearly change. Thus, the creation of approaches aimed at systematizing the experience of water use and treatment of formaldehyde-containing wastewater in a uniform regulatory electronic document, with the possibility of its prompt adaptation, is an urgent scientific and practical task.

**Task statement.** Substantiation of the creation of digital technological regulations in order to reduce the risks of abnormal technological situations and increase the environmental safety of diversion (discharge) of formaldehyde containing wastewater.

**Analysis of the principles of creating technological regulations and shortcomings of their production use**

GOST R 44.101-2025 «Production Process Preparation System. Process regulations. Basic provisions», technological regulations – a document containing a general description of the production of products, a description of the technological process in the sequence of its implementation, information on the composition of technological equipment, safe production conditions, as well as environmental protection requirements. As a rule, it includes [8] a detailed description of operations for the following items [9]: technical parameters, equipment used, algorithm for performing actions, set of instructions, safety measures (including environmental measures).

Generically, the development and implementation of technological regulation consists of three basic stages:

1. Systematic analysis of production processes, with an assessment of the technological architecture, key target technical and economic indicators, probable risks.
2. Creation of the process regulation, based on the results of the first stage and according to the developed and agreed nomenclature of technological regulation for a specific facility.
3. Approval, implementation and regular use, with correction of identified non-conforming aspects.

In practice, the following disadvantages arise (in a significant number of cases), which significantly reduce the effect of the use of technological regulations, or even lead to a further rejection of its use at facilities:

– there are no expected qualitative changes – production does not meet the set targets;

– requirements set forth in the technological regulations are either not fully implemented or only partially implemented in the field due to the weak consistency of the actual situation.

Analysis of the use of process regulations at real facilities allows us to identify the following factors leading to negative (compared to the planned) results:

– TR do not take into account the rapidly changing technological situation and, accordingly, under certain conditions, their implementation not only does not allow achieving the target parameter values, but can lead to undesirable abnormal situations;

– management and engineering personnel initially do not make sufficient efforts to create a system technological regulations;

– training of personnel for its practical implementation is extremely weak;

– with normal operation, a situation arises when it turns out that the outfit of allocated resources is insufficient – with the traditional approach of creating technological regulations, it is often necessary to re-develop it.

Summarizing, we can say that the complex disadvantages of the effective use of technological regulations are the non-obviousness at the stage of developing their effectiveness and the complexity in normal operation of the operational change of their requirements, primarily in terms of difficult to formalize production parameters.

**Substantiation of the content of technological regulations for diversion and treatment of formaldehyde containing waste water from wood processing enterprises**

Changes in the proposed regulatory documents of internal use of wood processing enterprises (their TR) relate to components directed to improving control over compliance with the quality of divtrsion and treatment of formaldehyde containing wastewater [10], resource efficiency, and countering the occurrence of emergency situations [11, 12]. At the same time, a certain requirement for the object is the declared need or expectations, which are fixed in technical regulations, standards, technical specifications or otherwise. The object of compliance is a specific material, product, installation, process, service, system, respectively, and units for the use, disposal and treatment of aqueous solutions correspond to this definition [13]. Therefore, tests should be carried out on them (determination of the characteristics of the subject of assessment) and an assessment of their compliance with regulatory documents (a process for confirming that the requirements regarding products, process, services, systems have been met). Such requirements are based precisely on technological regulations.

Mandatory components of technological regulations, the requirements of which must be met by documents valid at wood processing enterprises [14]:

– characteristics and peculiarities of operation of local treatment facilities;

– quality control of water solutions at the entrance to various equipment and treated waste water during diversion (discharge);

– information on: the volume of water use, water diversion (discharge), consumption of electricity and other consumables (for example, reagents) used to ensure the stable operation of the system for using process water and removing pollutants from wastewater.

At the same time, there are factors that comprehensively create prerequisites for the inefficiency of metrological activities within the framework of ensuring the uniformity of measurements of the technological regulations compliance assessment under dynamic conditions [15, 16]:

– impossibility to accurately predict changes in pollutant concentrations at different stages of water resources use, including their treatment;

– lack of adequate dynamic models of formaldehyde-containing wastewater formation and treatment processes.

Both of the above factors justify the main purpose of using technological regulations for water use, diversion and treatment of formaldehyde-containing wastewater to improve the observability of waste water pollution processes and their treatment on local treatment facilities. Both of the above factors justify the main purpose of using technological regulations for water use, disposal and treatment of formaldehyde-containing wastewater to improve the observability of waste water pollution processes and their treatment on local treatment facilities.

**Assessment of processes for diversion and treatment of formaldehyde containing waste water from wood processing plants**

At the initial stage, based on the regulatory framework of digital twins, it is possible to present technological regulation as a comprehensive monitoring system (Figure 1).

The general parametric scheme for the disposal and purification of formaldehyde containing wood processing waste water, which the digital technological regulation should programmatically simulate, includes data from automatic measuring instruments, test results from an accredited laboratory and expert opinions (Figure 2). It should be noted that the monitored parameters that determine the environmental safety of wastewater for geo-eco-systems are: "Formaldehyde concentration," "Chemical oxygen consumption" and "pH".

Within the framework of wood processing enterprises, the enlarged sequence of formaldehyde containing pollutants of waste water formation and their reduction will represent a phased multifactor model (Figure 3).

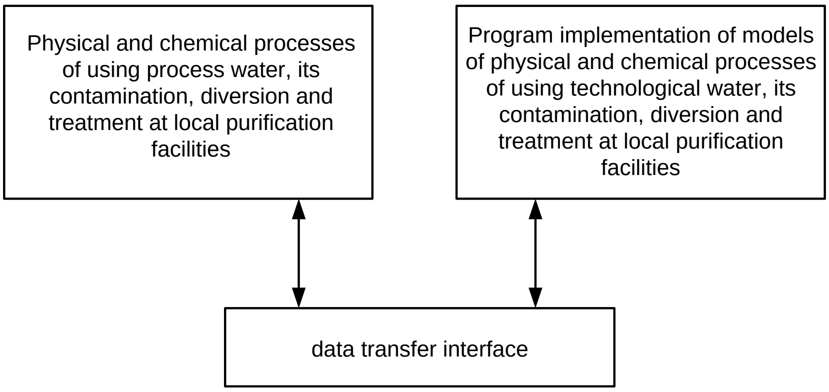


**Figure 1** – Information architecture of digital technological regulation for wastewater disposal and treatment


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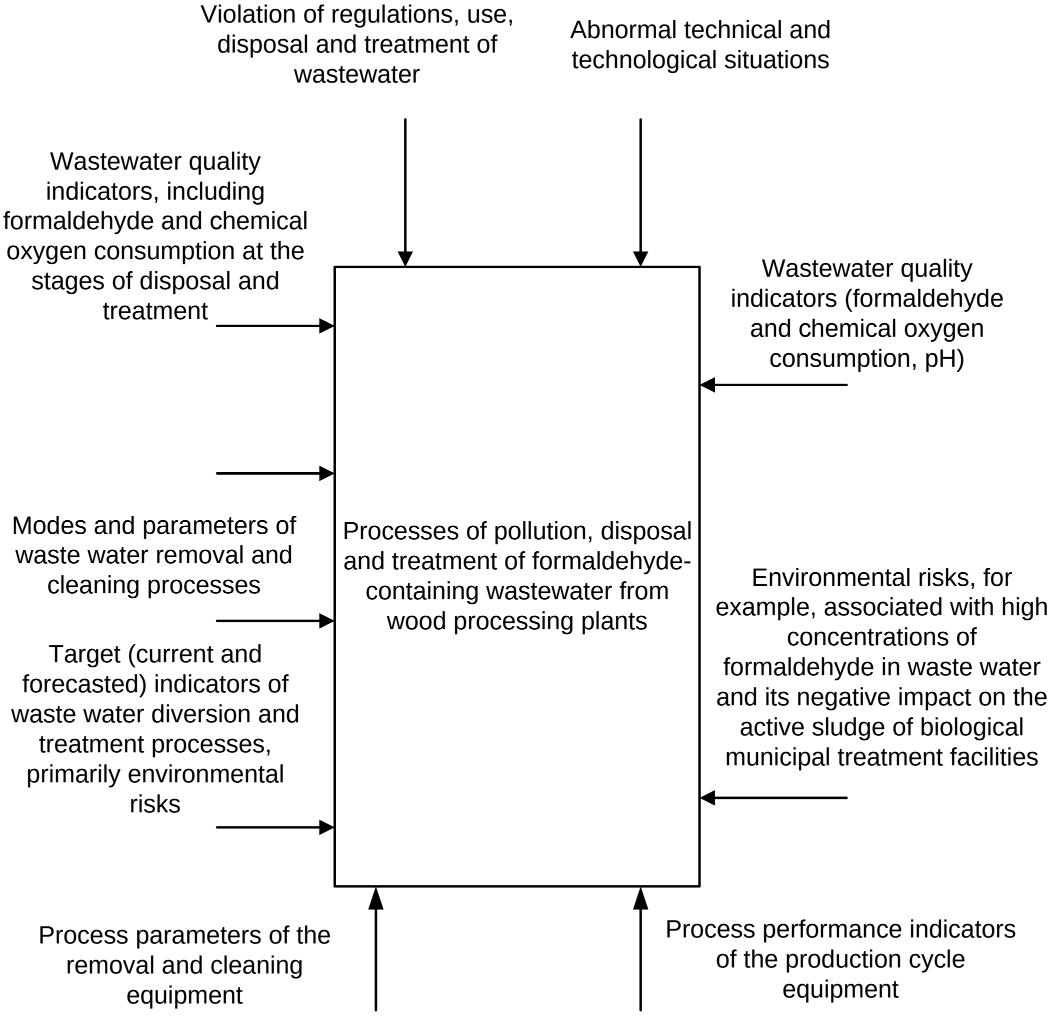



**Figure 2** – Parametric scheme of consumption, diversion and treatment of formaldehyde containing waste water

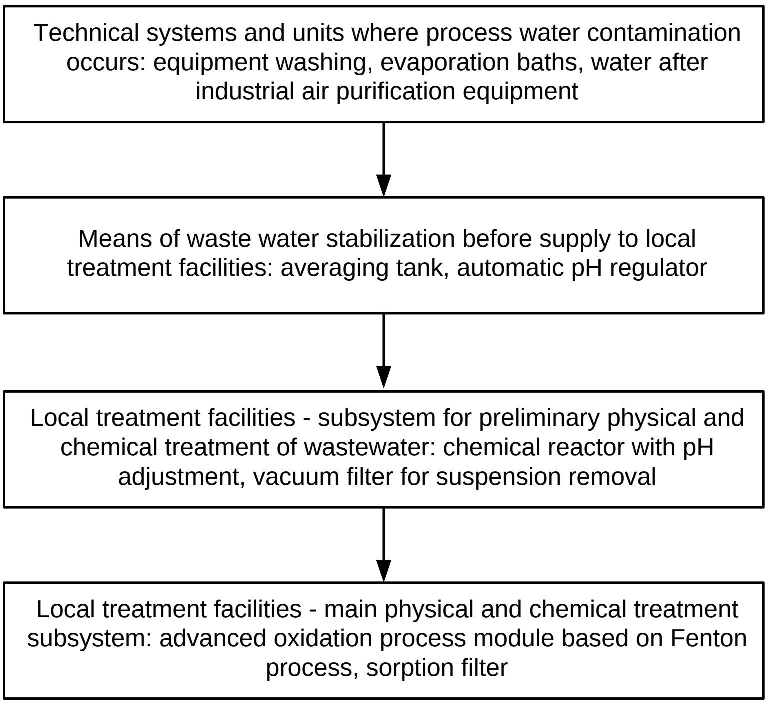



**Figure 3** – Variants of formaldehyde containing pollutants of waste water formation and their reduction at wood processing plants

Based on system analysis and experimental studies [2–5], processes were determined that mainly determine the environmental safety of the diversion of formaldehyde-containing wastewater:

– stabilization of waste water in the averaging tank before supply to local treatment facilities according to the “pH” parameter;

– control of preliminary physical and chemical cleaning of waste water in a chemical reactor according to “pH” and reaction time;

– control of the main physical and chemical treatment of waste water in the advanced oxidation processes module within the framework of the modified Fenton reaction in terms of “pH”, “reaction time”, “concentration of iron ions”, “concentration of hydrogen peroxide”.

To monitor precisely such processes that do not have adequate dynamic models in the form of, for example, differential equations, it is advisable to apply an intelligent approach, for example, based on the use of fuzzy neural networks [17].

**Neural network modeling and formation of production rules of the intellectual knowledge base**

Technical regulation of formaldehyde-containing wastewater treatment processes is implemented using fuzzy neural networks and an error propagation algorithm. It includes the following steps [18, 19].

1. Some $\eta$ $(0 < \eta < 1)$, $E_{max}$ and some small random weight of the neural network are set.

2. $k = 1$ and $E = 0$ are entered.

3. The next training pair $(x^k, y^k)$ and designations are set

$$x := x^k, \quad y := y^k, \tag{1}$$

and the network output value is calculated

$$O = \frac{1}{1+e^{-W^T o}}, \tag{2}$$

where $W$ is the vector of weights of the output neuron ($W^T$ is the transposed vector), $o$ is the vector of outputs of neurons of the hidden layer with elements

$$o_i = \frac{1}{1+e^{-w_i^T x}}, \tag{3}$$

$w_i$ – denotes the vector of weights associated with the $i$-th hidden neuron, $i = 1,2, ..., L$.

4. The weights of the output neuron are adjusted

$$W := W + \eta\delta o, \tag{4}$$

where

$$\delta = (y - O)O(1 - O). \tag{5}$$

5. The weight of neurons of the hidden layer is corrected

$$w_i := w_i + \eta\delta w_i o_i (1 - o_i), \quad i = 1,2,...,L. \tag{6}$$

6. The value of the error function is corrected (increased)

$$E := E + \frac{1}{2}(y - o)^2. \tag{7}$$

If $k < N$, then $k := k + 1$ and proceed to step 3.

7. Completion of the training cycle. If $E < E_{max}$, then the end of the entire training procedure.

If $E \geq E_{max}$, then a new learning cycle begins and proceeds to step 2.

Fuzzy neural networks synthesis is implemented in MatLAB ANFIS-Editor applied mathematical software package. The statistical data on the basis of which a fuzzy inference system was created were the results of laboratory studies of industrial wastewater from wood processing enterprises and systematic production analyzes of an accredited laboratory for assessing the quality of wood products [20].

Using the example of a chemical reactor and the "Formaldehyde concentration" environmental hazard indicator, a neural network modeling was tested (Figure 5) – 350 sets of training data were used.

As a result of fuzzy neural networks synthesis, production rules are formed on the basis of MatLAB ANFIS-Editor package of applied mathematical programs, which are the basis of the knowledge base of water treatment in a chemical reactor, it, in turn, acts as an intellectual component of the digital technological regulations of such a waste water purification unit (Figure 4).

Using the production rules of individual intellectual knowledge bases (stabilization of wastewater in the averaging tank before feeding to local treatment facilities, control of preliminary physical and chemical treatment of waste water in a chemical reactor, control of the main physical and chemical treatment of waste water in the module of advanced oxidative processes) with the implementation of fuzzy neural networks, a single block of the intellectual knowledge base is formed [21] of the digital regulations for the disposal and reduction of pollutants.

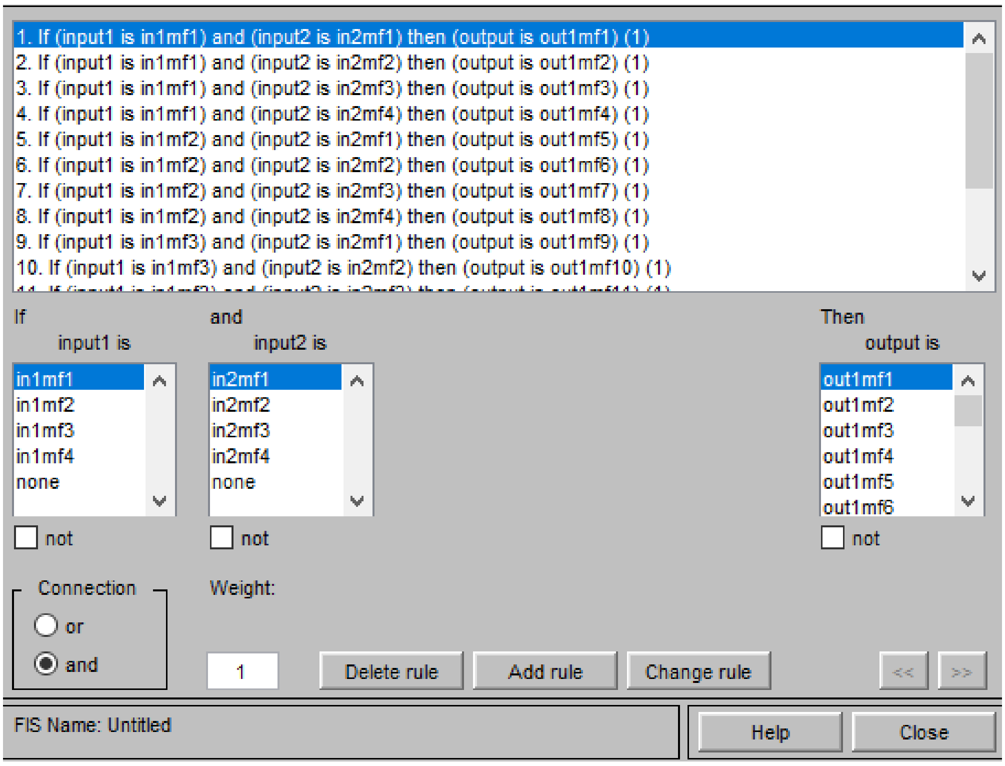
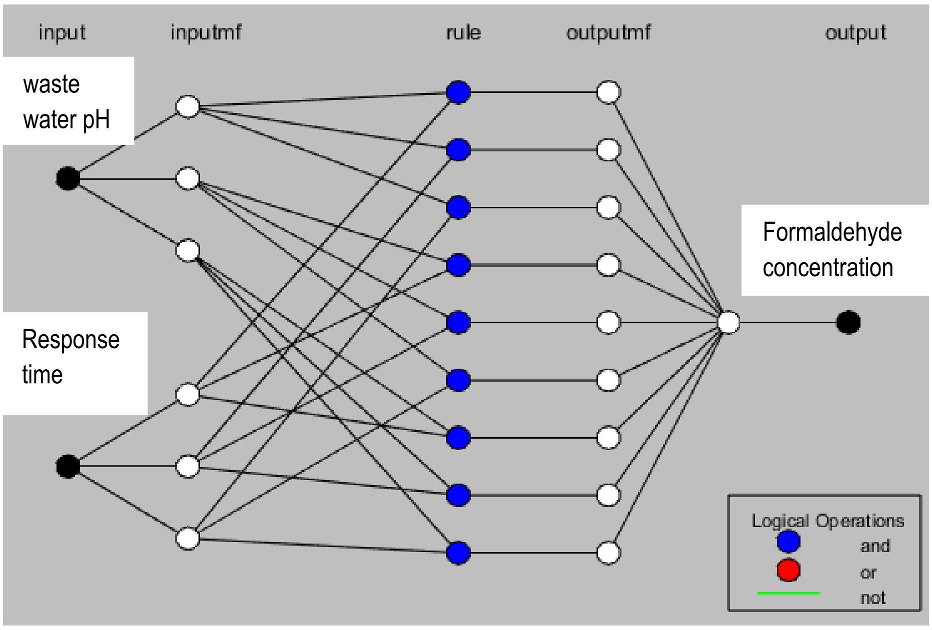
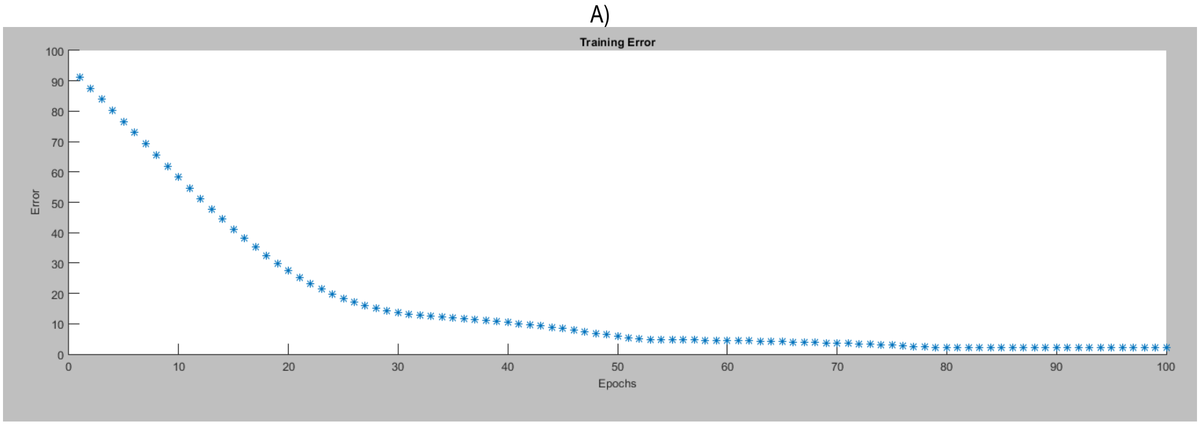


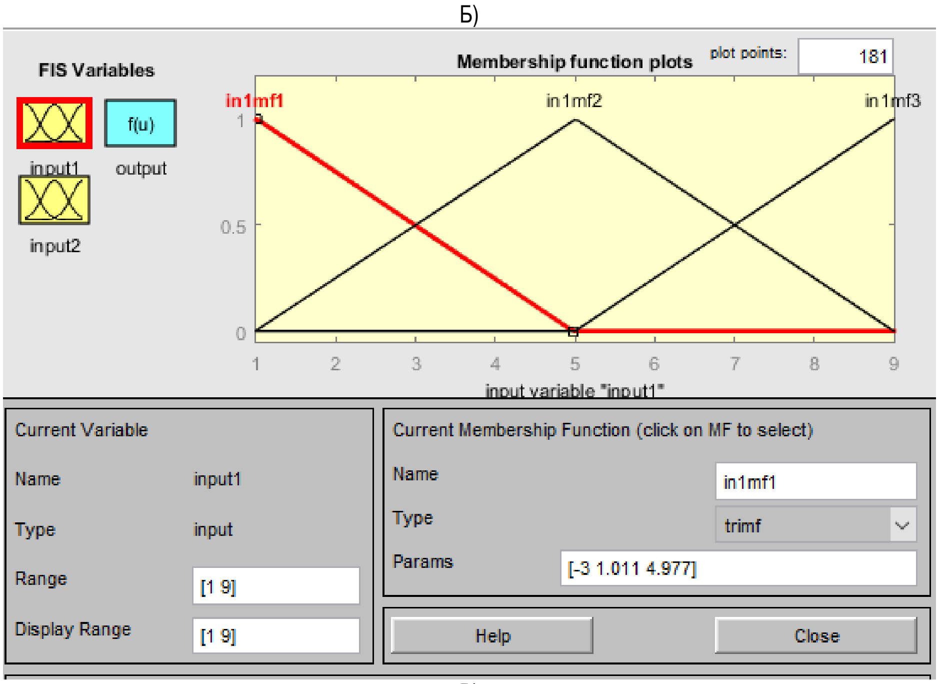

**Figure 4** – Production rules of the intellectual knowledge base for treatment of formaldehyde containing waste water from wood processing plants




A)




Б)




B)

A – neural network architecture; B – neural network training process (100 eras used, quality criterion – relative root-mean-square error); C – created fuzzy inference system (parameter membership functions)

**Figure 5** – Neural network modeling of processes for the treatment of formaldehyde containing wastewater from wood processing enterprises in a chemical reactor

**Methodological aspects of the functioning of digital technological regulations for the disposal and treatment of formaldehyde containing waste water from wood processing enterprises**

At the same time, the developed digital technological regulation consists of two main methodological and algorithmic blocks: one of them provides monitoring of processes having discrete control law (this program logic, as a rule, includes edge values of process parameters beyond the boundaries of which may lead to abnormal situations, including emergency situations, environmental risks or/and significant electricity overruns (other consumables); the second block is an intellectual knowledge base of processes that determine environmental safety, functioning using fuzzy neural networks, which also simulate technological risks (Figure 6).

In this case, the sequence of operation of the digital technological regulation (Figure 7) will include the initial use of expert settings obtained, including in laboratory conditions, with a phased transition to a comprehensive intelligent architecture (Figure 6).

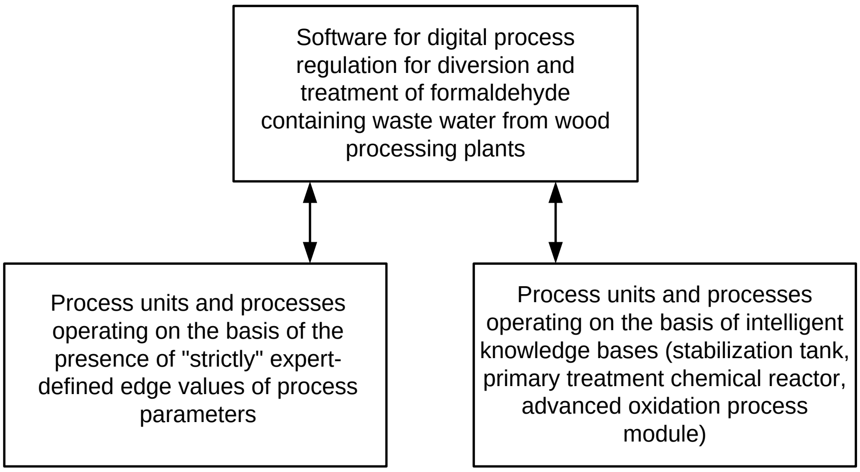



**Figure 6** – Scheme of algorithmic support of digital technological regulation for diversion and treatment of formaldehyde containing waste water of wood processing enterprises

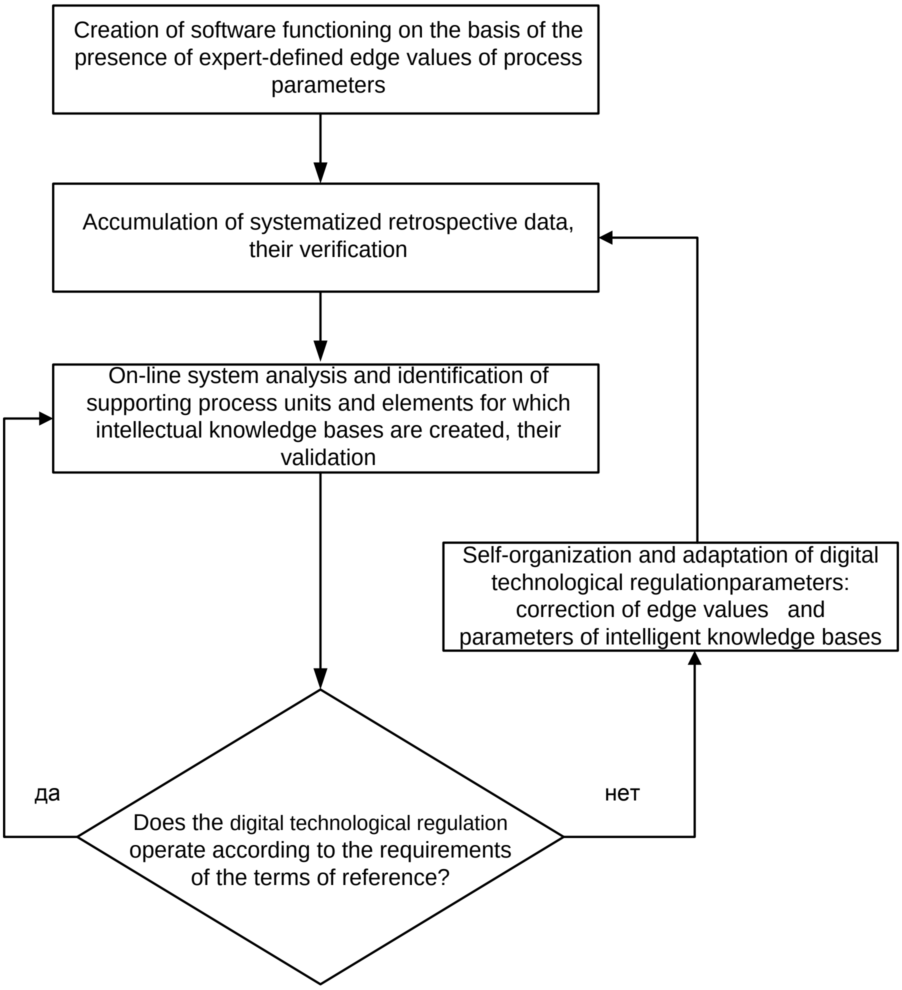



**Figure 7** – Block diagram of implementation and regular operation of digital process regulations for diversion and treatment of formaldehyde containing waste water from wood processing plants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Digital technological regulation for diversion and treatment of formaldehyde containing waste water:

– is an information and analytical tool for monitoring the operation of the entire complex of equipment and specialists of the water use system (increasing the productivity of employees of enterprises, resource-efficiency of processes and reducing environmental and technological risks);

– a tool for prompt (actually real-time) preparation of adequate technical specifications for modernization (reconstruction) of the water use system, diversion and treatment;

– a system for supporting management decisions aimed at improving the environmental safety and technical and economic efficiency of wood processing enterprises, capable of prompt adaptation and automatic adjustment of technological requirements for the passage of processes.

**Conclusion**

Wood processing enterprises pose a significant environmental hazard, including natural water reservoirs, primarily due to the content of formaldehyde, which is a highly toxic, carcinogenic substance of the first hazard class, which also negatively affects the active sludge of biological municipal treatment facilities – accordingly, effective regulation of the diversion and treatment of these waste water is an important task. At the same time, the analysis of the practical implementation of technological regulations at production facilities allows us to single out a number of important shortcomings of the existing approaches: technological regulation do not take into account the rapidly changing technological situation, management and engineering and technological personnel initially do not make sufficient efforts to create a system technological regulation, training of personnel for its practical implementation is extremely poorly performed, during normal operation there are situations when it turns out that the order of allocated resources for its implementation is insufficient.

To overcome such shortcomings, the digital technological regulation for the diversion and treatment of waste water, which is a software and hardware complex and has a structural similarity with a digital twin, must perform operational monitoring of the characteristics of the use of process water, its pollution, diversion and treatment at local treatment facilities. It is justified to divide the digital technological regulation into two main methodological and algorithmic blocks: monitoring of processes with static edge values of technological parameters, going beyond the boundaries of which can lead to emergency situations, including emergency situations, environmental risks, or/and significant excess consumption of electricity (other consumables); a single intellectual knowledge base of processes that determine environmental safety in terms of "Concentration of formaldehyde," "Chemical oxygen consumption" and "pH", functioning using fuzzy neural networks and capable of automatic adaptation.

Further studies should solve the problems of synchronizing the interaction of the equipment of "disposal-cleaning" of the waste water and the production cycle systems affecting the indicators of contamination of process water.

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# THE SIMULATION OF THE THERMAL REGIME OF SODDY-PODZOLIC SOILS OF BELARUSIAN POLESIE

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**Abstract**

This article presents the results of a comprehensive modeling study aimed at predicting heat transfer dynamics in soddy-podzolic soils in the Belarusian Polesie region. The study covers a time horizon up to 2035 and takes into account two key factors:

1) various land drainage standards, varying in intensity and technological parameters;

2) global climate change, expressed in a persistent trend of increasing average surface air temperature.

To achieve this goal, an original methodological framework based on mathematical modeling methods was developed. The proposed approach allows:

• for reproducing the spatiotemporal dynamics of the temperature field in a soil profile;
• comparing the thermal regimes of natural (unamendied) and drained soils;
• assessing the impact of atmospheric temperature anomalies on the thermal state of the soil cover.

The computational experiments resulted in the generation of a predictive data set, including:

• detailed soil temperature profiles for various drainage scenarios;
• quantitative assessments of temperature gradients across the depth of the soil profile;
• time series of temperature readings with a step corresponding to climatic seasonality.

The practical significance of the obtained results lies in their potential for application in reclamation agriculture. In particular, the developed predictive models can be used:

• in designing water management systems in reclaimed areas;
• optimizing water supply schedules and drainage measures;
• developing adaptive strategies for managing agricultural landscapes in a changing climate;
• assessing the risks of overheating or overcooling of the root zone under various drainage scenarios.

Thus, the conducted study creates a scientifically sound basis for making management decisions in the field of reclamation, allowing for consideration of both local hydrological conditions and macro-scale climate trends.

**Keywords:** Belarusian Polesie, modelling, soddy-podzolic soil, melioration, temperature, heat capacity, amount of heat.

## МОДЕЛИРОВАНИЕ ТЕПЛОВОГО РЕЖИМА ОСУШЕННЫХ ДЕРНОВО-ПОДЗОЛИСТЫХ ПОЧВ БЕЛОРУССКОГО ПОЛЕСЬЯ

**А. А. Волчек, В. В. Борушко**

**Реферат**

В настоящей статье представлены результаты комплексного моделирования, направленного на прогнозирование динамики теплопереноса в дерново подзолистых почвах региона Белорусского Полесья. Исследование охватывает временной горизонт до 2035 года и учитывает два ключевых фактора:

1) различные нормативы осушения земель, варьирующие по интенсивности и технологическим параметрам;

2) глобальные климатические изменения, выражающиеся в устойчивом тренде повышения средней температуры приземного слоя воздуха.

Для достижения поставленной цели разработана оригинальная методическая база, основанная на методах математического моделирования. Предложенный подход позволяет:

• воспроизводить пространственно временную динамику температурного поля в почвенном профиле;
• сравнивать термические режимы естественных (немелиорированных) и осушенных почв;
• оценивать влияние атмосферных температурных аномалий на тепловое состояние почвенного покрова.

В результате вычислительных экспериментов сформирован массив прогнозных данных, включающий:

• детализированные температурные профили почв для различных сценариев осушения;
• количественные оценки градиентов температуры по глубине почвенного профиля;
• временные ряды температурных показателей с шагом, соответствующим климатической сезонности.

Практическая значимость полученных результатов заключается в их прикладном потенциале для сферы мелиоративного земледелия. В частности, разработанные прогнозные модели могут быть использованы:

• при проектировании систем регулирования водного режима на мелиорированных территориях;
• оптимизации графиков водоподачи и дренажных мероприятий;
• разработке адаптивных стратегий управления агроландшафтами в условиях изменяющегося климата;
• оценке рисков перегрева или переохлаждения корнеобитаемого слоя при различных сценариях осушения.

Таким образом, проведенное исследование создает научно обоснованную базу для принятия управленческих решений в области мелиорации, позволяя учитывать как локальные гидрологические условия, так и макромасштабные климатические тренды.

**Ключевые слова:** Белорусское Полесье, моделирование, дерново-подзолистая почва, мелиорация, температура, теплоемкость, количество теплоты.

**Introduction**

The country's food security is linked to an increase in gross agricultural production. Its implementation is associated with the inclusion of more land in agricultural trade and increased crop yields. The solution to the first question is problematic. In addition to seed quality and fertilizer application, the maintenance of optimal water-air and heat regimes in agricultural soils is a major factor in improving crop yields. Soil thermal and water-air regimes are factors that often largely determine the agricultural productivity of land. Land productivity is primarily associated with the application of necessary fertilizers, use of new varieties, control of plant weeds etc [1–3]. Less attention is paid to the microclimate of dry areas. According to the theory of V. R. Williams, dewatering should reduce excessive soil moisture to such a size that provides the necessary water, air, heat, microbiological and nutritional regime of the soil. The climate change occurring in the territory of Belarus, as well as in Europe as a whole, in recent decades is expressed in increasing air temperature in all months of the year. Changes in agro-climatic indicators during the growing season are of particular importance for agricultural production efficiency. These changes are most noticeable in the territory of Belarusian Polesie, which, due to its geographical location, is characterized by the highest heat availability and length of the growing season in Belarus.

The decrease in the amount of precipitation over the past decades at the Poleskaya station, located on the territory of the Luninets swamp massif, and at nearby stations allows us to conclude that the implementation of reclamation work on large areas (Luninets swamp massif, Poleskaya station), which has led to a decrease in forest cover and roughness of the underlying surface, leads to an increase in wind speed and a decrease in the amount of precipitation, especially during the cold period [4].

The observed increase in atmospheric moisture runoff in the absence of a compensating increase in precipitation leads to a decrease in the resilience of the soil cover of the Belarusian Polesie to extreme temperature conditions and moisture deficit, with the most pronounced negative consequences recorded on the arable lands of the region in question.

Establishing patterns of microclimate change in land reclamation, and predicting its changes is one of the important tasks of agriculture.

The aim of this study is to investigate the patterns of formation of the thermal regime of meliorated bottom-soddy-podzolic soils of Belarusian Polesie under current conditions and estimate its change in the period until 2035 due to climate warming, which is one of the important tasks of agriculture.

The Research methods and raw data.

The thermal conductivity equation [5, 6, 7, 8] is used to describe the pattern of formation of the soil temperature profile

$$\rho C_p \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right), \quad (1)$$

where ρ – density, kg/m3; Cp – heat capacity, J/(mol K); k – thermal conductivity, W/mK; T – temperature, $^0$K; $\nabla$ – hamiltonian.

Solar radiation is the primary energy source responsible for the thermal regime of the Earth's surface. When interacting with the soil cover, radiant energy is converted into thermal energy, after which it is redistributed in two directions: conductive transfer to the underlying soil layers or emission into the atmosphere through thermal radiation and reflection [9]. The balance between absorbed and emitted energy represents the amount expended on heating the Earth's surface. An increased temperature gradient between the upper and lower soil horizons leads to an increase in the proportion of thermal energy migrating into the depths of the soil profile [10].

The numerical modelling of the thermal regime of soils [11] is reduced to computations of their temperature profiles [12].

For this purpose, a mathematical modelling method is used which allows, using the initial climatic conditions, to calculate the dynamics of the soil temperature profile and calculate the amount of accumulated heat [13].

To quantify the change in soil heat capacity, a numerical experiment was carried out according to the following scheme: 5 $m^3$ of soil with dimensions 1 m – width, 1 m – length and 5 m – depth, were taken as a conditional volume; the selected depth value corresponds to the level, at which the temperature fluctuations associated with the degree of heating of the air by solar rays [14, 15] cease.

The study considered the soddy-podzolic model as the most common in Belarusian Polesie and occupying more than 35 % of the territory [16]. The soil structure was chosen as follows: the top layer of sand 1 m deep, and the bottom layer of coarse-grained sand 4 m deep. Calculations were made for different ground water levels (WWS): 0 m, 0,4 m, 0,8 m and 1 m [17].

On the basis of specialized software, a model of heat transfer in soil has been created and the dynamics of its heating under natural and anthropogenic conditions have been studied [18]. The numerical solution of the mathematical model is obtained by the method of finite elements [19].

Based on meteorological information from the Poleska Weather Station, located in the Luninetsky Swamp and representative of the region [20]. The air temperature was assumed to be equal to the multi-year average value for that day at 7 pm, which corresponds approximately to the average value of the temperature on the day in question.

The projected values of the increase in average air temperature for warm months, given in table 1, are taken from one of the possible climate scenarios for the period up to 2035 [21, 22].

**Table 1** – Projected increase in monthly average air temperature, °C

| Month | April | May | June | July | August | September | October |
|---|---|---|---|---|---|---|---|
| Temperature difference | 1,71 | 1,49 | 1,7 | 2,08 | 1,97 | 1,77 | 1,61 |

Using the above method, a numerical experiment was carried out to simulate the temperature profile of soils for the following boundary conditions:

- on the surface of the model soil, a heat flux equal to the average monthly flow of solar radiation falling on one area of the horizontal surface was applied;
- at the lower boundary of the modular soil, temperature stabilization conditions were set at 9.1 °C [23], equal to the average annual surface air temperature [24];
- on the surface of the soil was given the condition of convective heat exchange $-\nabla(-k\nabla T) = 0$ [25];
- heat insulation conditions were applied on the lateral borders of the allocated volume;
- evaporation from the surface of the soil was defined as the change in the internal energy of water during evaporation by the formula [26]

$$Q = Lm - vRT, \quad (2)$$

where L – the specific heat of vapour formation, J/kg; m – the mass of evaporated water, kg; v – the amount of substance evaporated water, mol; T – the air temperature, °K; R – the molar gas constant, J/mol °K

**Results and their discussion**

As a result of the numerical experiment, the distribution of soil temperature over the entire thickness of the simulated profile was obtained with an interval of radiance for a day from May to October including, on the basis of the year-long average value of air temperature and its prognosis until 2035 [27, 28]. As an example, figure 1 shows graphs of the temperature dependence on the depth of soddy-podzolic soil without dewatering for June 3 with a dewatering rate of 0,4 m for current climatic conditions [29] and a projected temperature change up to 2035.

As the numerical experiment showed, the soil temperature dynamics is synchronized with the air temperature when the climate warms. However, the nature of the change in the heat regime of dried and undried areas has a different structure and is determined both by climatic factors and the degree of melioration [30, 31].

Depending on the degree of moisture content, soil systems exhibit significant variability in their thermophysical properties, primarily specific heat capacity. This phenomenon is due to the dramatically different heat capacities of the two main components of soil pore space – air and water.

According to experimental data, the specific heat capacity of dry air is $c_{air}$ = 1020 J/(kg·K), while the specific heat capacity of water reaches $c_{water}$ = 4200 J/(kg·K). Thus, the heat capacity of water is approximately four times greater than that of air. Since water displaces air in soil pores, the presence of moisture in the soil proportionally increases its overall heat capacity – also approximately four times greater than that of completely dry soil.

A similar pattern is observed with respect to thermal conductivity: moist soil is characterized by significantly higher thermal conductivity than dry soil. This is of fundamental importance for heat transfer processes in the soil profile. Due to the increased thermal conductivity of a moist substrate, solar radiation absorbed by the soil surface is more effectively


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distributed into the lower horizons. This results in uniform heating of the root zone, which is critical for the vital functions of plants and soil biota.

The difference in the heat capacity and thermal conductivity of dry and moist soils leads to two important thermodynamic consequences:

1) heating moist soil requires significantly more thermal energy than dry soil of the same mass and volume. This is due to the high heat capacity of the water filling the pores;

2) moist soil has greater thermal inertia: as the ambient temperature decreases, it releases accumulated heat more slowly. This effect is explained by both the high heat capacity and the improved thermal conductivity of a moist soil profile, which ensures a more uniform heat distribution across the depth.

Thus, moisture content is a key factor regulating the thermophysical properties of the soil and determining the dynamics of heat exchange between the earth's surface and the ground layer of the atmosphere.

From the graphs shown in Figure 1, it follows that the nature of the temperature change as it approaches the surface does not change. Due to the increase in air temperature, the soil temperature changes accordingly. These changes are most significant from the depth of 2 m on undrained soils. When water is discharged during the drying process, the temperature change rate changes abruptly at the depth of the upper groundwater level.

From the diagrams shown in Figure 2, it can be seen that the amount of energy accumulated per month increases with increasing air temperature.

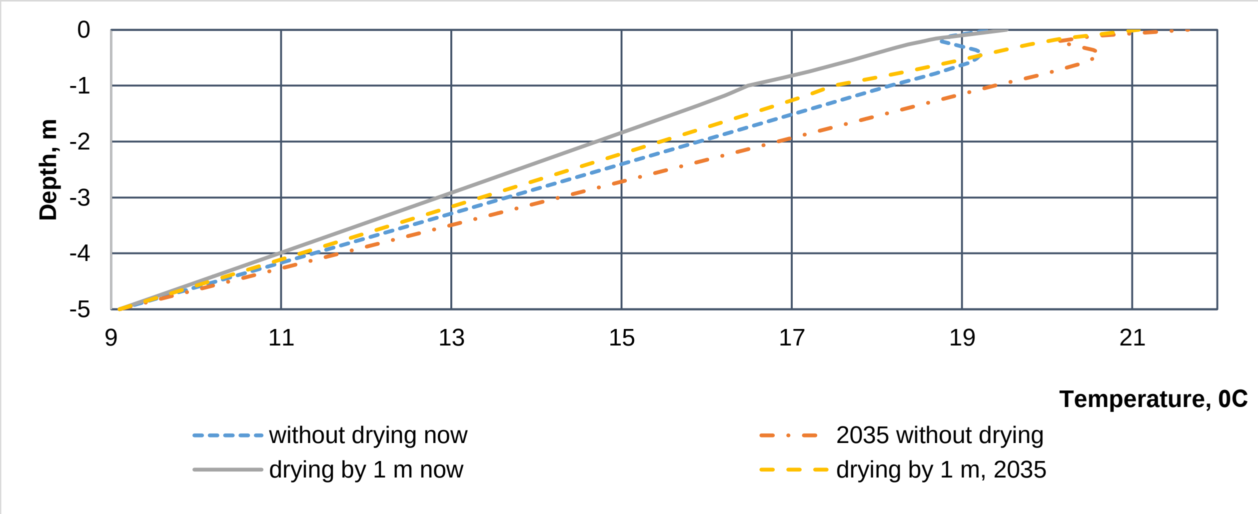
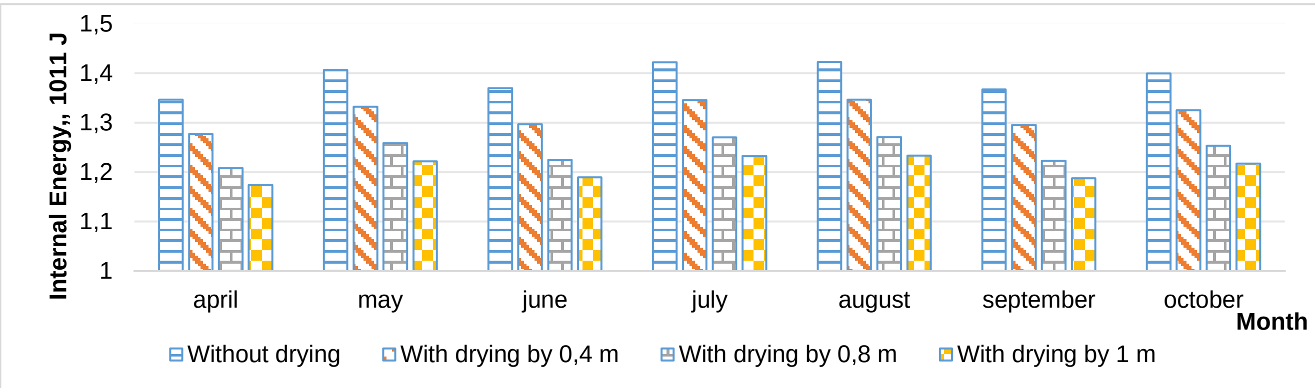
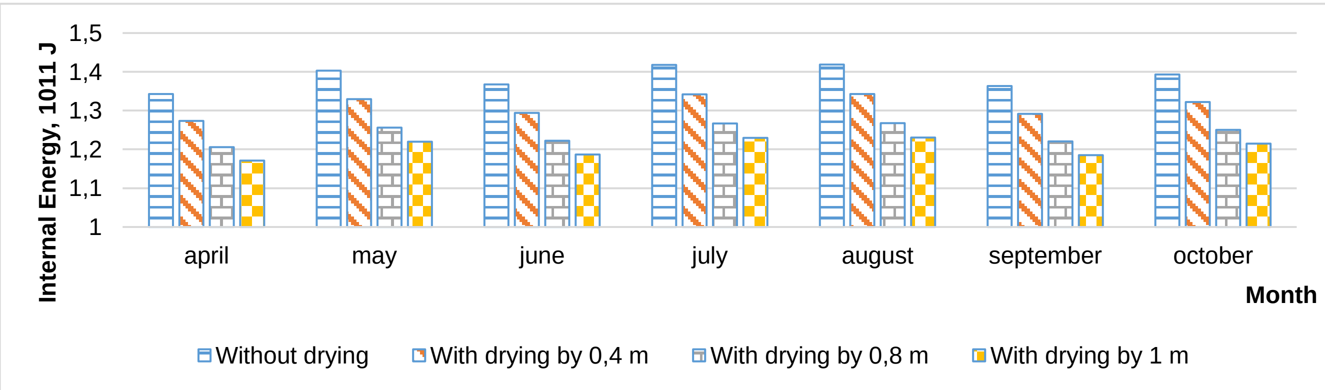



**Figure 1** – Depth distribution of the temperature of soddy-podzolic soil for June 3 without drying and with normal drying 1 m




a)




b)

a) the forecast to 2035; b) current status

**Figure 2** – The energy stored by bottom-seeded soils

The results shown in table 2 show that the most significant changes in the energy accumulated occur in soil without drying, since water in the soil has a greater heat capacity than air filling the soil pores. On drained soils, these changes are not as noticeable. The natural soil accumulates more heat energy and distributes it more evenly along its profile. In the process of prolonged negative temperatures during winter, at the depth of 150 cm, even by the end of the cold season, soil temperature was positive and was 2...2.1 °C. This phenomenon has been called «thermal inertia» [32, 33]. Water in the top layer of soil is more inert to changes in ambient air temperature, which helps plants to cope with late frosts in the spring and generally raises the temperature of the nutrient layer of soil and improves conditions for crop production, characteristic of more southern areas.

As it can be seen from table 2, the higher the rate of soil drying, the smaller the changes in the energy stored in the soil, therefore the soils dried out are less susceptible to climate change.

**Table 2** – Change in accumulated energy of soil, $10^8$ J

| | April | May | June | July | August | September | October |
|---|---|---|---|---|---|---|---|
| Without drying | 3,90 | 3,96 | 2,64 | 4,56 | 4,20 | 3,67 | 5,99 |
| Drying by 0,4m | 3,14 | 2,60 | 2,51 | 3,74 | 3,52 | 3,37 | 2,91 |
| Drying by 0,8m | 2,10 | 1,99 | 2,09 | 3,11 | 2,90 | 2,28 | 2,45 |
| With drying by 1m | 2,40 | 1,83 | 2,23 | 2,43 | 2,24 | 2,49 | 1,94 |

Depending on the heat capacity, only a certain amount of heat can be absorbed by the soil. Because the heat transfer from top to bottom is quite slow, excess energy will be added to the environment. And as a result, the ground air heats up more, resulting in its displacement to the lower pressure area. Thus, these air masses carry heat energy away from the drained areas [34].

Air with lower heat capacity accumulates less energy, therefore, as the temperature rises, the *energy* accumulated by the soil will change to a lesser extent. As a consequence, Table 2 does not show for all months the dependence of the increase in energy change at different rates of drying.

**Conclusion**

Based on the results of modelling the thermal regime of soil at a temperature change up to 2035, the energy, accumulated by the soddy-podzolic, soil is calculated. The most noticeable energy increase is for swamp soil. The change in accumulated energy was greatest for the undrenched soil in October and amounted to about 5,99 $10^8$ J, which corresponds to an increase of 0,43 % compared with the initial values. The minimum energy increase was in May for soil with a drying norm of 1 meter and amounted to 1,83 $10^8$ J, which corresponds to an increase of 0,15 %.

Thus, land reclamation accelerates the process of modification of the substrate surface and thermophysical properties of soddy-podzolic soils of Belarusian Polesie.

Climate warming and the resulting rise in soil temperature may lead to favourable conditions for crops grown in warmer regions. However, more extreme conditions for the cultivation of crops remain on meliorated soddy-podzolic soils, which is reflected in significant soil heating during the day and cooling at night. As a result, the number of frosts increases and the heating of the arable layer in the spring slows down, which can lead to partial crop loss.

In the system of adaptation measures to climate transformations in the Belarusian Polesie, revalidation (re-wetting) of previously drained lands occupies a key position as a method that allows for the effective regulation of heat and water balance and the increase of biological productivity of land resources [35].

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# MODERN TRENDS IN RIVER DISCHARGE VARIABILITY IN THE PRIPYAT BASIN AND THEIR FORCASTED ASSESSMENTS

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**Abstract**

This article presents the results of a study on the spatial and temporal variability of characteristic water discharges of the Pripyat River and its tributaries within Belarus, based on instrumental observations. At the Mozyr gauging station, a 145-year hydrological record from 1877 to 2021 was analyzed.

The findings indicate that climate change has increased the irregularity of flow fluctuations in the Pripyat basin rivers, affecting both the intra-annual seasonal distribution and variations related to catchment size. Notable changes were observed during the spring period, characterized by a reduction in flood runoff and an earlier onset of the spring flood. Distinct trends in flow variability were identified across spring, summer, and autumn, with a pronounced increase during summer.

Flow projections up to 2035 largely confirm the trends identified for the period 1961–2015. Although average annual flow is expected to change only slightly, there is a high likelihood of increased irregularity and divergent seasonal and monthly flow patterns. Enhanced unevenness in intra-annual flow distribution, combined with elevated flood risks due to abrupt winter thaws, earlier spring flood onset, and intensified rain-induced floods, may contribute to a greater frequency of extreme hydrological events.

The significance of these flow assessments and forecasts under changing climatic conditions lies in their critical role for informing water resource management and protection strategies. Incorporating these projections is essential for the effective planning and sustainable management of the Pripyat River basin.

**Keywords:** water discharge, annual runoff, spring flood, minimum summer-autumn flow, minimum winter flow, climate, forecast assessments.

## СОВРЕМЕННЫЕ ТЕНДЕНЦИИ В КОЛЕБАНИЯХ СТОКА РЕК БАССЕЙНА ПРИПЯТИ И ИХ ПРОГНОЗНЫЕ ОЦЕНКИ

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**Реферат**

В статье представлены результаты исследований пространственно-временных колебаний характерных расходов воды р. Припять и ее притоков, расположенных на территории Беларуси за период инструментальных наблюдений. Для створа г. Мозырь рассматривался гидрологический ряд в 145 лет, с 1877 по 2021 гг.

Показано, что изменение климата увеличило неравномерность колебаний стока, как для рек бассейна Припяти, так и его внутригодовому распределению по сезонам года, а также в зависимости от размера водосбора. Значительные изменения стока произошли в весенний период, связанные со снижением стока половодья и более ранним его наступлением. В весенний, летний и осенний период прослеживается разная направленность изменения стока, особенно в летний период – его увеличение.

Прогноз стока на период до 2035 года в основном подтвердил выявленные тенденции его изменения за период с 1961 по 2015 год. При незначительном изменении стока в среднем за год, высокая вероятность его неравномерности и разнонаправленности в сезоны и месяцы. Усиление неравномерности внутригодового распределения стока и увеличение рисков наводнений, обусловленных резкими оттепелями в зимний период, более ранним наступлением весеннего половодья и увеличением интенсивности дождевых паводков может привести к увеличению рисков экстремальных явлений.

Значимость оценок и прогнозов речного стока в условиях изменяющегося климата определяется целесообразностью их последующего учета при планировании водоохранных и водохозяйственных мероприятий, связанных с совершенствованием управления речным бассейном Припяти.

**Ключевые слова:** расход воды, годовой сток, весеннее половодье, минимальный летне-осенний сток, минимальный зимний сток, климат, прогнозные оценки.

**Introduction**

The issues surrounding the rational management of water resources have emerged as a critical focus for the international community, particularly in light of the growing scarcity of water resources globally and the continuously increasing demand for water in many countries.

In response, the international community has coordinated efforts among nations to establish 17 Sustainable Development Goals (SDGs) to be achieved by 2030. One of these goals is to ensure the availability and equitable distribution of river flow, alongside its sustainable use and sanitation for all [1]. This goal is especially pertinent to transboundary rivers. The Republic of Belarus actively participates in this initiative.

Most major rivers in Belarus are transboundary, making the management of their water regimes an intergovernmental responsibility. A primary objective is to provide an objective assessment of the current state of water resources, both for the river basin as a whole and for the individual countries through which these rivers flow. A key aspect of researching river water regimes involves forecasting water resource availability for both the near and distant future. The Pripyat River, one of the largest rivers in Belarus, serves as a pertinent case study in this context [2].

The objective of this study is to identify current trends in the fluctuations of river flow within the Pripyat basin in Belarus and to provide forecast assessments to facilitate rational and objective management of the water regime.

**Methods and materials**

The Pripyat River, with a length of 761 km, is a right-bank tributary of the Dnieper River. Its basin is transboundary, shared between Ukraine and Belarus. The basin's shape approximates a square with a somewhat indented watershed boundary. The catchment area encompasses 121,000 km², of which 52,700 km² (44 %) lies within Belarus. The basin's maximum length is 460 km, with an average width of 256 km and a mean elevation of 179 m. The catchment is predominantly flat and asymmetrical in shape, largely situated within the Polesie Lowland. The relief of the Pripyat basin within Belarus is characterized by alternating moraine hills and flat plains [3, 4, 5, 6, 7 et al.].

The Pripyat River originates near the city of Volodymyr-Volynskyi in Ukraine. It flows for approximately 200 km through Ukrainian territory, then nearly 500 km through Belarus before discharging into the Kyiv Reservoir on the Dnieper River. From its source to the city of Pinsk (Belarus), the river flows predominantly from southwest to northeast. At Pinsk, the Pripyat turns eastward and continues almost along a latitudinal course to Mozyr, where it shifts southeastward, maintaining this direction until its confluence.

The current hydrography of the basin comprises meandering, slow-flowing, and overgrown rivers, numerous reclamation canals, artificial reservoirs, and wetlands. The river system within the catchment includes approximately 800 watercourses longer than 1 km, with a combined length exceeding 46,000 km. The drainage density is 0.4 km/km². Most tributaries are fully or partially canalized. Forests cover 42 % of the catchment area within Belarus. Major tributaries include the Pina, Yaselda, Bobrik, Tsna, Lan, Sluch, Ptich, Tremlya, and Ipa (left bank), as well as the Stokhod, Styr, Horyn, Stvyha, Ubort, and Slovechna (right bank). The Pripyat is connected to the Mukhavets River (Western Bug basin) via the Dnieper-Bug Canal, linked to the Neman basin by the (currently inactive) Oginsky Canal, and connected to the Mikashevichi river port through the Mikashevichi Canal [3, 4, 5, 6, 7 et al.].

The river's hydrological regime is mixed, predominantly snowmelt-driven. A distinctive feature is the prolonged spring flood, a brief summer low-water period interrupted by rain-induced floods and nearly annual autumn water level rises. The spring flood accounts for 60 % of the annual flow, summer-autumn low water for 24 %, and winter low water for 16 %. Average annual discharge rates are 119 m³/s near the village of Korobye in the upper reaches, 264 m³/s near Turov, 383 m³/s at Mozyr, and 450 m³/s at the mouth [5].

The river regime has been studied at 21 hydrological stations; currently, seven remain operational: Pinsk, Kachanovichi (upper and lower reaches), Chernychi, Petrikov, Mozyr, and Narovlya.

The hydrographic network of the Pripyat River basin is illustrated in Figure 1.

*Climate Conditions*

The climate of the Pripyat River basin is classified as moderately continental, characterized by warm and humid summers and relatively mild winters. The degree of continentality increases toward the southeast. Annual sums of the radiation balance increase from the southwest to the east and southeast, ranging from 1200 MJ/m² to 1735 MJ/m². The radiation balance of the region significantly influences the temperature regime [8, 9]. The spatial and temporal distribution of the average monthly air temperature is dependent on radiation conditions, seasonal fluctuations in atmospheric circulation, and the physical and geographical features of the area. The average annual air temperature in the basin varies from +6.3 °C to +7.2 °C. The average temperature of the coldest month (January) ranges from –4.6 °C in the southwest to –7.0 °C in the northeast, while the average temperature of the warmest month (July) increases from +18.3 °C in the northwest to +19.2 °C in the southeast. The frost-free period lasts from 170 days in the southwest to 150 days in the eastern part of the basin. A key pattern in the spatial distribution of precipitation within the Pripyat River basin, influenced by general circulation factors, is a decrease in precipitation from the northwest and southwest toward the west and east. A slight increase in precipitation is observed at higher absolute elevations. Monthly precipitation totals exhibit a distinct annual cycle, with a minimum occurring in February and March and a maximum in June and July. Precipitation is predominantly of low intensity, although individual heavy showers can produce several tens of millimeters of rainfall. The highest daily precipitation recorded at various meteorological stations within the basin ranges from 114 to 177 mm.

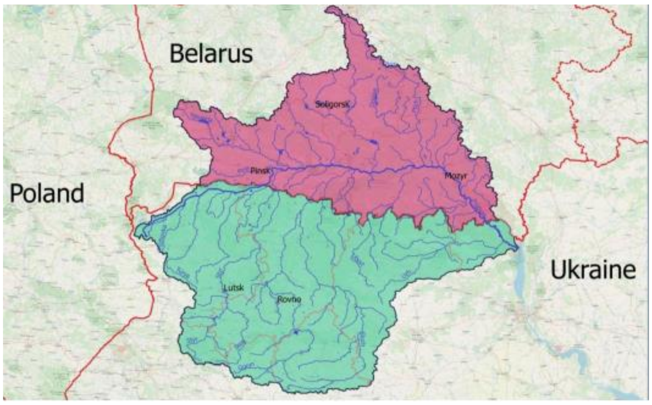


**Figure 1** – General Map-Scheme of the Pripyat River Basin

The snow cover within the basin is characterized by considerable instability. The timing of its onset fluctuates significantly, with average dates for the formation of stable snow cover ranging from December 20 in the northeast of the basin to December 30 in the southwest. A similar pattern is observed for the disappearance of snow cover, with average dates for the melting of stable snow cover varying in the opposite direction – from March 5 in the southwest to March 15 in the northeast of the Pripyat River basin. The average maximum snow depth ranges from 10 to 15 cm in the west to 20 to 25 cm in the east of the basin. The average depth of soil freezing is between 30 and 50 cm and depends not only on temperature and snow cover thickness but also on soil type [8]. The wind regime in the Pripyat River basin is influenced by macro-circulation processes in the atmosphere and the positioning of pressure centers over the Eurasian continent and the Atlantic Ocean [9]. A clear trend in the distribution of total evaporation indicates a decrease from the north and northwest of the basin toward the south and southeast, ranging from 590 mm to 525 mm. Winters in this region are mild and overcast, with frequent thaws. Average monthly temperatures below freezing persist from December through March, except in the southwestern part of the basin, where average temperatures in March exceed 0 °C. A characteristic feature of winter is the frequent intrusion of warm air masses, which are often accompanied by thaws. This phenomenon can lead to the complete disappearance of the snow cover, which typically re-establishes itself after several days. In some winters, when the basin is affected by ridges of high pressure, severe frosts can occur. Spring in the basin is prolonged and unstable, characterized by frequent alternations of cold and warm air masses. Cyclonic activity during spring diminishes due to the reduction of temperature contrasts between maritime Atlantic and continental air. Alongside a rapid increase in air temperature, significant temperature drops may also occur on certain days. Summer within the basin is warm and rainy. Ridges of high pressure from the Azores maximum extend into the area, facilitating the transport of moist air from the west. More than 200 mm of precipitation falls during the summer months, with a significant portion occurring as showers associated with cyclones moving from the southwest. The average temperature during the summer months (June–August) remains around +16 °C to +20 °C. The transition from summer to autumn is gradual, with frequent returns of warm weather.



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Autumn is prolonged, predominantly overcast, and characterized by drizzly rain, especially in November, when approximately 75 % of days are cloudy, of which 25 % are rainy.

*Characteristics of Water Resources*

The volume of river runoff for the Pripyat River over the long-term observation period and for the year 2023 is presented in Table 1 [10].

**Table 1** – River runoff of the Pripyat River (km³/year) for the long-term period and the year 2023

| Gauge Station | Catchment area, thousand km$^2$ | Long-term river runoff | | | River runoff in 2023 |
|---|---|---|---|---|---|
| | | average | maximum | minimum | |
| Kachanovichi<br>Chernychi<br>Petrikov<br>Mozyr<br>Narovlya | 13.8<br>74.0<br>87.8<br>101.0<br>103.0 | 12.2 | 22.3 | 4.5 | 16.3 |

The hydrometric station in the city of Mozyr, established in 1876, has the longest period of river runoff observations in this basin, spanning from 1877 to 2021, i. e., 145 years. At the preliminary stage, statistical analyses were conducted, and missing data were reconstructed using the methodology described in [11], employing the software package Gidrolog-2 [12]. To assess the impact of recent climate warming, a comparative analysis was performed for two intervals: 1877–1986, representing the pre-warming period, and 1987–2021, representing the warming period. Additionally, observation series from the last 50 years (1972–2021) were analyzed separately, corresponding to the standard calculation period recommended for determining statistical hydrological characteristics.

Within the Pripyat River network, small watercourses predominate both in number and total length; the catchments of these watercourses generate the majority of the local river runoff.

The primary data were obtained from the State Institution "Republican Center for Hydrometeorology, Radioactive Contamination Control, and Environmental Monitoring" (Belhydromet) of the Ministry of Natural Resources and Environmental Protection of the Republic of Belarus. These data encompass various types of runoff from active hydrological stations across Belarus for the period of instrumental observations up to and including 2021, as published in official state cadastres. In studies evaluating runoff changes during the period 1961–2015 and forecasting through 2035, data from 11 stations with the longest and most continuous observation records were utilized, provided data were available for the specified period (Table 2) [13].

**Table 2** – List of hydrological stations used for the assessment and projection of surface runoff changes

| River – Gauge station | Catchment area, km$^2$ |
|---|---|
| Pripyat – Chernichi (Turov) | 74000 |
| Pripyat – Mozyr | 101000 |
| Yaselda – Beryoza | 1040 |
| Yaselda – Senin | 5110 |
| Tsna – Diatlovichi | 1100 |
| Horyn – Malye Vikorovichi | 27000 |
| Sluch – Lenin | 4480 |
| Ubort – Krasnoberezhye | 5260 |
| Ptich – Luchitsy | 8770 |
| Shat – Shatsk | 208 |
| Oressa – Andreevka | 3580 |

The analysis of the internal structure of time series can be performed using various methods, including the construction of difference-integral curves, correlation, autocorrelation, and spectral functions, as well as spectral-temporal analysis. Each of these methods has its own advantages and limitations [14].

Trends or systematic changes in runoff associated with anthropogenic factors typically develop slowly and gradually, which complicates their detection. Only in certain cases, when anthropogenic influence is minimal, can trends be discerned through graphical analysis of data homogeneity using the method of analogy.

Objective identification of anthropogenic trends is possible provided the time series is representative. Representativeness is assessed by comparison with an analogous river and involves analyzing an even number of periods characterized by varying flow conditions. Following this assessment, trends are determined analytically.

For practical calculations, linear trends can be employed with sufficient accuracy, expressed as:

$$Q(t) = Q(0) \pm \Delta Q \cdot t, \quad (1)$$

where $Q(t)$ is the water discharge at time t, m³/s; $Q(0)$ is the water discharge at the start of the calculation period, m³/s; $\Delta Q$ is the rate of change of water discharge, m³/s/year; and t is the calendar year.

In some cases, more complex forms of trends have also been utilized.

*Climate Forecasting Methodology*

Both global and regional climate models must be employed for climate change projections. These models are based on the description of dynamic processes and rely on numerical solutions to systems of partial differential equations from mathematical physics [15 et al.]. Moreover, the necessity of using climate models to forecast meteorological parameters, rather than relying solely on statistical methods for processing meteorological data, arises from the complexity and diversity of both natural and anthropogenic factors – at global and regional scales – that influence, and potentially may influence, climate change [16].

Studies assessing and forecasting climate change for the territory of Belarus, conducted in accordance with the Republic of Belarus's commitments under the UN Framework Convention on Climate Change, are described in our work [16]. Here, we focus on specific issues related to climate forecasting within Belarus.

According to the Fourth National Communication, submitted pursuant to the Republic of Belarus's obligations under the UN Framework Convention on Climate Change (2006), a decrease in water availability has been observed in river basins since 1988, with runoff reductions ranging from 4 % to 13 % [17]. A notable characteristic of the period under review is the change in the distribution of average monthly runoff throughout the year, particularly during the winter and spring months, when monthly river discharges across the country increase significantly – by 30 % to 90 % from January through March. The increase in winter runoff is associated with a higher frequency of thaws and the occurrence of winter floods. Conversely, runoff decreases sharply in April and May. The Communication provides an overall conclusion indicating a decline in the maximum runoff of rivers in the Pripyat basin.

The Fifth National Communication of the Republic of Belarus, submitted in accordance with its obligations under the UN Framework Convention on Climate Change (2009), employs the LEAP model [18].

This Communication concludes that "climate change will lead to increased variability of runoff and a higher frequency of extreme events (droughts, intense floods)."

In Belarus, climate research is also conducted within the framework of the cross-border cooperation project TACIS SKPI, titled "Support for the Implementation of the Kyoto Protocol in the CIS Countries" [19]. This project employs models such as ECHAM5, the atmospheric circulation model from the Max Planck Institute, and the CSIRO Mk3 bioproductivity model.

According to this scenario, in the 21st century, the average surface air temperature across Belarus is expected to continue rising, primarily due to increases in minimum temperatures. These trends, along with many other characteristics of the changing climate, will have significant impacts on the living conditions of citizens and economic activities [20 et al.].

The consequences of rapid variability in climatic conditions will manifest as an increase in the frequency of hazardous hydrometeorological phenomena and adverse abrupt weather changes, which lead to socio-economic damage and directly affect the efficiency of vital sectors of the economy, such as agricultural production, forestry, energy, transportation, construction, housing and communal services, as well as public health.

Based on an analysis of data from the Republican Hydrometeorological Center (RHMC), researchers have obtained the following results.

At the turn of the 20th and 21st centuries, Belarus experienced the longest period of warming recorded in nearly 130 years of instrumental temperature observations. This warming is notable not only for its unprecedented duration but also for the higher air temperatures, which, on average over a 20-year period (1989–2009), exceeded the climatic norm by 1.1 ºC. Of the 20 warmest years since the post-war period (1945), 16 occurred between 1989 and 2010.

Temperature increases were observed in nearly every month, with the most significant rises occurring during the winter and early spring months. A trend towards an extended frost-free period is emerging. Frosts of varying intensity in May are observed annually and pose particular risks to heat-loving crops. The risk of autumn frosts is less significant, as rising temperatures in spring and summer accelerate the maturation of agricultural crops.

Increased temperatures during the early spring months lead to earlier snowmelt and a transition of air temperatures above 0 ºC towards higher values. On average, this transition occurred 10 to 15 days earlier than the long-term averages during the period under consideration. The duration of the snow cover period in the Republic of Belarus has decreased by 10 to 15 days, and the depth of frost penetration has reduced by 6 to 10 cm. The growing season begins a decade earlier.

In a scientific and methodological context, a comprehensive study of climate change and its consequences for the economy of Belarus has been conducted by Academic V.F. Loginov [9]. His work provides a comparative analysis of various atmospheric and ocean circulation models (AOGCMs). According to his findings, the HadCM2 model (United Kingdom) [21] best simulates the baseline period data, taking into account the combined increase of greenhouse gases and sulfate aerosols. The CSIRO Mk2 model (Australia) [22] and CGCM1 model (Canada) [23] demonstrate somewhat poorer comparative results.

Forecast data using the HadCM2 model for the period 2010–2039 indicate an increase in the average annual air temperature by 1 ºC, with the average annual daily temperature rising by 0.92 ºC and the nightly temperature by 1.15 ºC. Increases in temperature sums above 0.5 and 10 ºC are expected to be approximately equal, around 200–220 ºC, while the increase for 15 ºC is significantly higher.

Existing assessments of climate change for the territory of Belarus are consistent with the concept of global warming. In recent decades, a clear trend of warming has been observed, particularly in the winter and spring months (January-April). The end of the 20th century and the beginning of the 21st century represent the longest period of warming in over 120 years of systematic instrumental observations in Belarus.

It should be noted that the results of the studies and assessments conducted in Belarus are of a general and approximate nature. In terms of river basins, the impact of global climate change on water resources in Belarus has not been thoroughly investigated. Only a few individual studies can be noted [24, 25, 26, et al.].

*Methodology for Assessing the Impact of Climate Change on River Runoff*

For forecasting changes in river flow, we have adapted the hydrological-climatic calculation method (HCC) proposed by V.S. Mezentsev, which is based on the simultaneous solution of water and thermal energy balance equations [27]. Building upon Mezentsev's hydrological-climatic hypothesis [27], we developed a multifactorial model incorporating the standard water balance equation for a land area, with independent assessments of the main balance components—atmospheric precipitation, total evaporation, and climatic runoff—on an annual basis. This approach has been implemented as a computer system, which we have used to evaluate potential changes in river water resources under various hypotheses concerning climate variability and anthropogenic influences on watershed characteristics [28].

The water balance equation for a river basin over a given time interval is expressed as follows:

$$H(I) = E(I) + Y_K(I) \pm \Delta W(I), \quad (2)$$

where *H*(*I*) denotes the total moisture resources (mm); *E*(*I*) is the total evaporation (mm); $Y_K(I)$ represents the total climatic runoff (mm); $\Delta W(I)$ is the change in moisture reserves in the active soil and ground layer (mm); and *I* is the averaging interval.

Total evaporation is calculated using the formula:

$$E(I) = E_m(I)\left[1+\left(\frac{\frac{E_m(I)}{W_{HB}}+V(I)^{1-r(I)}}{\frac{KX(I)+g(I)}{W_{HB}}+V(I)}\right)^{n(I)}\right]^{-\frac{1}{n(I)}}, \quad (3)$$

where $E_m(I)$ is the maximum possible total evaporation (mm); $W_{HB}$ is the minimum soil moisture capacity (mm); $V(I) = W(I)/W_{HB}$ is the relative humidity of the soil at the start of the calculation period; *KX*(*I*) is the sum of measured atmospheric precipitation (mm); *g*(I) is the groundwater component of the water balance (mm); *r*(*I*) is a parameter dependent on the water-physical properties and mechanical composition of the soil; and *n*(*I*) is a parameter accounting for the physical-geographical conditions of runoff.

The relative humidity of the soil at the end of the calculation period is determined as follows:

$$V(I+1) = V(I)\cdot\left(\frac{V_{cp}(I)}{V(I)}\right)^{r(I)}; \quad (4)$$

$$V_{cp}(I) = \left(\frac{\frac{KX(I)+g(I)}{W_{HB}}+V(I)}{\frac{E_m(I)}{W_{HB}}+V(I)^{1-r(I)}}\right)^{\frac{1}{r(I)}}. \quad (5)$$

The obtained values of $V_{cp}(I)$ are compared with the relative value of the total moisture capacity $V_{\Pi B}$. If $V_{cp}(I) \le V_{\Pi B}$, the calculated value of the relative average soil moisture is accepted; otherwise, when $V_{cp}(I) \ge V_{\Pi B}$ the calculation assumes $V_{cp}(I) = V_{\Pi B}$, and the difference $(V_{cp}(I) - V_{\Pi B})\cdot W_{HB}$ is attributed to surface runoff.

The amount of atmospheric precipitation during the cold months, after subtracting total evaporation, is transferred to the flood period, i. e., to March.

The maximum possible total evaporation was determined according to the methodology described in [29, 30].

Total moisture resources are determined as follows:

$$H(I) = KX(I) + W_{HB}(V(I) - V(I+1)). \quad (6)$$

The system of equations (2) – (6) is solved iteratively until the value of relative soil moisture at the beginning of the calculation interval equals the value of relative soil moisture at the end of the previous interval. At the start of the calculation, the initial moisture value is taken as equal to the minimum moisture capacity, i. e., $W(1) = W_{HB}$, from which it follows that $V(1) = 1$. Convergence of the HCC method is typically achieved by the fourth iteration.

Adjustment of the climatic runoff is performed using coefficients that account for the influence of various factors on the formation of channel runoff, i. e.,

$$Y_P(I) = k(I)\cdot Y_K(I), \quad (7)$$

where $Y_P(I)$ denotes the total channel runoff (mm), and *k*(*I*) is a coefficient reflecting the hydrographic characteristics of the watershed.

The water balance modeling of the river under study has been implemented as a computer program and is conducted in two stages. In the first stage, the model is calibrated using known components of the water and thermal balances of the river under study. The objective of this calibration is to achieve the best possible agreement between the calculated climatic and channel runoff. This stage concludes with the construction of graphs for climatic and channel runoff and the presentation of the modeling error.

A good agreement between measured and calculated runoff indicates the model's validity. The obtained model parameters were subsequently used in conducting numerical experiments.

The second stage involves directly calculating the water balance of the river under study using parameters obtained during model calibration. The calculation of the water balance components for the river takes into account the specific characteristics of the watershed being analyzed [28].

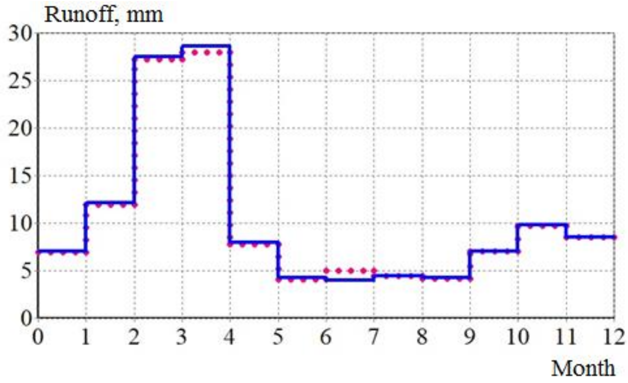
The modeling results demonstrate a high level of accuracy in estimating the water balance, suitable for both practical applications and theoretical research. This has been validated on numerous rivers in Belarus with watershed areas of about 1000 km², where hydrometric observations are conducted. Thus, given data on atmospheric precipitation, air temperature, air moisture deficits for the calculation period, current river runoff values, and hydrographic characteristics of the watershed, this methodology makes it possible to produce predictive estimates of the water balance of small rivers in Belarus for the forecast period.

Solving the water balance equation for a watershed involves determining average values of the components observed at specific points within the watershed. Therefore, one of the key aspects of modeling the water regime is accurately assessing climatic characteristics and averaging them across the watershed. This issue is discussed in detail in [28].

During model calibration using the proposed methodology, difficulties arose in determining parameters for the winter months. The problem was that the model did not adequately account for the increasingly frequent thaws in recent years. As a result, the model was adjusted to incorporate the effects of thaws. The difference between channel runoff and climatic runoff obtained during calibration was attributed to runoff generated during thaw periods, which was recorded in the model settings.

Predictive estimates of changes in river runoff were made according to the following procedure. The model was calibrated using long-term average data on river runoff, atmospheric precipitation, air temperature, and air moisture deficits. Then, forecasted values for the relevant period were input for the meteorological stations used in the calibration. The calibration parameters were applied, and a predictive assessment was conducted. The resulting climatic runoff values were compared according to the ratio $\Delta_{кл.} = Y^{пр.}_{кл.} / Y^{сов.}_{кл.} \cdot 100\ \%$. The direct predictive estimate of channel runoff was derived from the relationship $Q^{пр.} = Q^{сов.} \cdot \varDelta_{кл.} \cdot 100,\ м^3/с.$

An example of modeling the long-term average annual runoff and its intra-annual distribution (model calibration and forecast) for the Grivda River near the town of Ivatsevichi is shown in Figure 2.




—— measured runoff, - - - calculated runoff

**Figure 2** – Measured and calculated runoff of the Grivda River at Ivatsevichi

**Results and discussions**

*Analysis of Long-Term Variations in Annual Runoff Annual Runoff*

The long-term average flow of the Pripyat River was estimated based on observations at the Mozyr hydrological station for the period from 1877 to 1881. Accordingly, the long-term average runoff of the Pripyat over the past 145 years at the Mozyr gauge station is 391 m³/s, increasing to 450 m³/s near the river's mouth. The maximum average annual discharge recorded at the Mozyr station occurred in 1958, reaching 643 m³/s, while the minimum was observed in 1954, at 142 m³/s. Analysis of the available data enables experts to conclude that the Pripyat's runoff exhibits an increasing trend and is greater than that of the Dnieper or Desna rivers.

As part of this study, a statistical analysis was conducted on the long-term fluctuations in the annual runoff of the Pripyat River at the Mozyr gauge station over the period 1877–2021, with the aim of identifying quasi-periodic patterns and trends.

The chronological series of average annual discharges of the Pripyat River at the Mozyr station is presented in Figure 3.

The main statistical characteristics of the analyzed series are presented in Table 3.

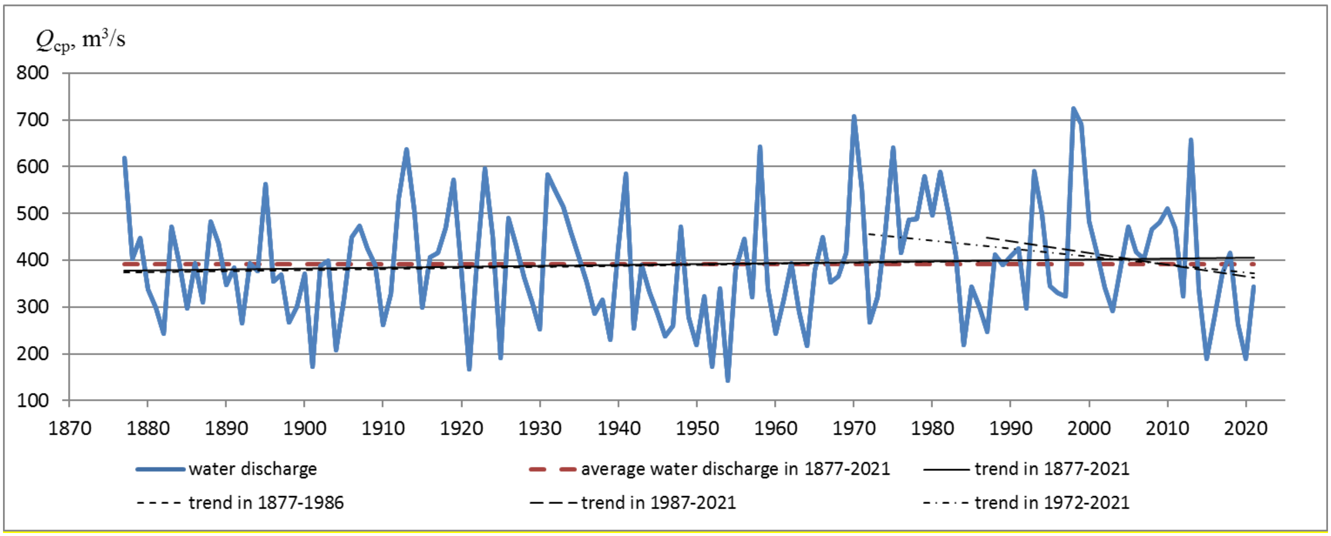



**Figure 3** – Chronological series of average annual discharges of the Pripyat River at the Mozyr station

Note – Explanatory notes in Figures 4–6 correspond to the ones in Figure 3.

**Table 3** – Key statistical characteristics of the average annual discharges of the Pripyat River at the Mozyr gauge station for different averaging intervals

| Characteristics | Averaging interval | | | |
|---|---|---|---|---|
| | 1877–2021 (145 years) | 1877–1986 (110 years) | 1987–2021 (35 years) | 1972–2021 (50 years) |
| $Q_{cp}$, m³/s | 391 | 387 | 405 | 414 |
| $C_v$ | 0.31 | 0.31 | 0.31 | 0.30 |
| $C_s$ | 0.44 | 0.34 | 0.74 | 0.47 |
| $r$(1) | 0.28 | 0.26 | 0.30 | 0.37 |
| $\Delta Q$ 10, m³/s | 2.00 | 2.20 | –25.18 | –17.35 |
| $r$ | 0.07 | 0.06 | –0.20 | –0.20 |
| $r_{кр,\ p=5\ \%}$ | *0.16* | *0.19* | *0.33* | *0.28* |
| % of $Q_{cp}$ | 0.51 | 0.57 | –6.22 | –4.19 |
| Maximum in the period/year | 725/1998 | 708/1970 | 725/1998 | 725/1998 |
| Minimum in the period/year | 142/1954 | 142/1954 | 189/2020 | 189/2020 |

Note – $Q_{cp}$ is long-term average annual water discharge; $C_v$ is a coefficient of variation; $C_s$ – is a coefficient of skewness; r(1) is an autocorrelation coefficient; $\Delta Q$ 10 is a gradient of change in water discharge over 10 years; r is a correlation coefficient of model (1); $r_{кр,\ p=5\ \%}$ is critical values of the correlation coefficient [31]; % of $Q_{cp}$ is percentage change in water discharge over 10 years relative to the long-term average annual discharge. Statistically significant correlation coefficients are highlighted.

No statistically significant differences were found in the mean water discharge values between the periods 1877–1986 and 1987–2021. The critical value for the one-tailed Student's t-test is $t_{кр}$ = 1.67, where as $t_{статистика}$ = 0.76. No differences were detected in the variances (coefficients of variation). The coefficient of skewness has changed significantly, which should be taken into account when selecting probability distribution models. The gradient of discharge changes did not undergo any statistically significant transformations. The results obtained are in good agreement with our previously published findings [32, 33, 34].

*Refinement of Water Resources in the Pripyat Basin*

In recent years, the country's water resources have undergone transformations due to the influence of both natural and anthropogenic factors on runoff [35]. The refined surface water resources of the Pripyat basin for the period from 1956 to 2015, along with data on runoff transformations over the studied 60-year interval relative to the period of instrumental observations prior to 1996 for the Pripyat basin, are presented in Table 4.

The total surface water resources of the Pripyat basin have remained largely unchanged. However, there has been a redistribution of natural water resources among the basins of individual rivers. A slight increase in the water flow of the Pripyat River has been observed in recent years.

The rivers of the Pripyat basin are characterized by a slight increase in runoff values. Changes in river runoff volumes and hydrological regimes under current conditions are attributed to an intensification of general atmospheric circulation.

*Spring Floods*

The study included a statistical analysis of long-term fluctuations in the maximum water discharges during the spring flood of the Pripyat River at the Mozyr gauge station over the period from 1877 to 2021, with the aim of identifying quasi-periodicity and trends [36].

The chronological series of maximum water discharges during the spring flood of the Pripyat River at the Mozyr gauge station is presented in Figure 4.

**Table 4** – Natural resources of the Pripyat basin and Belarus as a whole during 1956–2015 (Numerator) and changes in runoff relative to the period prior to 1996 (Denominator)

| River basin | River runoff, km³/year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Local | | | | | Total | | | | |
| | Exceedance probability, % | | | | | Exceedance probability, % | | | | |
| | 5 | 25 | 50 | 75 | 95 | 5 | 25 | 50 | 75 | 95 |
| Pripyat | 11.2 / 1.3 | 7.6 / 1.1 | 6.6 / 1.0 | 5.0 / 0.6 | 3.5 / 0.4 | 23.9 / 1.7 | 16.8 / 1.5 | 14.4 / 1.4 | 11.0 / 0.9 | 8.3 / 1.3 |
| **Entire Belarus** | **51.8 / 0.3** | **37.9 / 0.4** | **34.1 / 0.1** | **28.1 / -0.2** | **22.7 / -0.1** | **88.2 / 1.1** | **64.3 / 0.9** | **56.9 / 0.7** | **46.4 / 0.2** | **37.5 / 1.2** |

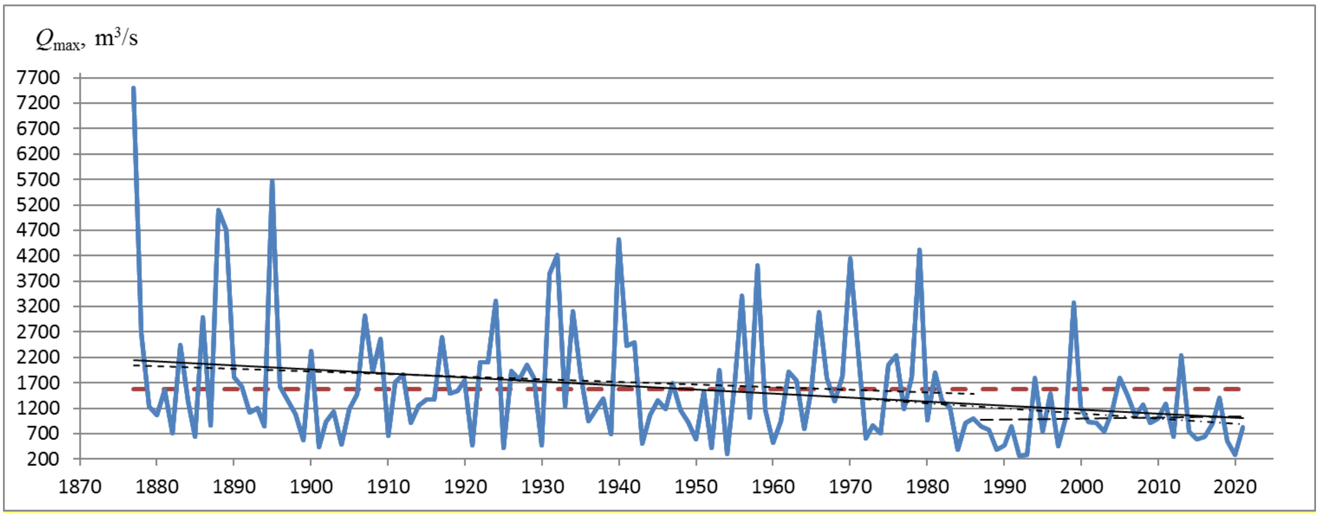



**Figure 4** – Chronological series of maximum water discharges during the spring flood of the Pripyat River at the Mozyr gauge station



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Principal statistical characteristics of the analyzed time series are presented in Table 5.

A statistically significant difference is observed in the maximum water discharges during the spring flood between the periods 1877–1986 and 1987–2021. The critical value for the one-tailed Student's t-test is т $t_{кр}$ = 1.67, while $t_{статистика}$ = 4.87. Significant differences were also found in the variances (coefficients of variation). The critical value for the one-tailed F-test is 1.64, whereas the calculated F-statistic is 4.19. No significant differences were detected in the coefficients of skewness. The gradient of runoff change has undergone a statistically significant transformation, as confirmed by the correlation coefficient.

In the rivers of the Pripyat basin, maximum runoff is generated either from snowmelt or from heavy rainfall events. A characteristic phase of the hydrological regime in this region is the spring flood, which occurs annually in spring as a result of snowmelt and precipitation during the snowmelt period [37, 38]. On the Pripyat River, the spring flood typically begins in the first half of March, although in some years it may shift to February or April. The long-term average duration of floodplain inundation ranges from 80 to 110 days, extending up to 150–180 days in certain years [39]. The width of the spring floodplain on the Pripyat River varies from 5 to 15 km, reaching up to 30 km in specific sections (notably near the city of Pinsk). The duration of the flood on smaller rivers ranges from 40 to 45 days.

**Table 5** – Principal statistical characteristics of the maximum water discharges during the spring flood of the Pripyat River at the Mozyr gauge station across different averaging intervals

| Characteristics | Averaging interval | | | |
|---|---|---|---|---|
| | 1877–2021 (145 years) | 1877–1986 (110 years) | 1987–2021 (35 years) | 1972–2021 (50 years) |
| $Q_{ср}$, m³/s | 1577 | 1760 | 1005 | 1133 |
| $C_v$ | 0.73 | 0.70 | 0.60 | 0.66 |
| $C_s$ | 2.05 | 1.88 | 1.84 | 2.16 |
| $r(1)$ | 0.14 | 0.07 | 0.06 | 0.15 |
| $\Delta Q$ 10, m³/s | –79.39 | –51.68 | 23.53 | –103.11 |
| $r$ | **–0.29** | –0.13 | 0.04 | –0.20 |
| $r_{кр,\ p=5\ \%}$ | *0.16* | *0.19* | *0.33* | *0.28* |
| % of $Q_{ср}$ | –5.03 | –2.94 | 2.34 | –9.10 |
| Maximum in the period/year | 7500/1877 | 7500/1877 | 3270/1999 | 4310/1979 |
| Minimum in the period/year | 272/1992 | 306/1954 | 272/1992 | 272/1992 |

Table 6 presents the water discharges of the ten most significant spring floods [36].

The peak of the spring flood on the majority of rivers occurs from late March to early April. On the tributaries, compared to the Pripyat River, the timing of the flood onset varies somewhat: on the left-bank tributaries, the flood begins later, while on the right-bank tributaries, it begins earlier. However, during a prolonged spring, nearly simultaneous ice break-up can occur across the basin's rivers, resulting in elevated flood levels on the Pripyat River. The rise in water level primarily depends on water availability as well as the morphology of the river valley or its specific sections. The highest levels of the spring flood are generally the maximum levels recorded during the year. The average height of the spring flood above the minimum summer level ranges from 3.5 to 4.5 meters on the Pripyat River, 1.5 to 3.0 meters on the left-bank tributaries, and 1.0 to 2.5 meters on the right-bank tributaries. On small rivers, floodplain inundation typically lasts an average of 25 to 30 days, while on medium and large rivers, it lasts approximately 1.5 to 2 months. The maximum historical value of spring flood runoff on the Pripyat River occurred in 1845, when the discharge was estimated at 11,000 m³/s, with a runoff modulus of 113 L/s·km². Considering the maximum flood level of 1845, the conditions of flood formation, and the available historical data, it can be inferred that at least since the late 19th century to the present, the height of this flood remains unsurpassed. The maximum level and discharge of the Pripyat River during the 1845 flood can be approximately considered to recur no more frequently than once every 800 years. Data analysis indicates that the maximum runoff moduli during the spring flood vary between 34.6 and 364 L/s·km². As a general rule, with increasing catchment area, the maximum runoff moduli decrease. This trend is also characteristic of the average runoff moduli over the flood period. The spring flood begins earlier in the southwest (on average in early March) and somewhat later in the northeast (mid-March). The onset dates of the spring flood vary significantly from year to year. There exists a certain relationship between the timing of the flood onset, its intensity, and its duration. Typically, during late springs with rapid snowmelt, the flood is higher and shorter, exhibiting the greatest peak discharges. In early springs, snow cover melts gradually, leading to increased losses of meltwater due to infiltration, resulting in a flood that is usually low and prolonged. The duration of the flood also depends on the river length, forest cover, swampiness, and karst features of the catchments. For small rivers with karstified and swampy catchments, the average duration is 40 to 45 days, whereas for large rivers, it can reach up to 80 days. For rivers with non-karstified and slightly swampy catchments, the duration is significantly shorter, amounting to 36 and 55 days, respectively. Currently, there is a trend toward earlier onset and peak of spring floods [40, 41].

Relatively regular observations of hydrological runoff parameters began in the late 19th century. However, unsystematic data on levels and discharges from the early period are not utilized in hydrological calculations of design values due to the absence of elevation referencing. The maximum hazardous water levels recorded during the spring flood observation period on the rivers of the Pripyat basin are presented in Table 7 [42].

*Characteristics of Floods on the Rivers of the Pripyat Basin*

The highest water level recorded on the Pripyat River at the Mozyr monitoring station was observed in the spring of 1895, measuring 742 cm (or 113.33 m above sea level), while the lowest level was recorded in the summer of 1961 at 53 cm. The maximum amplitude of the water level fluctuations reached 6.89 m.

Long-term observations indicate that the amplitude of water levels in the Pripyat River varies from 2 to 3 m in the upper reaches, increasing to 4 to 5 m in the middle and lower reaches. The most significant changes in water levels have been documented at the Mozyr monitoring station, which can be attributed to the relatively high river banks and the corresponding lower channel capacity of the river [43].

Throughout the entire observation period, the average maximum discharge of the Pripyat River during the spring flood is approximately 1620 m³/s. The highest recorded discharges occurred in the spring of 1895 (5670 m³/s), 1932 (4220 m³/s), 1958 (4010 m³/s), 1979 (4310 m³/s), and 1999 (4150 m³/s). An overall trend indicates a gradual decline in maximum discharge values over time.

**Table 6** – Maximum water discharge of spring floods on the Pripyat River at the Mozyr gauge station

| Years | 1845 | 1877 | 1895 | 1888 | 1889 | 1940 | 1979 | 1932 | 1970 | 1958 |
|---|---|---|---|---|---|---|---|---|---|---|
| Q,m³/s | 11000 | 7500 | 5670 | 5100 | 4700 | 4520 | 4310 | 4220 | 4140 | 4010 |
| *P*, % | 0.8 | 1.6 | 2.3 | 3.1 | 3.9 | 4.7 | 5.4 | 6.2 | 7.0 | 7.6 |

**Table 7** – Maximum hazardous water levels during spring floods on the Pripyat River and its tributaries for the observation period

| River – Gauge station | Water levels, cm | | | |
|---|---|---|---|---|
| | Hazardous high, (exceedance probability, %) | Maximum, (exceedance probability, %) / date | Maximum stream ice / date | Longest duration, days / year |
| **Pripyat – Pinsk** | 250 (43) | 302 (1)<br>29.03.1979 | 302<br>29.03.1979 | 50<br>1980, 1981 |
| Pripyat – Koroby | 420 (40) | 486 (2)<br>20.04.1958 | 460<br>31.03.1979 | 32<br>1979 |
| Pripyat – Turov | 340 (22) | 410 (1)<br>02-03.04.1979 | 405<br>31.03.1979 | 28<br>1979 |
| **Pripyat – Chernichi** | 520 (57) | 637 (2)<br>21-22.03.1979 | 637<br>21-22.03.1999 | 46<br>1999 |
| Pripyat – Petrikov | 800 (45) | 933 (1)<br>03-04.04.1979 | 924<br>01.04.1979 | 40<br>1999 |
| Pripyat – Mozyr | 550 (30) | 742 (1)<br>22-24.04.1995 | 670<br>21.04.1931 | 31<br>1941 |
| Pina – Pinsk | 335 (8) | 366 (2)<br>01.04.1979 | 347<br>29.03.1979 | 12<br>1979 |
| Yaselda – Senin | 195 (37) | 247 (0,9)<br>27.03.1999 | 234<br>06-12.031999 | 127<br>1999 |
| Horyn – Rechitsa | 530 (52) | 635 (2)<br>11.04.1956 | 635<br>11.04.1956 | 26<br>1979 |

The long-term average date for the peak of the flood is April 11; however, in recent decades, this date has been progressively shifting to an earlier timeframe. It is noteworthy that the maximum flood discharges on the Pripyat River are significantly lower than those observed during the spring floods. During the observation period, the highest flood discharge recorded at the Mozyr monitoring station (1260 m³/s) occurred in mid-August 1993, while the lowest discharge (22.0 m³/s) was recorded in November 1921, a period characterized by drought across the entire East European Plain [44].

Table 8 presents the most significant floods on the rivers of the Pripyat basin caused by spring floods during the period of instrumental observations [45].

The highest level of water on the Pripyat basin rivers is presented in Table 9.

**Table 8** – Years with floods during spring floods

| River – Gauge station | Scale of flood | | |
|---|---|---|---|
| | Catastrophic *P* < 1 % | Outstanding *P* = 1–2 % | Big *P* = 3–10 % |
| Pripyat – Lyubanskii | | 1979 | 1999, 213 |
| Pripyat – Koroby | | 1958 | 1957, 1966, 1979 |
| Pripyat – Turov | | 1979 | 1932, 1940, 1956, 1958, 1970 |
| Pripyat – Chernichi | | 1999 | |
| Pripyat – Petrikov | | 1979 | 1931, 1932, 1940, 1956, 1958, 1966, 1970, 1999 |
| Pripyat – Mozyr | 1845 | 1888, 1895, 1979, 1999 | 1886, 1889, 1907, 1924, 1931, 1932, 1934, 1940, 1956, 1958, 1966, 1970, |
| Pina – Pinsk | | 1979 | 1928,1932,1940,1958 |
| Yaselda – Senin | | 1999 | 1958, 1979, 1981 |
| Horyn – Rechitsa | | 1956 | 1966, 1979, 1996, 1999 |
| Ubort – Krasnoberezhye | | 1932 | 1934, 1966, 1970, 1999 |
| Ptich – Luchitsy | | 1931, 1999 | 1895, 1896, 1900, 1907, 1917, 1956, 1958 |

**Table 9** – Water levels on the Pripyat basin rivers (data date 01.01.2018)

| River – Gauge station | Zero mark at the gauge station in Baltic Height System, m | Average level, $H_{сред}$, cm | Maximum level | |
|---|---|---|---|---|
| | | | cm | date |
| Pripyat – Pinsk | 133.18 | 112 | 302 | 21.04.2013 |
| Pripyat – Chernichi | 119.23 | 356 | 637 | 21–22.03 1999 |
| Pripyat – Petrikov | 112.55 | 562 | 933 | 03–04.04.1979 |
| Pripyat – Mozyr | 110.93 | 224 | 742 | 22–24.04.1895 |
| Pina – Pinsk | 132.29 | 169 | 366 | 01.04.1979 |
| Yaselda – Senin | 134.39 | 126 | 247 | 27.03.1999 |
| Horyn – Malye Vikorovichi | 129.67 | 298 | 635 | 11.04.1956 |
| Sluch – Lenin | 129.97 | 114 | 314 | 20.04–21.04.1958 |
| Ubort – Krasnoberezhye | 126.26 | 157 | 390 | 11.04.1932 |
| Ptich – Daraganov | 150.00 | 186 | 339 | 13.04.1999 |

*Changes in Maximum Discharges of Spring Floods and Their Causes*

In recent years, anthropogenic factors, alongside natural influences, have increasingly contributed to the frequency and severity of destructive flooding events. Among these factors, deforestation stands out, as it can lead to an increase in maximum surface runoff by 250 to 300 %. Other significant contributors include floodplain development, unsustainable agricultural practices, and additional human activities. The notable reduction in maximum discharges, coupled with an increase in minimum winter and summer-autumn runoff, can be attributed to both natural processes and modifications to floodplains, which act as vital natural regulators of runoff.

Since the mid-1960s, a discernible trend of decreasing maximum discharges has been observed, supported by statistical significance tests of average values across various time periods. For example, the averages for the periods from 1877 to 1965 ($\overline{Q}$ = 1770 m³/s) and from 1966 to 2021 ($\overline{Q}$ = 1270 m³/s) show statistically significant differences at the 5 % significance level. Similarly, the averages for the periods from 1877 to 1986 ($\overline{Q}$ = 1760 m³/s) and from 1986 to 2021 ($\overline{Q}$ = 1010 m³/s) also reveal significant distinctions.

In the current century, the water discharges during spring floods on the Pripyat River at the Mozyr monitoring station exceeded the normative value of $\overline{Q}$ =1580 m³/s only in 2013, with a recorded discharge of $Q_{2013}$ = 2240 m³/s. At the Lyuban Bridge monitoring station, the spring flood norm of $\overline{Q}$ = 182 m³/s was surpassed in several years: $Q_{2013}$ = 420 m³/s, $Q_{2011}$ = 237 m³/s, $Q_{2005}$ = 231 m³/s, $Q_{2002}$ = 210 m³/s, $Q_{2000}$ = 195 m³/s, $Q_{2007}$ = 184 m³/s, and $Q_{2009}$ = 184 m³/s. At the Turov monitoring station, the spring flood norm of $\overline{Q}$ =1010 m³/s was exceeded, with $Q_{2013}$ = 1320 m³/s and $Q_{2005}$ = 1100 m³/s. On the Horyn River at the Rechitsa gauge station, the spring flood norm of $\overline{Q}$ =597 m³/s was exceeded, with $Q_{2013}$ = 1090 m³/s, $Q_{2006}$ = 943 m³/s, $Q_{2003}$ = 813 m³/s, $Q_{2005}$ = 775 m³/s, and $Q_{2008}$ = 733 m³/s. On the Ubort River at the Krasnoberezhye gauge station, the spring flood norm of $\overline{Q}$ = 153 m³/s was surpassed, with $Q_{2013}$ = 271 m³/s, $Q_{2005}$ = 251 m³/s, and $Q_{2006}$ = 204 m³/s. On the Ptich River at the village of Luchosy, the spring flood norm of $\overline{Q}$ = 213 m³/s was exceeded, with $Q_{2013}$ = 220 m³/s.

The stability of statistical measures (means, coefficients of variation, and coefficients of autocorrelation) for the time series of maximum water discharges during spring floods was evaluated across four distinct periods (refer to Table 5).

Analysis of long-term variations in river discharge within the basin reveals persistent fluctuations in indicative discharges over the years. These fluctuations manifest as alternating sequences of high-flow and low-flow annual periods, generating cycles of varying duration and amplitude in water availability. Examination of differential integral curves constructed for 30 river gauge stations across the Pripyat River basin indicates a synchronous pattern between high-flow and low-flow phases [46].

The analysis demonstrates that the percentage difference in runoff during spring reaches its maximum in both high-flow (5 %) and low-flow (95 %) years, while minimal differences are observed during summer and autumn. This suggests that, in low-flow years, the majority of the total annual river discharge is generated in spring (50–60 %), whereas in high-flow years, runoff predominantly occurs during summer and autumn (40–50 %). Based on this, distinct low-flow and high-flow periods have been identified in the fluctuations of maximum discharge. Two hydrological regimes are clearly discernible in the maximum discharge records: a high-flow period prior to the early 1980s, characterized by pronounced maxima in 1953, 1955, 1956, 1958, 1966, 1967, 1974, 1977, 1979, and 1980; and a low-flow period from 1982 to the present, with exceptions in 1998, 1999, and 2013. Given that maximum discharges primarily reflect spring flood runoff, it can be confidently concluded that the proportion of spring runoff within the intra-annual distribution has steadily declined in recent decades.

The marked reduction in maximum spring flood discharges observed at the end of the twentieth century is attributed to an increased frequency of winter thaws, during which substantial snow reserves are converted into runoff during the winter low-flow period. This phenomenon results in elevated winter runoff, occasionally causing winter floods, and consequently diminishes peak flows in spring.

To substantiate this hypothesis, the long-term trend of minimum winter runoff is presented, revealing an increasing tendency supported by a statistically significant positive linear trend.

Significance testing of linear trends indicates that, for the Pripyat River at the Mozyr gauge station, correlation coefficients are statistically significant at the 5% level over the entire study period.

In light of the observed decreasing runoff trends, a comparative analysis of design values for maximum spring flood discharges was undertaken for the periods 1877–1965 and 1966–2021. Employing the Pearson Type III distribution, design discharge values were derived for the respective periods (see Table 10).

**Table 10** – Design values of maximum spring flood discharges of the Pripyat River at the Mozyr gauge station for various periods, m³/s

| Period | Exceedance probability, % | | | |
|---|---|---|---|---|
| | 1 | 5 | 10 | 50 |
| **1877–2021** | **6650** | **4200** | **3090** | **1250** |
| 1877–1965 | **7680** | **4610** | **3220** | **1470** |
| 1966–2021 | **4410** | **3400** | **2270** | **994** |
| **Change, %** | **–33.7** | **–19.0** | **–26.5** | **20.5** |

The analysis presented in Table 10 reveals significant discrepancies in the design values across the periods under consideration. This underscores the necessity of accounting for the heterogeneity of the time series of maximum spring flood discharges when developing probabilistic forecasts for the rivers of the Pripyat basin.

Furthermore, the examination of the spatial structure of changes in maximum spring flood discharges indicates a general decline in spring flood runoff throughout nearly the entire Pripyat River basin.

For instance, the scale of hydromelioration efforts in the Western Dvina River basin is considerably smaller than that in the Pripyat River basin. Nevertheless, the observed reduction in maximum spring flood discharges in both river systems is consistent. It can be hypothesized that the primary driver behind the decrease in maximum spring flood discharges in the Pripyat basin rivers is of a natural origin, with lesser influence from anthropogenic factors [13].

Additionally, the long-term analysis of maximum spring flood discharges within the Pripyat basin has identified a clear trend of decreasing spring flood runoff across all rivers, particularly pronounced since the mid-1960s. To quantitatively evaluate these transformations, trend lines have been constructed for various averaging periods (see Table 5).

*Minimum Flow*

The Pripyat River basin is located within a region characterized by excess moisture, where groundwater discharge into the river network is relatively sustained and continuous. As a result, the baseflow contribution from groundwater to surface watercourses in this area is constant. Minimum water levels and flows during the summer period typically occur under conditions of elevated mean daily air temperatures combined with prolonged precipitation deficits; in winter, minimum flows correspond to periods of low temperatures. During drought years, drying of watercourses has been observed across 36 catchments exceeding 1000 km² in area. The summer–autumn low-flow period generally begins from late May to mid-June and persists until October. In certain years, when the spring flood recedes uniformly, the onset of low flow in the rivers can occur considerably earlier, in late April to early May. Conversely, in years with prolonged flooding or when rainfall occurs during the recession phase, the low-flow period may be delayed until late June to mid-July. In some years, in the absence of autumn floods, low flow conditions may extend until the onset of ice formation, typically from mid-November to early December. The average runoff during the summer–autumn low-flow period for small and medium rivers ranges between 3 mm and 15 mm. The most pronounced low-flow conditions within this period generally occur in July and August, less frequently in September. The duration of low flow for small and medium-sized watercourses may reach up to 130 days, whereas for the Pripyat River, it typically spans 85 to 90 days. Winter low flow usually establishes by late December.

The earliest occurrence of low flow is recorded in late October to early November, while the latest onset can be as late as January, with termination coinciding with the onset of the spring flood. The average duration of low flow on small and medium rivers varies from 49 to 100 days. Within the Polesie region, zero-flow events have been documented on 17 watercourses with catchment areas ranging from 11 to 1280 km². The average duration of zero-flow episodes can reach up to 195 days during summer and 75 to 100 days during winter [47, 48].

Table 11 summarizes the calculated minimum flow values for rivers within the Pripyat basin along with their corresponding statistical parameters.

Chronological series of minimum summer-autumn discharges of the Pripyat River at the Mozyr station is presented in Figure 5.

The main statistical characteristics of the analyzed series are presented in Table 12.

**Table 11** – Calculated minimum runoff values and statistical parameters for rivers in the Pripyat basin

| River | Gauge Station | Normal annual runoff | | Cv | Cs/Cv |
|---|---|---|---|---|---|
| | | Discharge, $m^3/s$ | runoff module, l/s $km^2$ | | |
| Pripyat | Mozyr | 154 | 1.53 | 0.52 | 4.0 |
| Yaselda | Beryoza | 1.25 | 1.36 | 0.82 | 2.0 |
| Tsna | Diatlovichi | 0.89 | 0.91 | 0.90 | 4.0 |
| Sluch | Novodvortsy | 0.45 | 0.50 | 1.02 | 3.0 |
| Ptich | Luchitsy | 14.3 | 1.63 | 0.49 | 2.5 |
| Oressa | Andreevka | 5.68 | 1.59 | 0.53 | 2.5 |

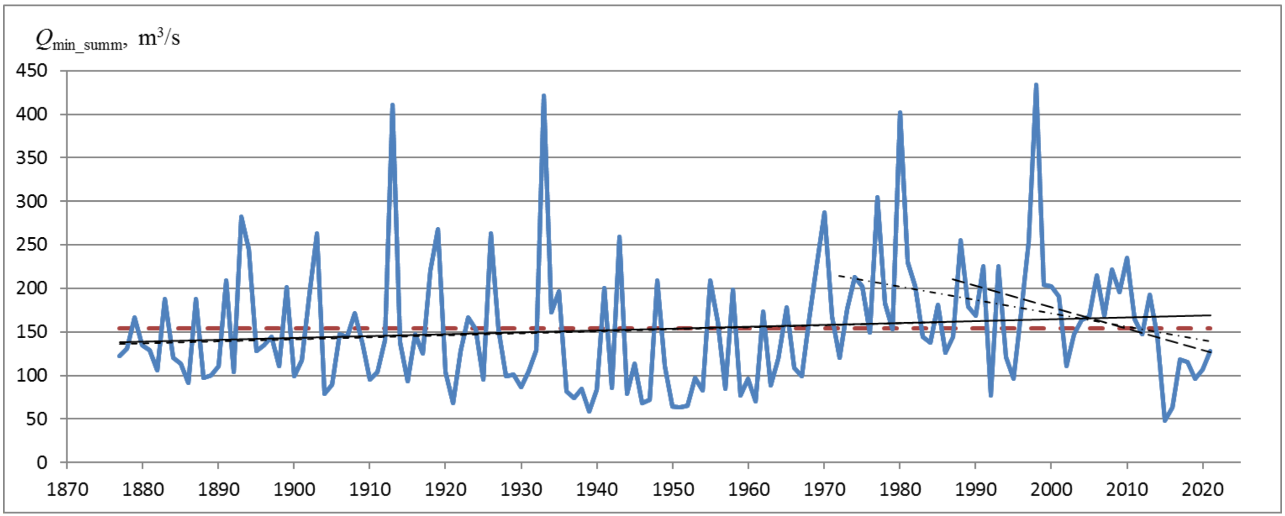


**Figure 5** – Chronological series of minimum summer-autumn discharges of the Pripyat River at the Mozyr station

**Table 12** – Main statistical characteristics of minimum summer-autumn discharges of the Pripyat River at the Mozyr station for various averaging intervals

| Characteristics | Averaging intervals | | | |
|---|---|---|---|---|
| | 1877–2021 (145 years) | 1877–1986 (110 years) | 1987–2021 (35 years) | 1972–2021 (50 years) |
| $Q_{cp}$, $m^3/s$ | 154 | 149 | 169 | 176 |
| $C_v$ | 0.47 | 0.48 | 0.42 | 0.41 |
| $C_s$ | 1.49 | 1.59 | 140 | 1.43 |
| $r(1)$ | 0.20 | 0.14 | 0.36 | 0.27 |
| $\Delta Q$ 10, $m^3/s$ | 2.16 | 2.34 | –24.76 | –15.44 |
| $r$ | 0.13 | 0.10 | **–0.36** | **–0.31** |
| $r_{кр,\ p=5\ \%}$ | *0.16* | *0.19* | *0.33* | *0.28* |
| % of $Q_{cp}$ | 1.41 | 1.57 | –14.69 | –8.75 |
| Maximum in the period/year | 434/1998 | 421/1933 | 434/1998 | 434/1998 |
| Minimum in the period/year | 48.0/2015 | 58.7/1939 | 48.0/2015 | 48.0/2015 |

Statistically significant differences in minimum summer-autumn water discharges between the periods of 1877–1986 and 1987–2021 were not identified. The critical value for the one-tailed Student's t-test is $t_{кр}$ = 1.67, while the calculated $t_{статистика}$ = 1.43. Additionally, no differences in variances (coefficients of variation) were observed. There were no significant changes in the coefficient of skewness or transformations of the flow gradient.

The onset of winter low flow generally occurs during the third decade of November to the first half of December. The average duration of winter low flow ranges from 60 to 80 days, with the longest durations reaching between 100 and 120 days. The conclusion of winter low flow typically falls in March, although in some years it may occur in February. For the Pripyat River, winter low flow usually establishes by the end of December and concludes in late February to early March, with an average duration of 69 days. In certain years, winter low flow may be interrupted by winter floods. The most pronounced low water period during winter low flow is typically observed in late February to early March, lasting from 7 to 18 days.

Analysis of observational data indicates that the values of the lowest average monthly summer discharges systematically decrease across the basin, trending from the northwest and north toward the south and southeast, in accordance with geographical zonation patterns in larger and medium-sized rivers. Conversely, in small rivers, an intra-zonal pattern of changes is observed, which is dependent on local hydrogeological characteristics, such as the presence and thickness of groundwater horizons, the nature of their exposure through river valleys, and the conditions governing their drainage.

The most water-rich aquifers are found in fractured and karstified carbonate-sulfate rocks of the Upper Cretaceous and Neogene periods.



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Cretaceous waters emerge within the Polesie lowland as ascending springs with discharges of up to 200 m³/h. The module of minimum average daily discharge for these rivers, at 97 % exceedance probability, varies from 0.07 to 0.18 l/s·km². Rivers that are fed by aquifers in alluvial and fluvioglacial deposits exhibit low minimum discharge modules, and during drought years, their flow can cease completely for periods ranging from 15 to 120 days. Flow cessation in these rivers can also occur during cold, thawless winters. The module of minimum average daily discharge at 97 % exceedance probability for this group of rivers ranges from 0.00 to 0.02 l/s·km² during summer low flow and from 0.00 to 0.05 l/s·km² during winter.

Research and analysis of minimum flow characteristics, based on data from several hydrological stations located in the upper reaches of the Pripyat River, indicate that human economic activities significantly influence the formation of low flow in this region. An increase in watershed area is associated with a decrease in minimum water discharges and flow modules. The primary water management facilities affecting the formation of minimum flow in the upper reaches of the Pripyat River include the Upper Pripyat drainage and irrigation system and the water intake from the Dnieper-Bug Canal, whose operation contributes to the reduction of flow. For most rivers in the Pripyat basin, a clear trend of increasing minimum flow modules with increasing watershed area is observed. This trend can be attributed to the growing proportion of groundwater contribution to the total discharge and the presence of numerous groundwater horizons that are drained by the river. In most cases, minimum water discharges in the right-bank tributaries of the Pripyat River are recorded during the autumn season. Approximately 20 to 30 % of the minimum discharges are recorded in the summer, with a similar percentage in the winter. Freezing is observed only in small rivers and for a limited duration.

Chronological series of minimum winter discharges of spring flood of the Pripyat River at the Mozyr station is presented in Figure 6.

The main statistical characteristics of the analyzed series are presented in Table 13.

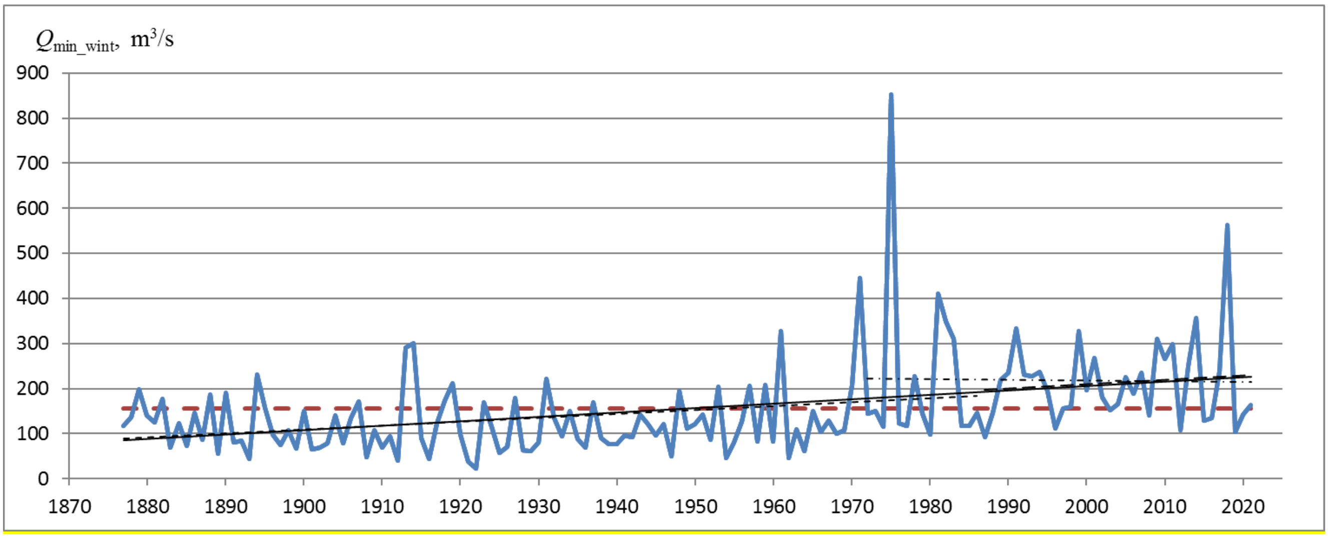


**Figure 6** – Chronological series of minimum winter discharges of spring flood of the Pripyat River at the Mozyr station

**Table 13** – Main statistical characteristics of minimum winter discharges of the Pripyat River at the Mozyr station for various averaging intervals

| Characteristics | Averaging intervals | | | |
|---|---|---|---|---|
| | 1877–2021 (145 years) | 1877–1986 (110 years) | 1877–2021 (145 years) | 1972–2021 (50 years) |
| $Q_{cp}$, m³/s | 155 | 136 | 214 | 218 |
| $C_v$ | 0.68 | 0.75 | 0.43 | 0.60 |
| $C_s$ | 2.87 | 3.83 | 1.65 | 2.79 |
| $r(1)$ | 0.14 | 0.07 | -0.06 | –0.10 |
| $\Delta Q$ 10, m³/s | 9.75 | 8.54 | 9.73 | –1.45 |
| $r$ | **0.39** | **0.27** | 0.11 | –0.02 |
| $r_{кр,\ p=5\ \%}$ | *0.16* | *0.19* | *0.33* | *0.28* |
| % of $Q_{cp}$ | 6.29 | 6.27 | 4.55 | –0.67 |
| Maximum in the period/year | 852/1975 | 852/1975 | 562/2018 | 852/1975 |
| Minimum in the period/year | 22.0/1922 | 22.0/1922 | 92.5/1987 | 92.5/1987 |

A statistically significant increase in minimum winter water discharges has been observed for the period from 1987 to 2021, in comparison to the preceding period from 1877 to 1986. The critical value for the one-tailed Student's t-test is $t_{кр}$ = 1.68, while the calculated t-value is t = 4.22. No significant differences in variances (coefficients of variation) were detected. However, the coefficient of skewness has undergone notable changes, which should be considered when selecting probability distribution curves. Additionally, the gradient of flow changes has transformed significantly over the entire study period, as well as during the interval from 1972 to 2010, as corroborated by correlation coefficients.

*Observed Climate Change*

In recent decades, several changes in climate characteristics have been documented, with the average annual air temperature in this region (as well as across the entire Northern Hemisphere) exhibiting a consistent upward trend. In the Pripyat River basin, this increase has been approximately +0.7 °C to +0.9 °C over the past century. This trend is particularly pronounced during the cold season, where the rate of temperature increase is two to three times higher. In terms of atmospheric precipitation, a downward trend has been identified. Concurrently, the average height of snow cover is decreasing, primarily attributed to rising winter temperatures. These climatic shifts significantly influence the hydrological dynamics of the basin, particularly affecting the intra-annual distribution of river flow. Specifically, the proportion of spring runoff is declining, while the contribution of summer-autumn runoff is increasing. Moreover, the role of rain-induced floods in shaping runoff patterns is becoming increasingly prominent [49, 50].

For the rivers within the Pripyat basin, a comprehensive analysis of hydrological data led to the selection of seven meteorological stations and eleven hydrological posts. The selection of specific stations and posts was based on their availability in 1961 and their continuous operation through 2015 up to now, ensuring the integrity of observational data for climate and flow characteristics.

The initial climate data were sourced from various repositories, including open information resources from the World Meteorological Organization (WMO) and other organizations and centers dedicated to climate research, as well as from climate reference publications.

Figures 7 and 8 illustrate the final results of climate change within the Pripyat River basin.

Based on the assessments of climate change from 1961 to 2015, the following generalized conclusions can be drawn:

– There has been an average increase in air temperature across the basin of 1.0 °C, with the most significant increase observed during the winter season at 1.9 °C, and the least notable increase occurring in the autumn season, with a maximum rise of 0.1 °C.

– The total precipitation across the basin has not changed significantly, exhibiting a slight average increase of 0.7 %, with a maximum increase of up to 16 %.

The results of the changes in climate characteristics for the period from 1961 to 2010 are presented graphically in Figures 7 and 8.

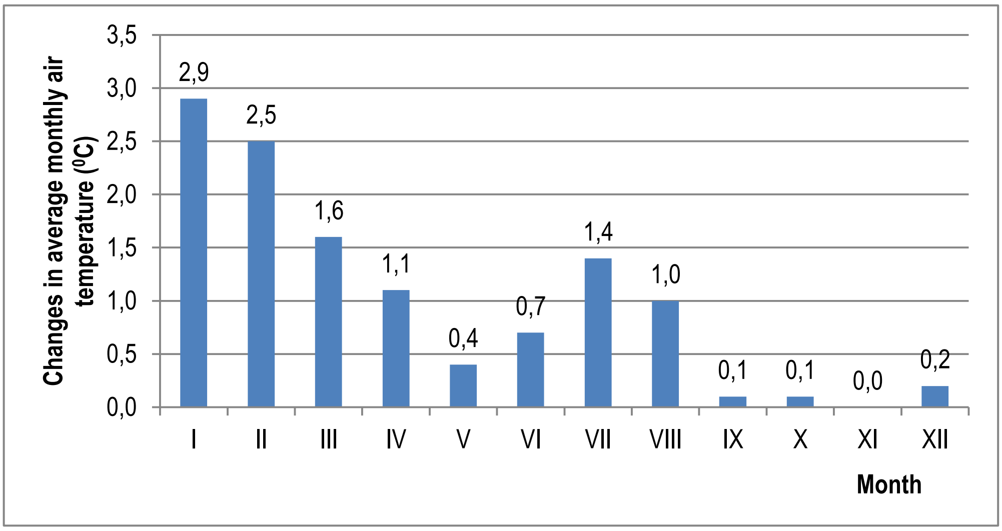


**Figure 7** – Changes in average monthly air temperature ($^0$C) within the Pripyat basin (1986–2010) – (1961–1985)

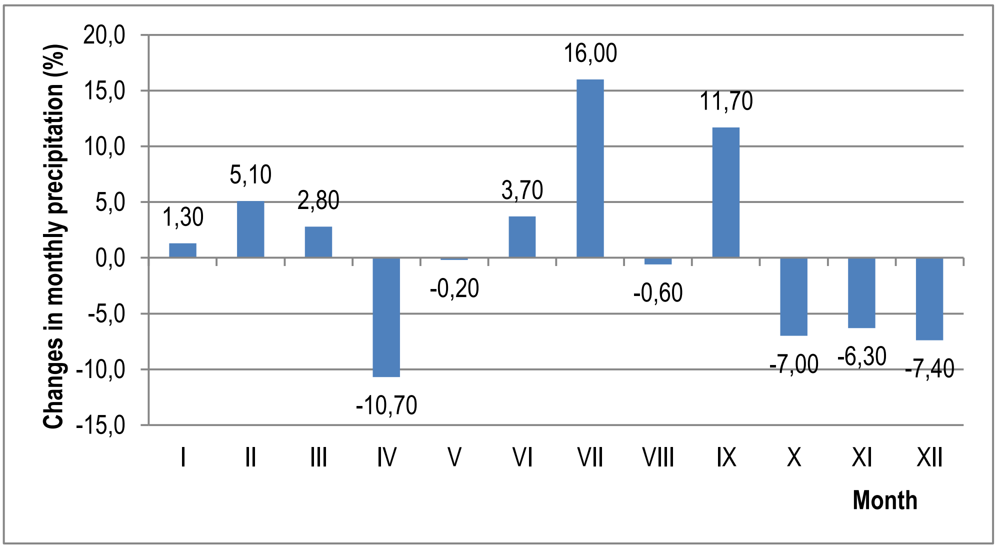


**Figure 8** – Changes in monthly precipitation (%) within the Pripyat basin (1986–2010) – (1961–1985)

*Observed Changes in River Flow*

The assessment of changes in river flow (water discharge) has been conducted for hydrological stations, analyzing both monthly and annual averages for the period from 1986 to 2015, in comparison to the period from 1961 to 1986.

The summarized results of the river flow assessments for the Pripyat River basin, covering the period from 1961 to 2015, are presented in Tables 14 and 15 [13].

Based on the essessment of river flow changes from 1961 to 2015, the following generalized conclusions can be drawn [13]:

– The average annual river flow has experienced only a slight change, with a maximum decrease of 9 %;

– There has been a significant reduction in spring flood flow, which has decreased by 42 %, accompanied by an earlier onset of its peak;

– Winter flow has increased by 20 %;

– Summer flow has not changed significantly over the entire period from 1961 to 2015; however, in recent years (including 2015, 2016, 2017, and 2019), there has been a notable decline in flow, with measurements falling below the minimum recorded levels for the entire specified period.

Maps of changes in river flow from 1961 are provided in Appendix B [13].



https://doi.org/10.36773/1818-1112-2025-138-3-141-158

**Table 14** – Changes in river flow in the Pripyat River basin for the period from 1961 to 2015

| River, Gauge station | Catchment area, km² | Characteristic | Water discharge values in intervals 1986–2015 and 1961–1985, m³/s, difference, % | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | January | February | March | April | May | June | July | August | September | October | November | December |
| Pripyat – Chernichi (Turov) | 74000 | $Q_{cp.}$ | 226 | 237 | 396 | 644 | 438 | 271 | 211 | 183 | 165 | 181 | 211 | 215 |
| | | $Q_{1961–1985}$ | 215 | 195 | 365 | 767 | 502 | 295 | 212 | 173 | 162 | 176 | 225 | 222 |
| | | $Q_{1986–2015}$ | 235 | 271 | 421 | 546 | 387 | 252 | 209 | 190 | 167 | 185 | 200 | 209 |
| | | Δ% | *9.4* | *39.3* | *15.2* | *–28.9* | *–23.0* | *–14.6* | *–1.6* | *10.2* | *3.6* | *5.4* | *–11.0* | *–6.2* |
| Pripyat – Mozyr | 101000 | $Q_{cp.}$ | 337 | 357 | 576 | 983 | 684 | 415 | 317 | 278 | 241 | 258 | 298 | 315 |
| | | $Q_{1961–1985}$ | 322 | 293 | 509 | 1110 | 723 | 435 | 318 | 262 | 232 | 245 | 303 | 326 |
| | | $Q_{1986–2015}$ | 350 | 410 | 632 | 879 | 651 | 398 | 316 | 291 | 249 | 268 | 294 | 306 |
| | | Δ% | *8.7* | *39.6* | *24.2* | *–20.7* | *–9.9* | *–8.6* | *–0.7* | *11.2* | *7.3* | *9.7* | *–2.7* | *–6.0* |
| Yaselda – Beryoza | 1040 | $Q_{cp.}$ | 4.60 | 4.24 | 6.95 | 8.96 | 4.69 | 3.26 | 3.04 | 3.45 | 4.69 | 4.58 | 4.37 | 4.59 |
| | | $Q_{1961–1985}$ | 4.27 | 3.60 | 8.63 | 12.5 | 5.33 | 3.07 | 2.31 | 2.13 | 2.37 | 3.33 | 4.47 | 4.86 |
| | | $Q_{1986–2015}$ | 4.88 | 4.78 | 5.56 | 6.00 | 4.15 | 3.41 | 3.65 | 4.55 | 6.63 | 5.62 | 4.29 | 4.36 |
| | | Δ% | *14.3* | *32.8* | *–35.6* | *–52.1* | *–22.1* | *11.1* | *58.0* | *114.6* | *180.0* | *68.8* | *–4.0* | *–10.3* |
| Yaselda – Senin | 5110 | $Q_{cp.}$ | 19.1 | 19.3 | 31.1 | 44.4 | 27.7 | 17.5 | 12.9 | 10.1 | 9.88 | 13.3 | 17.7 | 18.8 |
| | | $Q_{1961–1985}$ | 18.6 | 15.9 | 33.6 | 56.7 | 33.0 | 19.8 | 12.7 | 8.89 | 8.41 | 12.3 | 18.7 | 20.5 |
| | | $Q_{1986–2015}$ | 19.5 | 22.2 | 28.9 | 33.8 | 23.1 | 15.6 | 13.1 | 11.2 | 11.2 | 14.1 | 16.9 | 17.3 |
| | | Δ% | *5.0* | *39.7* | *–14.0* | *–40.5* | *–30.1* | *–20.9* | *3.7* | *25.9* | *32.6* | *14.8* | *–9.9* | *–15.3* |
| Tsna – Diatlovichi | 1100 | $Q_{cp.}$ | 4.04 | 4.02 | 8.07 | 13.3 | 6.29 | 3.51 | 2.85 | 2.19 | 1.76 | 2.39 | 3.45 | 3.63 |
| | | $Q_{1961–1985}$ | 3.23 | 2.74 | 7.80 | 15.8 | 6.85 | 3.13 | 1.88 | 1.43 | 1.42 | 2.17 | 3.60 | 3.31 |
| | | $Q_{1986–2015}$ | 4.72 | 5.08 | 8.29 | 11.1 | 5.82 | 3.83 | 3.65 | 2.82 | 2.03 | 2.58 | 3.33 | 3.91 |
| | | Δ% | *46.1* | *85.4* | *6.3* | *–29.9* | *–15.0* | *22.4* | *94.2* | *97.2* | *43.0* | *18.9* | *–7.5* | *18.2* |
| Horyn – Malye Viktorovichi | 27000 | $Q_{cp.}$ | 90.1 | 106 | 191 | 243 | 117 | 86.9 | 86.3 | 71.9 | 63.5 | 67.8 | 75.9 | 80.6 |
| | | $Q_{1961–1985}$ | 83.3 | 92.4 | 215 | 296 | 140 | 90.9 | 99.2 | 77.7 | 71.5 | 74.8 | 87.7 | 86.0 |
| | | $Q_{1986–2015}$ | 95.3 | 117 | 173 | 202 | 98.7 | 83.8 | 76.5 | 67.4 | 57.4 | 62.4 | 66.8 | 76.6 |
| | | Δ% | *14.4* | *27.0* | *–19.6* | *–31.5* | *–29.5* | *–7.8* | *–22.9* | *–13.2* | *–19.8* | *–16.6* | *–23.9* | *–11.0* |
| Sluch – Lenin | 4480 | $Q_{cp.}$ | 15.4 | 15.1 | 29.8 | 46.6 | 20.6 | 12.0 | 9.61 | 8.68 | 10.3 | 12.7 | 14.5 | 14.5 |
| | | $Q_{1961–1985}$ | 14.8 | 11.9 | 30.2 | 64.4 | 24.9 | 12.3 | 9.08 | 8.14 | 9.90 | 13.1 | 16.2 | 15.6 |
| | | $Q_{1986–2015}$ | 15.9 | 17.7 | 29.4 | 31.8 | 17.0 | 11.7 | 10.1 | 9.12 | 10.7 | 12.3 | 13.0 | 13.6 |
| | | Δ% | *7.2* | *49.5* | *–2.6* | *–50.6* | *–31.5* | *–4.5* | *10.7* | *12.0* | *7.7* | *–6.0* | *–20.2* | *–12.6* |
| Uborts – Krasno-berezhie | 5260 | $Q_{cp.}$ | 18.1 | 19.7 | 45.0 | 62.7 | 26.7 | 20.0 | 17.9 | 13.8 | 9.15 | 9.59 | 14.0 | 17.5 |
| | | $Q_{1961–1985}$ | 13.4 | 14.3 | 48.0 | 77.0 | 31.0 | 19.4 | 18.8 | 14.6 | 9.14 | 9.81 | 15.9 | 19.6 |
| | | $Q_{1986–2015}$ | 21.2 | 23.6 | 43.0 | 51.7 | 23.5 | 20.2 | 17.2 | 13.3 | 9.15 | 9.42 | 12.5 | 15.9 |
| | | Δ% | *57.8* | *65.1* | *–10.4* | *–32.9* | *–24.3* | *4.4* | *–8.5* | *–9.1* | *0.1* | *–4.0* | *–21.2* | *–18.9* |
| Ptich – Luchitsy | 8770 | $Q_{cp.}$ | 40.5 | 39.0 | 64.6 | 99.6 | 58.9 | 37.0 | 29.8 | 25.7 | 27.0 | 31.9 | 38.3 | 40.5 |
| | | $Q_{1961–1985}$ | 38.6 | 32.6 | 65.4 | 125 | 67.7 | 39.3 | 30.9 | 28.0 | 28.4 | 33.1 | 42.1 | 44.5 |
| | | $Q_{1986–2015}$ | 42.0 | 44.3 | 63.9 | 78.6 | 51.5 | 35.1 | 28.9 | 23.9 | 25.9 | 30.9 | 35.2 | 37.1 |
| | | Δ% | *8.9* | *35.6* | *–2.2* | *–37.0* | *–24.0* | *–10.6* | *–6.4* | *–14.6* | *–8.6* | *–6.6* | *–16.2* | *–16.6* |
| Shats – Shatsk | 208 | $Q_{cp.}$ | 1.00 | 1.06 | 2.08 | 2.91 | 1.25 | 1.03 | 0.96 | 0.85 | 0.77 | 0.76 | 0.94 | 0.95 |
| | | $Q_{1961–1985}$ | 0.75 | 0.81 | 2.11 | 3.70 | 1.31 | 1.15 | 1.23 | 1.11 | 0.95 | 0.81 | 0.95 | 0.88 |
| | | $Q_{1986–2015}$ | 1.20 | 1.26 | 2.04 | 2.26 | 1.21 | 0.92 | 0.74 | 0.63 | 0.63 | 0.71 | 0.94 | 1.00 |
| | | Δ% | *60.0* | *55.6* | *–3.3* | *–38.9* | *–7.6* | *–20.0* | *–39.8* | *–43.2* | *–33.7* | *–12.4* | *–1.1* | *13.6* |
| Oressa – Andreevka | 3580 | $Q_{cp.}$ | 16.8 | 17.2 | 25.6 | 31.6 | 18.2 | 13.9 | 12.3 | 11.6 | 13.9 | 15.6 | 16.4 | 16.8 |
| | | $Q_{1961–1985}$ | 16.2 | 15.0 | 25.7 | 37.4 | 20.7 | 15.4 | 12.9 | 12.9 | 14.7 | 16.4 | 18.2 | 18.7 |
| | | $Q_{1986–2015}$ | 17.3 | 19.1 | 25.4 | 26.8 | 16.1 | 12.6 | 11.8 | 10.4 | 13.3 | 14.8 | 14.9 | 15.1 |
| | | Δ% | *6.9* | *27.2* | *–1.2* | *–28.3* | *–22.2* | *–180* | *–8.1* | *–19.4* | *–9.1* | *–9.7* | *–17.9* | *–19.2* |

*Scenarios and Projections of Climate Change*

Climate change scenarios for the river basins of the Dnieper and Pripyat rivers, extending to the year 2035, have been developed using materials presented in the Atlas of Global and Regional Climate Projections, which serves as an appendix to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [51]. For the overarching climate and hydrological projections up to 2035, a multimodel ensemble consisting of four scenarios – RCP8.5, RCP6.0, RCP4.5, and RCP2.6 – has been employed alongside cartographic representations created by the IPCC using global climate models, as detailed in the atlas.

The climate change scenarios have been formulated based on two greenhouse gas emission pathways (widely recognized in global practice and frequently utilized for climate change assessments) [52, 53]:

Scenario I: A1B (Relatively High-Emission Scenario) – This scenario is characterized by relatively high greenhouse gas emissions resulting from rapid economic development and population growth until the mid-21st century. Following this period, it anticipates a deceleration in population growth, the swift adoption of modern technologies, and a balanced approach to energy resource utilization.

**Table 15** – Changes in water discharge (numerator m3/s and demoninator %) within the Pripyat River basin from 1961 to 2009

| River – Gauge station | Catchment area, km2 | Average | Maximum spring flood | Minimum summer-autumn low flow | Minimum winter low flow |
|---|---|---|---|---|---|
| Pripyat – Chernichi (Turov) | 74000 | 282/–6.8 | 973/–18.3 | 120/2.3 | 141/–1.8 |
| Pripyat – Mozyr | 101000 | 422/–0.6 | 1410/–30.0 | 179/–0.8 | 205/2.6 |
| Yaselda – Beryoza | 1040 | 4.79/1.7 | 20.8/–66.0 | 1.72/98.2 | 2.63/39.4 |
| Yaselda – Senin | 5110 | 20.2/–12.4 | 67.6/–47.1 | 6.20/20.0 | 10.9/12.1 |
| Tsna – Diatlovichi | 1100 | 4.62/6.8 | 22.6/–42.8 | 0.94/16.3 | 1.96/31.7 |
| Horyn – Malye Viktorovichi | 27000 | 107/–16.7 | 631/–45.7 | 40.9/–6.9 | 49.8/3.9 |
| Sluch – Lenin | 4480 | 17.5/–16.5 | 79.5/–39.0 | 4.34/–33.0 | 8.58/–5.3 |
| Uborts – Krasnoberezhie | 5260 | 22.8/–10.5 | 162/–49.6 | 4.23/8.7 | 8.47/14.6 |
| Ptich – Luchitsy | 8770 | 44.4/–13.5 | 152/–44.6 | 17.6/–10.7 | 24.3/3.8 |
| Shats – Shatsk | 208 | 1.21/–13.7 | 8.76/–53.6 | 0.39/–31.9 | 0.49/13.0 |
| Oressa – Andreevka | 3580 | 17.5/–11.7 | 53.9/–26.9 | 6.72/–24.8 | 10.0/–1.1 |

Scenario II: B1 (Low-Emission Scenario) – This scenario presents a more "lenient" outlook, characterized by low greenhouse gas emissions. It suggests a probable sudden onset of globalization, with population dynamics mirroring those outlined in Scenario A1. However, it envisions a rapid transformation of the economic system into an information-driven model, with society becoming less consumer-oriented and a significant emphasis on the adoption of new clean technologies.

For the Pripyat basin, a more detailed climate forecast has been constructed, accounting for regional variability as identified through meteorological station data from 1961 to 2015. This forecast employs the most unfavorable (conservative) scenarios projecting the highest temperature increases and reductions in precipitation. Additionally, it incorporates linear interpolation and delineates climate change scenarios utilizing the regional model CCLM, with outputs derived from the global climate model ECHAM5, as illustrated in Figures 9 and 10.

Under the most conservative climate change scenarios, the average annual temperature in the Pripyat basin is projected to increase by up to 1.9 °C, with the greatest seasonal rises occurring in winter (up to 2.53 °C), followed by summer (2.1 °C), and approximately 1.7 °C during spring and autumn. Annual precipitation is expected to undergo minimal change, with an overall decrease of approximately 2.2 %. Seasonal variations include a slight reduction in winter precipitation (less than 1 % on average), a pronounced increase in summer precipitation (approximately 6.2 %), a moderate rise in spring (3.3 %), and a minor decrease in autumn (around 1.6 %).

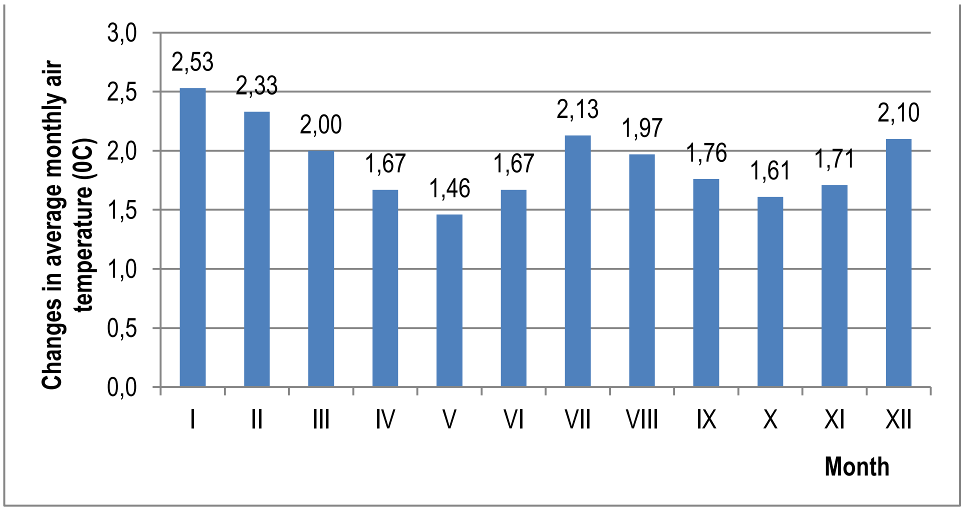


**Figure 9** – Forecast of changes in average monthly air temperature ($^0$C) within the Pripyat basin up to 2035. (mean value for 2021 – 2050)

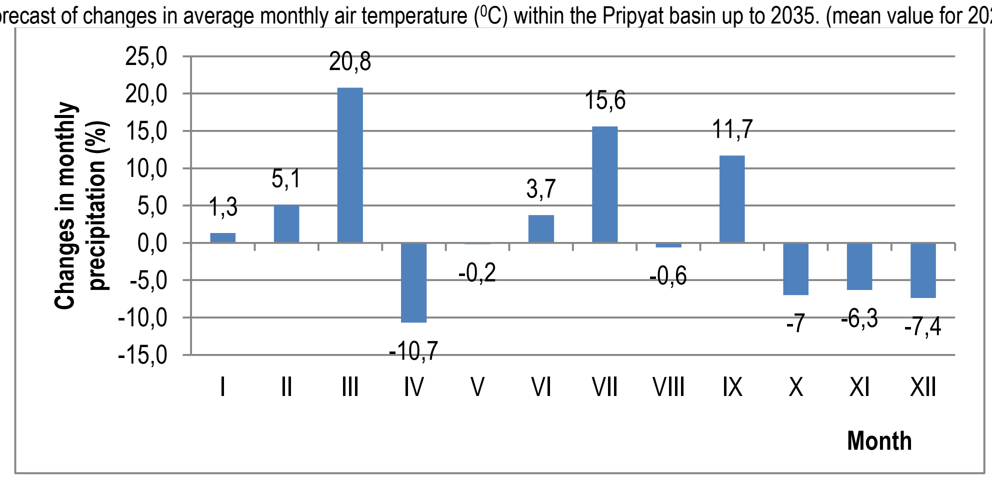


**Figure 10** – Forecast of changes in average monthly precipitation (%) within the Pripyat basin up to 2035 (mean value for 2021–2050)

*Runoff Change Projections*

Applying the hydrological and climatic calculation methodology outlined previously, projections of river runoff changes in the Pripyat basin have been developed for the period up to 2035. These projections integrate observed climate and river discharge data from 1961 to 2015, alongside refined climate forecasts for the basin based on a multimodel ensemble comprising four scenarios recommended by the Intergovernmental Panel on Climate Change (IPCC), incorporating regional climate variability.

A synthesis of the projected runoff changes for rivers within the Pripyat basin through 2035 is presented in Table 16 and illustrated in the cartographic schemes of Appendix G [13].

Key findings from the runoff projections for the Pripyat basin rivers by 2035 include:

A decline in mean annual runoff;

A slight reduction in winter runoff across most rivers;

A likely decrease in spring runoff, with some exceptions;

A substantial and the most pronounced reduction in runoff during summer compared to other seasons;

A decrease in runoff during autumn, particularly in early autumn (up to mid-October).

Table 16 summarizes the anticipated changes in river runoff for the Pripyat basin, based on a combination of the A1B and B1 emission scenarios, further refined using a multimodel ensemble of four CMIP5 scenarios as outlined in the IPCC's Fifth Assessment Report (2013) [54].

**Table 16** – Projected changes in surface runoff by 2035 for rivers in the Pripyat basin, expressed as a percentage of current condition, %

| River – Gauge station | Winter | Spring | Summer | Autumn | Average annual |
|---|---|---|---|---|---|
| Pripyat – Chernichi (Turov) | 4.9 | 5.5 | –19.2 | 0.6 | –2.1 |
| Pripyat – Mozyr | 0.2 | 1.6 | –20.6 | –2.4 | –5.3 |
| Yaselda – Beryoza | –0.3 | –27.0 | –41.7 | –23.3 | –23.1 |
| Yaselda – Senin | –3.9 | –10.6 | –37.7 | –11.8 | –16.0 |
| Tsna – Diatlovichi | –3.7 | –8.9 | –26.9 | –19.9 | –14.9 |
| Horyn – Malye Viktorovichi | –4.0 | –11.8 | –20.1 | –16.7 | –13.2 |
| Sluch – Lenin | 10.1 | 5.7 | –15.8 | 1.6 | 0.4 |
| Uborts – Krasnoberezhie | –13.4 | –5.6 | –25.2 | –38.8 | –20.8 |
| Ptich – Luchitsy | 10.3 | –0.2 | –24.0 | 16.7 | 0.70 |
| Shats – Shatsk | –0.2 | –9.2 | –10.7 | –4.4 | –6.1 |
| Oressa – Andreevka | –14.7 | –10.7 | –28.4 | 5.4 | –12.10 |
| ***Average in catchment:*** | ***–1.3*** | ***–6.5*** | ***–24.6*** | ***–8.5*** | ***–10.2*** |

**Conclusion**

The assessment of changes in river runoff within the Pripyat Basin, as well as across Belarus as a whole, over the period from 1961 to 2015 indicates that, on average, these changes have been modest. Nevertheless, climate change has contributed to increased spatial and seasonal variability in runoff patterns, as well as differences related to catchment area size. Specifically, rivers in the Pripyat Basin have experienced runoff reductions in nearly all seasons except winter, during which runoff has increased. Notably, significant alterations have occurred in the spring period, characterized by a decline in spring flood runoff and an earlier onset of the flood season. Divergent trends in runoff changes are evident across spring, summer, and autumn, with summer showing a particularly marked decrease.

Projections extending to 2035 largely corroborate the observed trends from 1961 to 2015. Forecasts suggest a pronounced differentiation in runoff volumes between small and medium-sized rivers. Although average annual runoff may change only slightly, there is a high likelihood of increased seasonal and monthly variability, with summer months expected to experience especially substantial declines across all rivers in the Pripyat Basin. Moreover, the magnitude of projected runoff changes in the Pripyat Basin is anticipated to exceed those for rivers located in northern Belarus.

It is important to emphasize that these runoff projections under changing climatic conditions should be interpreted probabilistically, reflecting inherent uncertainties arising from several sources, including:

– Limitations in detecting trends of meteorological and hydrological variables, accounting for their statistical significance.

– Ambiguities and uncertainties inherent in climate change scenarios.

– Uncertainties in hydrological model outputs due to model imperfections, calibration challenges, and data limitations.

– Unpredictability of anthropogenic influences on water resources under evolving climate conditions.

The value of runoff assessments and forecasts lies in their critical role for informing water management and protection strategies aimed at enhancing governance of the Pripyat Basin.

Among the most significant adverse impacts of climate change on river runoff is the potential increase in the frequency and intensity of extreme hydrometeorological events. These include heavy precipitation, droughts, late frosts, and floods driven by snowmelt and rainfall, especially when wet snow and rain coincide, potentially prolonging flood durations.

Enhanced intra-annual runoff variability and elevated flood risks – due to abrupt winter thaws, earlier spring floods, and intensified rain-induced flood events – may substantially increase the occurrence of extreme hydrological phenomena.

The issue of low-flow periods is particularly pertinent for rivers in the Pripyat Basin. Although current and near-future conditions do not indicate an imminent water resource deficit, the probability of extended low-flow episodes is rising. Such periods may lead to ecological degradation and diminished recreational value of surface water bodies and adjacent lands, altered groundwater regimes, and soil depletion in floodplain areas.

Furthermore, increased frequency and duration of droughts elevate the risk of significant runoff reductions in small rivers, resulting in lowered water levels, deteriorated water quality, and diminished recreational potential.

Consequently, the development and implementation of adaptive measures aimed at optimizing water resource management in response to climate change represent an urgent priority.

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# STUDY OF SURFACE PROPERTIES OF MAGNETIC SORBENTS

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**Abstract**

Ensuring environmental safety and creation of favorable environment is one of the directions of the National Strategy of Sustainable Social and Economic Development of the Republic of Belarus for the period up to 2030. One of the methods of rehabilitation of polluted and other ecologically destabilized territories is the use of sorbents. Magnetic sorbents, which combine high sorption and magnetic properties, have been recently considered as promising sorbents. The latter allow controlling the movement of the sorbent in the treated medium.

The paper presents the results of the study of surface properties of sorption materials (magnetic sorbents) obtained from iron-containing industrial wastes, composite magnetic sorbents obtained on the basis of activated carbon particles and magnetic sorbents, and initial activated carbon particles. The sizes of the obtained particles and elemental composition were determined by scanning electron microscopy. The integral acidity of the surface of the obtained samples of sorbents and initial particles of activated carbon was evaluated by pH-metry. Acid-base properties of the surface of the obtained samples were investigated by spectrophotometric method using Gammet indicators. Identification of surface centers of the investigated composites was carried out by comparing the values of pKa constants corresponding to the peaks with the known ionization constants of functional groups. The amount of detected functional groups was determined by Boehm titration. It was found that CMC-105 has a higher adsorption activity to a wide range of organic compounds than the initial particles MS-105 and AC, which indicates a synergetic enhancement of the sorption properties of the obtained CMC. Based on the results obtained, the mechanism of sorption of organic compounds by the studied sorbents is given.

**Keywords:** iron-containing waste, raw materials, processing, method, recycling.

## ИЗУЧЕНИЕ СВОЙСТВ ПОВЕРХНОСТИ МАГНИТНЫХ СОРБЕНТОВ

**Е. Н. Казимирская**

**Реферат**

Обеспечение экологической безопасности и создание благоприятной окружающей среды является одним из направлений Национальной стратегии устойчивого социально- экономического развития Республики Беларусь на период до 2030 года. Одним из методов обеспечения реабилитации загрязненных и иных экологически дестабилизированных территорий является применение сорбентов. В качестве перспективных сорбентов в последнее время рассматривают магнитные сорбенты, объединяющие в себе высокие сорбционные и магнитные свойства. Последние позволяют контролировать перемещение сорбента в обрабатываемой среде.

В работе представлены результаты исследования свойств поверхности сорбционных материалов (магнитных сорбентов), полученных из железосодержащих отходов производства, композиционных магнитных сорбентов, полученных на основе частиц активированного угля и магнитных сорбентов, и исходных частиц активированного угля. Методом сканирующей электронной микроскопии определены размеры полученных частиц, а также элементный состав. Методом pH-метрии проведена оценка интегральной кислотности поверхности полученных образцов сорбентов, а также исходных частиц активированного угля. Исследованы кислотно-основные свойства поверхности полученных образцов спектрофотометрическим методом с помощью индикаторов Гаммета. Проведена идентификация поверхностных центров исследуемых материалов путем сопоставления значений констант pKa, соответствующих пикам, с известными константами ионизации функциональных групп. Титрованием по методу Боэма определено количество обнаруженных функциональных групп. Установлено, что сорбент КМС-105 обладает более высокой адсорбционной активностью к широкому кругу органических соединений, в сравнении с материалами из которых данный сорбент был получен, что свидетельствует о синергетическом усилении сорбционных свойств полученного КМС-105. На основании полученных результатов приведен механизм сорбции органических соединений исследуемыми сорбентами, а также сделан вывод о типе загрязняющих веществ, адсорбция которых полученными материалами будет наиболее эффективной и целесообразной.

**Ключевые слова:** железосодержащий отход, сырье, переработка, метод, повторное использование.

### Introduction

The development of new methods for processing industrial waste is a pressing and important task facing modern researchers. Of particular interest are finely dispersed iron-containing wastes characterized by a multicomponent composition. Currently, there are no registered uses for such wastes [1]. One method of processing such wastes is to extract iron (II, III) salts from them and then obtain the target product [2–6]. In this work, magnetic particles were obtained from the isolated iron (II, III) salts, which were considered as sorbents and magnetic cores for the production of composite magnetic sorbents (CMS) based on them [7].

When selecting a sorbent for use in certain technologies for cleaning contaminated environments, the characteristics of the sorbent surface play an important role. It is heterogeneous and consists of a set of Lewis and Brønsted adsorption centers that are quite strongly bound to the solid. On the surface of any sorbent, there are a number of active centers with different dissociation constants ($K_a$). One of the primary tasks in studying the properties of the sorbent surface is the experimental study and determination of the type and number of these active centers. A complete description of the surface properties of solids involves not only determining the total acidity, but also quantitatively assessing the content of active centers and differentiating them by strength and type.

The aim of this work is to study the surface properties of sorbents obtained from finely dispersed iron-containing waste (FDIW) by chemical co-precipitation of iron (II, III) hydroxides.

### Research methods and baseline data

One of the most common methods for obtaining magnetic sorbents is the Massart co-precipitation method [8]. This method was modified for the synthesis of magnetic sorbents (MS) and composite magnetic sorbents (CMS) from FDIW. Scale was used as FDIW. This waste is a mixture of mainly iron (II, III) oxides formed by the direct action of oxygen when metals are heated in air.

The essence of the modified Massart method for obtaining magnetic sorbents from scale was as follows: iron ions were pre-leached from the scale with a sulfuric acid solution. A hot KOH solution was added to the resulting solution to a pH of 8–10. The resulting suspension was allowed to settle for 30 minutes, after which it was filtered. The retained sediment was washed with distilled water to a pH 7. The sediment was then dried at 105 °C to a constant weight. CMS was obtained by co-precipitation of iron (II, III) hydroxides on the surface of activated carbon (AC). The resulting particles were then washed and dried at 105 °C. The resulting sorbent samples were designated MS-105 and CMS-105.

The surface structure, particle size, and elemental composition of the obtained MS-105 and CMS-105 samples were studied using scanning electron microscopy (SEM) on a JEOL JSM-5610 LV microscope.

The acid-base properties of the surface of the obtained samples were studied using the pH measurement method. The essence of the method was that electrodes were immersed in 30 cm$^3$ of double-distilled water, and after the pH values stabilized, 0.3 g of the sample was added. Then, the change in pH values over time was recorded, and pH = *f* (τ) curves were plotted. Glass and silver-chloride electrodes were used. Measurements were taken at room temperature (20.9 °C).

The distribution of surface centers according to acid-base properties was studied by spectrometric method using Hammett indicators (16 indicators with dissociation constants (pKa) ranging from –0.29 to +12.9) and determined according to the method described in [9–11].

For the MS-105 sorbent, indicator solutions with a concentration of $10^{-4}$ mol/dm$^3$ were prepared, and for CMS-105 and AC, $10^{-3}$ mol/dm$^3$. Next, a certain volume of indicator solution ($V_{ind}$) was added to graduated test tubes and brought to 5 cm$^3$ with distilled water. After 30 min, the optical density of the resulting solution ($D_0$) was measured.

Next, 0.1 g of the sorbent sample was added to the resulting indicator solutions, mixed, and left for 120 min, after which the solution was separated from the sample (using a magnet for MS-105 and CMS-105, and decantation for AC) and its optical density ($D_1$).

A blank experiment was conducted in parallel. For this purpose, 0.1 g of sorbent was placed in 5 cm$^3$ of distilled water, the suspension was stirred, after 120 min the decantate was brought to 5 cm$^3$ and the optical density of the new solution ($D_2$) was measured.

The concentration of active centers (q, mmol/g) corresponding to specific pKa values, equivalent to the amount of indicator adsorbed on the sample surface, was calculated using the following equation

$$q = \frac{C_{ind} \bullet V_{ind}}{D_0} \bullet \left( \frac{D_0 - D_1}{m_1} \pm \frac{D_0 - D_2}{m_2} \right), \qquad (1)$$

where $C_{ind}$ is the concentration of the indicator in the solution (mmol/dm$^3$), $V_{ind}$ is the volume of the indicator taken for the study (dm$^3$), $m_1$ and $m_2$ are the masses of the test substance in the first and second samples (g), $D_0$ is the optical density of the initial indicator solution, $D_1$ and $D_2$ are the optical densities of the indicator solution after treatment with the sorbent sample and in a blank experiment.

The distribution curves of adsorption centers by acid strength on the surface of the samples were plotted in the coordinates q(pKa) = *f* (pKa).

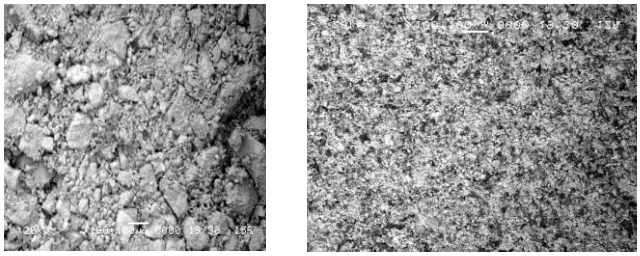
To characterize the acid properties of the obtained sorbents, the surface acidity function was used, which was calculated using the equation

$$H_0 = \frac{\sum q(pK_a) \bullet pK_a}{\sum q(pK_a)}. \qquad (2)$$

The number of functional groups was determined by titration using the Boehm method [12–13]. We placed 0.1 g of the sample into 20 cm³ conical flasks. We added 10 cm³ of 0.011 M of the corresponding solution to the samples: sodium bicarbonate solution to determine carboxyl groups; sodium carbonate solution to determine the sum of carboxyl and lactone groups; hydrochloric acid solution – to determine basic groups. The mixture was shaken and left for 24 hours to reach equilibrium at room temperature. After filtration, three 3 cm3 samples were taken from the equilibrium solutions, transferred to 20 cm$^3$ conical flasks, and then titrated with hydrochloric acid and sodium hydroxide solutions with methyl orange and phenolphthalein indicators, respectively.

**Results and discussion**

The particle sizes of the samples obtained were determined using SEM; the data are presented as micrographs of the particles (Figure 1), from which their shape and size can be determined based on the resolution of the photographs.



a b

**Figure 1** – Micrographs of samples MS-105 (a) and CMS-105 (b)

The size of the particles obtained ranges from 20 to 200 µm for MS-105 and from 2 to 15 µm for CMS-105.

The elemental composition of the materials obtained was determined. The results are presented in Table 1.

As can be seen from the table, the iron content in the obtained magnetic sorbents is higher than in CMS. The obtained samples also contain Al and Cr impurities, which, according to [14], may be present in scale. The S and K content is explained by the residual $K_2SO_4$ content (part of the stock solution) on the particle surface. The absence of carbon in the composition of CMS-105 is explained by the specifics of the sample analysis using the SEM method.

To characterize the surface of the obtained samples and establish the belonging of surface centers to the Brønsted or Lewis type, the integral acidity of their surface was evaluated using pH-metry.

Figure 2 shows the curves of changes in the pH values of aqueous suspensions of sorbent samples over time.

**Table 1** – Elemental composition of the obtained MS-105 and CMS-105 samples

| Sample | Element content, wt. % | | | | | | |
|---|---|---|---|---|---|---|---|
| | Al | Si | S | K | Cr | Fe | O |
| MS-105 | 0,36 | 0,71 | 0,45 | 0,96 | 0,86 | 73,30 | 23,36 |
| CMS-105 | 1,16 | 2,31 | 0,26 | 1,68 | 0,75 | 69,10 | 24,74 |

As can be seen in Figure 2, when sample MS-105 (No. 1) interacts with deionized water, a smooth increase in the basicity of the medium is observed, which indicates the presence of already hydroxylated Brønsted centers.

A sharp change in pH to the basic range during the first 40 seconds after immersion of the CMS-105 sample (No. 2) in deionized water indicates the presence of rapidly hydrated Lewis aprotonic centers, which, when interacting with water, transform into Brønsted centers.

When sample AC (No. 3) interacts with deionized water, an increase in the acidity of the medium is observed during the first 20 seconds, which may indicate the presence of Lewis acid centers on the sorbent surface. A further increase in pH indicates that $OH^-$ groups are associated with the sorbent surface, which exhibit weak acidic properties and donate $H^+$ protons. However, the acidity of such centers is weak, and with further adsorption of water molecules, an increase in pH values is observed, which indicates the weakly basic properties of the surface [15].

To determine the number of adsorption centers, adsorption center distribution curves (ACDC) were constructed on the surface of the sorbents (Figures 3, 4).



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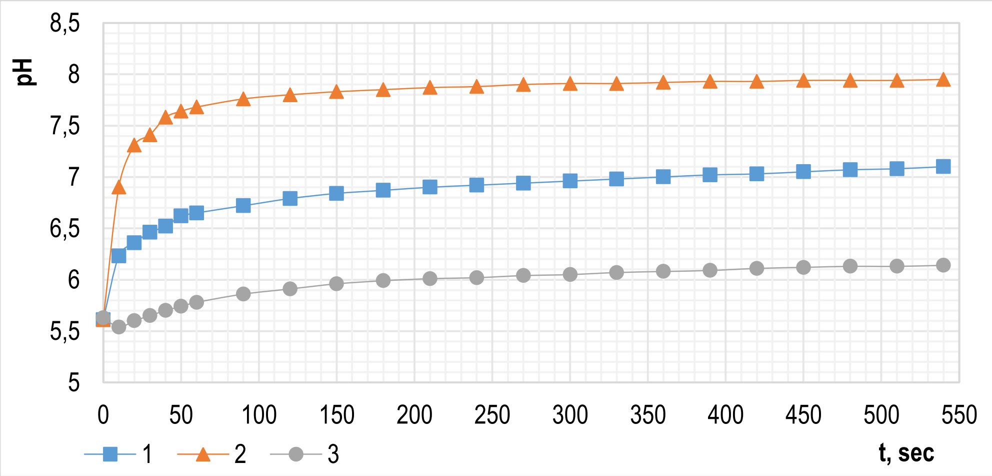


1 – aqueous suspension of sorbent MS-105; 2 – aqueous suspension of sorbent CMS-105; 3 – aqueous suspension of sorbent AC

**Figure 2** – Curves showing changes in the pH values of aqueous suspensions of sorbent samples over time

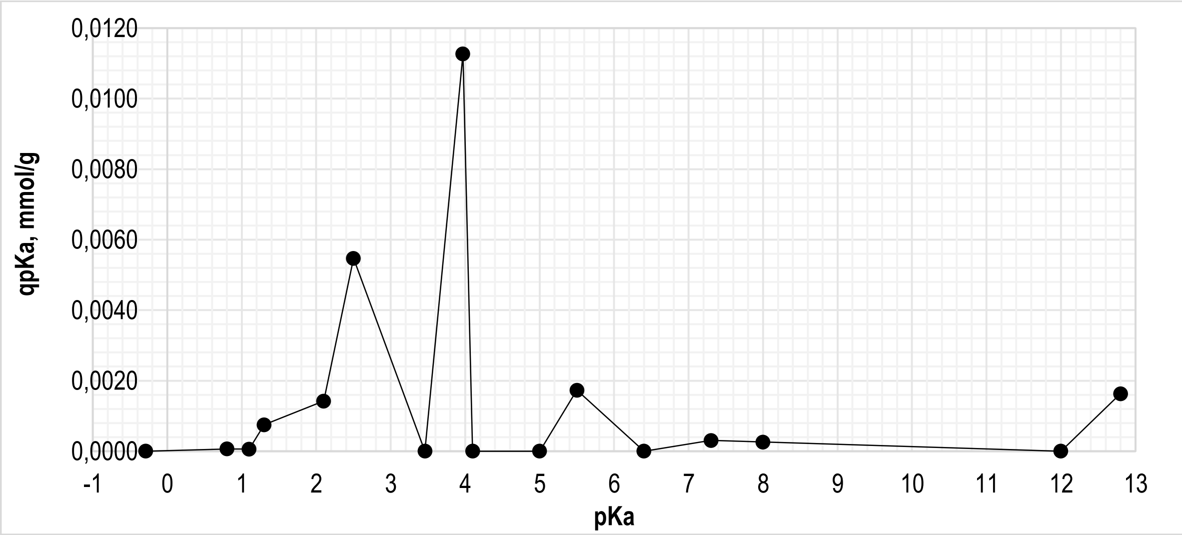


**Figure 3** – Distribution of adsorption centers on the surface of MS-105

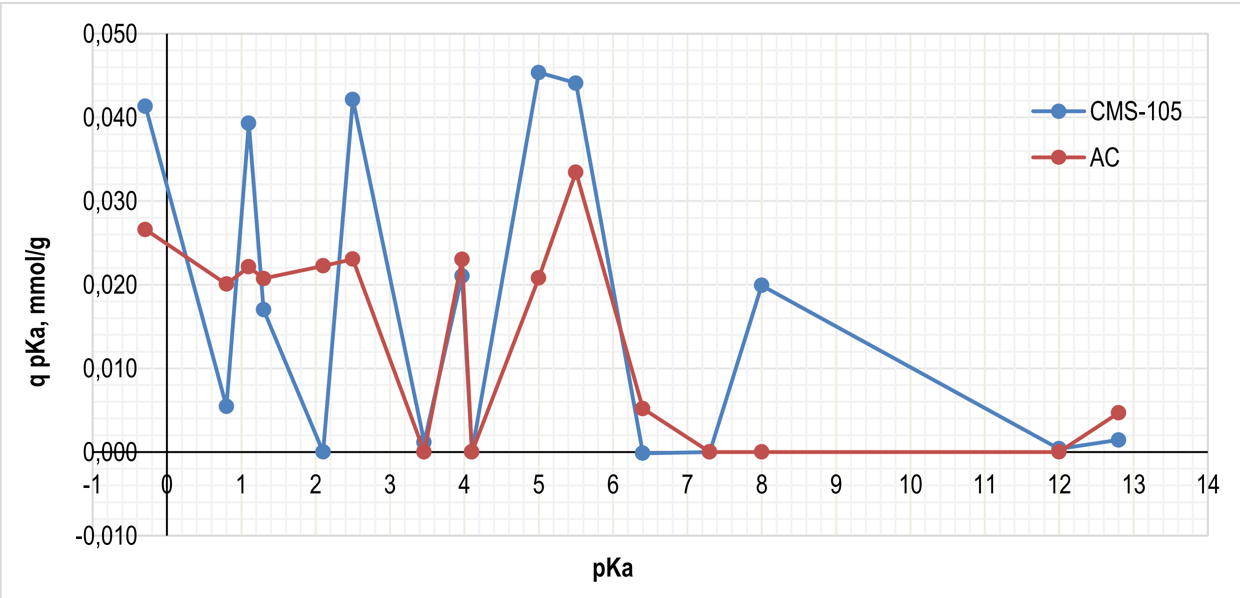


**Figure 4** – Distribution of adsorption centers on the surface of CMS-105 and AC

The distribution of active centers across a wide energy range of the controlled parameter (pKa) allows us to determine the presence or absence of certain groups of adsorption centers.

Analysis of the obtained ACDC curves shows that in the presence of water, the surface of MS-105 is dominated by Brønsted acid centers (pKa = 1.2 – 5.5), which are hydroxyl groups of the acid type, and neutral Brønsted centers (pKa = 7.3).

On the surface of KMS-105 and AC in the presence of water, Lewis basic centers (pKa = –0.29) and Brønsted acidic centers (pKa = 1.1 – 5.5) predominate, which indicates the presence of acidic centers on the surface of the studied samples in the presence of water, which tend to donate a free hydrogen proton. It is also worth noting that the number of adsorption centers detected on the surface of KMS-105 exceeds the number of these centers on the surface of MS-105 and AC. However, the surface of AC is characterized by a large number of types of active centers.

Having determined the acidity function $H_0$ for MS-105, CMS-105, and AC, which amounted to 1.92, 1.91, and 1.67, respectively, it was concluded that the surface of the obtained sorbents has weak acidic properties, although they are more pronounced in AC.

The nature of the active centers on the surface of the obtained sorbents was determined by comparing the pKa values corresponding to the peaks shown in Figures 3 and 4 with the known ionization constants of the active centers. The data obtained indicate that the surface of the obtained sorbents mainly contains various acidic centers (Table 2).

The content of functional groups in the sample under study is shown in Table 3, the data in which indicate the presence of different types of acid Brønsted centers on the surface of the sorbent. The pKa range of 3.6–4.9 in the spectrum corresponds to easily dissociating carboxyl groups. The presence of bands in the pKa 5.0–6.4 region is associated with the presence of weaker carboxyl groups in the sorbent structure that do not have acceptor substituents in their immediate vicinity. The chemical environment of these Brønsted centers is probably represented by variously substituted aromatic rings, carbohydrate, and aliphatic fragments.

In a study of the surface active centers of iron(III) oxide, the authors [19] also found predominantly weak acid Brønsted centers.

The data in Table 3 show that the surface of the samples under study is characterized by the presence of a larger number of basic functional groups. Based on this, there is a need for a more detailed study of the basic Lewis-type centers.

It is also worth noting that CMS-105, obtained from materials of different nature, is characterized by a pronounced synergistic effect of the composite material.

**Table 2** – Types of active centers on the surface of MS-105, CMS-105, and AC sorbents

| Sorbent | pKa | Functional groups |
|---|---|---|
| MS-105 | 1,2, 2,1, 2,5 | Strong Brønsted acid sites (hydroxyl groups) [16] |
| | 4,0 5,5 | Weak Brønsted acid sites [18] |
| | 7,3 | Neutral centers [17] |
| | 12,8 | Weak Brønsted bases [20] |
| CMS-105 | –0,29–0 | Lewis's weak foundation [17] |
| | 0,8-3,97 | Strong Brønsted acid sites (hydroxyl groups) [16] |
| | 5 | Weak carboxyl groups [18] |
| | 8 | Lactone groups [18] |
| | 12,8 | Weak silanol groups [18] |
| AC | –0,29–0 | Lewis's weak foundation [17] |
| | 0–2,5, 3,97 | Strong Brønsted acid sites (hydroxyl groups) [16] |
| | 5-5,5 | Weak Brønsted acid sites [18] |
| | 12,8 | Weak Brønsted bases [18] |

**Table 3** – Titration results using the Boehm method

| Sorbent | Number of functional groups, mmol/g | | |
|---|---|---|---|
| | Carboxylic | Lactones | Basic |
| MS-105 | 0,00 | 0,00 | 1,017 |
| CMS-105 | 0,05 | 0,07 | 1,667 |
| AC | 0,08 | 0,10 | 0,683 |

Based on the results of this work, as well as on the basis of literature data [20], the surface centers of the obtained materials were identified (Table 4).

According to [20], based on the research results obtained, it is more expedient to use sorption materials MS-105 and KMS-105 for collecting basic compounds, petroleum products, and heavy metal ions from the surface of contaminated environments.

Thus, the sorption properties of the obtained materials in relation to these pollutants were studied (Table 5).

**Table 4** – Active centers located on the surface of the studied sorbents

| Sorbent | MS-105 | CMS-105 | AC |
|---|---|---|---|
| Functional groups (FG) | $FeO\text{-}H^+$, $Fe\text{-}O\text{-}H^{\delta 0}$, $Si\text{-}OH^{\delta-}$ | $AlO^-$, $FeO\text{-}H^+$, R—CH—$(CH_2)_n$—C=O, $Fe\text{-}O\text{-}H^{\delta 0}$, $Si\text{-}OH^{\delta-}$ | Ar-OH, R—CH—$(CH_2)_n$—C=O, -COOH, $Si\text{-}OH^{\delta-}$ |
| pKa | 0–7, 7, 7–14 | –1,7–0, 0–7, 7–14 | –1,7–0, 0–7, 7–14 |
| Acid-base centers | Strong acid, weak acid, weak base Brønsted centers | Lewis bases, strong acids, weak acids, weak bases, Brønsted centers | Lewis bases, strong acids, weak acids, weak bases, Brønsted centers |

**Table 5** – Sorption properties of the sorbent samples studied

| Sorbent | Sorption capacity value relative (mg/g) to | | | |
|---|---|---|---|---|
| | CSA | $Fe^{3+}$ | $Cu^{2+}$ | petroleum products |
| MS-105 | 167,02 | 0,70 | 30,60 | 1110,00 |
| CMS-105 | 185,00 | 1,76 | 46,70 | 1450,00 |
| AC | 81,10 | 2,09 | 21,80 | 2430,00 |

Studies have shown that magnetic sorbents (MS-105) and composite magnetic sorbents (CMS-105) obtained from finely dispersed iron-containing waste have pronounced sorption properties.

Analysis of the data presented in Table 5 confirms the direct dependence of the sorption capacity of materials on their acid-base properties. The KMS-105 sample, which has the largest number of basic and acidic centers, demonstrated the highest efficiency in relation to cationic surfactants (CSA), $Fe^{3+}$ and $Cu^{2+}$ ions, and petroleum products, exceeding the performance of MS-105 and AC (activated carbon) in most parameters.

AU showed the highest result in relation to petroleum products (2430.00 mg/g), while KMS-105 demonstrated a sorption capacity of 1450.00 mg/g. Despite this, KMS-105 proved to be more effective for the sorption of heavy metal ions ($Fe^{3+}$ and $Cu^{2+}$) and surfactants. These results confirm that the creation of a composite material based on magnetic particles and AC leads to a synergistic effect, which allows obtaining a material with improved sorption characteristics for a wide range of pollutants.

Thus, the proposed method for processing iron-containing waste to obtain composite magnetic sorbents is promising for the creation of effective materials capable of cleaning contaminated environments.

**Conclusion**

The studies conducted allowed us to draw the following conclusions:

1. The diversity of Brønsted centers on the surface of the obtained KMS-105, and their greater number, suggests its high adsorption activity to a wide range of organic compounds than that of the initial MS-105 and AC particles.

2. The studies indicate the possibility of applying iron-based hydroxide-oxide systems to the surface of activated carbon in the process of co-precipitation of iron (II, III) hydroxides, with the subsequent use of the obtained materials as sorbents. In this case, the co-precipitated hydroxides to some extent change the distribution of the acid-base activity of the activated carbon particle surface and, consequently, their sorption activity with respect to various pollutants.

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## ECONOMICS

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# KNOWLEDGE ECONOMY: FEATURES AND INDICATORS ANALYSIS

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**Abstract**

The article reveals the essence of the knowledge economy and identifies problematic aspects in its theoretical justification. The author proposes his own definition of the knowledge economy based on the analysis of different approaches to defining the concept. The article highlights the role of innovation, science, and education in shaping the knowledge economy. It also points out the complexity of assessing the level of development of the knowledge economy due to the lack of a comprehensive approach to quantifying accumulated and created knowledge. The article emphasizes the importance of growing inequality caused by the lack of access to knowledge through quality education and digital technologies in certain regions. The labor market in the context of the knowledge economy is characterized by unstable labor relations. The author proposes an assessment based on key indicators (aspects), such as the Global Knowledge Index, the Global Innovation Index, the Human Development Index, the scientific content of GDP, the number of applications for patent cooperation agreements, and the cluster approach to economic development, which allow for the assessment and determination of the level of development of the knowledge economy in different countries. Special attention is paid to analyzing China's experience in building a knowledge-based economy. The author covers government policies to support high-tech industries, the combination of planning and market incentives, and the development of large-scale national programs. It emphasizes China's leadership in ICT development, increased investment in science and education, the importance of human capital, and the creation of innovative clusters and venture capital ecosystems. The author presents a comparative analysis based on key indicators, which helps to identify key differences and determine areas for development.

**Keywords:** knowledge economy, innovation, indices, science intensity, patents, clusters.

## ЭКОНОМИКА ЗНАНИЙ: ОСОБЕННОСТИ И АНАЛИЗ ПОКАЗАТЕЛЕЙ

**А. А. Бажина**

**Реферат**

В статье раскрыта сущность экономики знаний и определены проблемные аспекты в ее теоретическом обосновании. На основе проведенного анализа разных подходов к определению понятия, автор предлагает собственное определение. Отмечается роль инноваций, науки и образования в формировании экономики знаний. Также указывается сложность оценки уровня развития экономики знаний по причине отсутствия комплексного подхода в количественной оценке накопленных и создаваемых знаний. Отмечается важность роста неравенства по причине отсутствия доступа к знаниям посредством качественного образования и цифровых технологий для отдельных регионов. Рынок труда в контексте формирования экономики знаний характеризуется нестабильностью трудовых отношений. Автором предложена оценка на основании ключевых показателей (аспектов), таких как глобальный индекс знаний, глобальный инновационный индекс, индекс человеческого развития, наукоемкость ВВП, число заявок на договора о патентной кооперации, кластерный подход формирования экономики, которые позволяют оценить и определить степень развитости экономики знаний в странах мира. Особое внимание уделяется при анализе опыту Китая в построении экономики знаний. Интерес представляет государственная политика поддержки высокотехнологичных отраслей, сочетание планирования и рыночных механизмов стимулирования и развитие масштабных национальных программ, отмечается лидерство Китая в развитии ИКТ, рост инвестиций в науку и образование, первостепенная роль и развитие человеческого капитала, создание инновационных кластеров, создание венчурных экосистем и др. Автором представляется сравнительный анализ по показателям предложенным в качестве основных, который позволил выявить ключевые диспропорции, которые и позволяют выявить проблематику и определить направления развития.

**Ключевые слова:** экономика знаний, инновации, индексы, наукоемкость, патенты, кластеры.

**Introduction**

The theoretical foundations of the role of innovation in the formation of the knowledge economy are laid in the works of D. Bell, J. Galbraith, P. Drucker, E. Toffler, J. Quinn, R. Rich, F. Machlup, J. Schumpeter, S. Kuznets, F. von Hayek, G. Becker, P. Krugman, K. J. Arrow, D. North and others.

Scientific publications by Russian and Belarusian researchers, in particular A. V. Bondar, K. I. Ryabova, K. S. Okrut, K. I. Zhukov, Z. O. Adamanova, E. A. Borodavko, N. O. Vasetskaya, S. V. Chirikov, V. Z. Yampolsky, N. R. Kelchevskaya, I. M. Chernenko and others also play an important role.

In the current conditions of socio-economic development, knowledge, information, human and intellectual capital have become key factors, which determines the relevance of the study and its theoretical significance. This has been facilitated by globalization and the challenges it has brought, as well as the processes of digitalization, scientific and technological progress, and the transformation and complexity of the production and consumption processes.

**The theoretical foundations of the knowledge economy and the system of indicators for assessing development**

The concept of the knowledge economy was first introduced by the Austrian-American economist Fritz Machlup in 1962 in his work "The Production and Distribution of Knowledge in the United States" [1]. The researcher defined the knowledge economy, provided a classification of knowledge and methods for its production, highlighted the role of invention and patent protection, the role of education, and more.

In the 1970s, P. Drucker in his book "The Age of the Discountity: Guidelines to Our Changing Society", analyzed the role of knowledge as a resource. He introduced the concepts of the knowledge economy and the knowledge-based society, and examined the impact of knowledge on enterprise productivity and, consequently, product competitiveness. He also noted the role of innovation and entrepreneurship [2]. G. Kleiner defines the knowledge economy "as economic state in which knowledge becomes a full-fledged commodity; any commodity embodies unique knowledge; and knowledge becomes one of the main factors of production" [3].


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Alvin Toffler highlights knowledge as the most important economic resource, arguing that its production "becomes the driving force of a country's and society's development" and the engine of progress. He emphasizes that knowledge takes on a commodity form, which can be sold and profitably exploited [4].

V. V. Glukhov notes that the knowledge economy can be viewed as a system that integrates theoretical concepts, a set of practical achievements, and a set of methods for creating conditions conducive to research activities [5].

V. L. Makarov points out that in a knowledge economy, "knowledge, skills, and abilities of workers play a crucial role in the production and distribution process". This highlights the importance of skilled labor [6].

G. B. Kleiner emphasizes that the knowledge economy is characterized by the transformation of knowledge into a full-fledged commodity and the development of a knowledge market alongside traditional markets for natural resources, labor, and capital [7].

A. V. Bondar defines the knowledge economy as an economy in which knowledge acquires the status of the main economic resource, which is present in every type of economic activity, and its accumulation and effective use ensure high rates of economic growth, development of economic entities, and the entire society [8, p. 29].

The World Bank experts have proposed the following definition: "A knowledge-based economy is an economy in which knowledge is the main driver of economic growth" [9].

In our opinion, a knowledge-based economy is an economy in which knowledge is the main factor of production, embodied in intellectual capital and serving as a source of innovation, leading to the dominance of knowledge-intensive services and high-tech manufacturing.

Thus, the concept of "knowledge economy" is currently being studied and transformed under the influence of modern trends, and is being researched within the framework of various scientific schools and methodological traditions. The diversity of theoretical approaches is due to the various aspects inherent in the concept under analysis, including the role of knowledge in production, its institutionalization, the impact on global processes and the transformation of social and labor relations, as well as the changing forms of employment and the role and influence of innovation on the formation of the knowledge economy.

However, the problems that accompany the study of the knowledge economy relate to the definition and change of knowledge, and it is still unclear what exactly should be considered knowledge (applied R&D, technologies, software products, and the skills of workers, etc.) and what indicators would be appropriate for measuring it. There is no real way to quantify the accumulated knowledge and the knowledge created over certain periods of time. Additionally, the study of the knowledge economy raises fundamental questions such as the growing global inequality, where knowledge is generated in developing countries and benefits are reaped by developed countries. Social and economic inequality is also evident in the availability of quality education and digital technologies. In turn, the labor market in the knowledge economy is characterized by unstable labor relations.

Based on the generally accepted understanding of the essence of the knowledge economy, the possibility of its development is formed due to a high level of education, science and innovation. The government, which focuses on building such an economy, increases spending on scientific research, modernizes the education system, and introduces the concept of "lifelong learning." Scientists have noted an increase in the number of intellectual workers, support for high-tech and knowledge-intensive industries and the development of innovative activity of business entities. There is an active growth in the field of ICT, and a high share in the structure of the economy belongs to the service sector.

The knowledge economy is most characteristic of developed countries such as the United States, Germany, the United Kingdom, and France, as well as countries in East Asia, such as the Republic of Korea, the People's Republic of China, and Japan, where the production of knowledge-intensive and high-tech products is the primary source of economic growth [10, p. 8].

The Global Knowledge Index (GKI) is a tool for knowledge and development, and serves as a comprehensive framework for measuring the effectiveness of knowledge use worldwide. It consists of seven sub-indices: pre-university education; technical and vocational education and training; higher education; research, development, and innovation; information and communication technologies; economic development; and a supportive environment conducive to a knowledge-based climate. This indicator assesses the creation of knowledge, the quality of its dissemination, and its application.

According to the 2024 Global Knowledge Index, Sweden (index 68,3) topped the list of 141 countries in the knowledge index report. Finland (index 68) came in second place, Switzerland (67,9) came in third place, and Denmark (66,8) came in fourth place. It is worth noting that the top ten also includes the United States (66,2) and the United Kingdom (65,8). Hong Kong (China) took 29th place (60,1), the UAE took 26th place (60,9), China took 49th place (51,6). The Republic of Belarus took 50th place in this index (51,4 %), overtaking the Russian Federation (61st place) and Kazakhstan (72nd place) [11].

The Global Innovation Index provides the most comprehensive comparison of countries focused on knowledge-based economies in the technological sector. In 2024, as in 2023, Switzerland (67,5), Sweden (64,5), and the United States (62,4) remained at the top of the ranking. Switzerland is characterized by effective business policies and a high number of patent applications. Sweden also has unique approaches to business development, knowledge-intensive employment, and the number of researchers per capita. The United States is characterized by the largest amount of venture capital raised and a high level of investment in R&D. The three leaders are followed by the United Kingdom (61,0), Finland (59,4), Germany (58,1), and China (56,3). Among the post-Soviet countries, Estonia (52,3), Lithuania (40,1), Russia (29,7), and the Republic of Belarus (24,2) have the best results [12].

Comparing the Global Knowledge Index and the Global Innovation Index, we can conclude that the Republic of Belarus has high scores in the former, but low scores in the latter (unlike China and Russia, for example). This indicates that there are disparities in the level of human capital development and its effective application in science and innovation. The reasons for these disparities lie in the difficulties of transforming knowledge into innovation. If we compare the economies of Belarus and China, the problem lies primarily in the scale of the economies and the amount of investment in R&D, the formation and level of domestic demand, and the ability of the economy to be diversified. It also depends on the level of the country's innovation ecosystem (including venture capital investments, developed clusters and technology parks, and the degree of collaboration between science and business for the commercialization of knowledge), as well as its integration into global value chains. These findings are supported by the Human Development Index and the science intensity of GDP, as shown below.

According to the United Nations Development Programme's Human Development Report 2025, the countries with the highest Human Development Index (a composite measure of average achievements in the three main dimensions of human development: long and healthy life, access to knowledge, and a decent standard of living) are Iceland (0,972), Norway (0,970), Switzerland (0,970), Germany (0,595), Sweden (0,959), and Austria (0,955). The UK ranks 13th (0,946), the US ranks 17th (0,938), and China ranks 78th (0,797). For Belarus, the Global Human Development Index in 2025 was 0,824 (65th place among 193 countries) [13].

An important indicator of the development of science is the level of national R&D spending, or the science intensity of GDP, which represents the share of research and development costs in a country's GDP. It is worth noting that Israel and South Korea are the leaders in this indicator in 2024 (5,56 % and 4,93 %, respectively), in the United States (3,46 % of GDP). Among other countries developing a knowledge economy, high values of science intensity are typical for Sweden (3,42 %), Japan (3,3 %), the UK (2,91 %), China (2,43 %), France (2,22 %), the UAE (1,5 %). The Republic of Belarus is characterized by a relatively low share of R&D spending in the country's GDP (0,48 %), which is also observed in Argentina and Romania (0,52 and 0,47 %, respectively). At the same time, among the neighboring countries, only Poland (1,44 %) and Lithuania (1,11 %) reached a science intensity indicator exceeding the critical level of economic security (1 %) in 2024, surpassing Russia (0,94 %) and Latvia (0,74 %) in this indicator [14].

Investing in research and development is a key mechanism for creating competitive advantages through the creation of innovative products, processes, and services. These developments, which have the potential for patentability, not only provide technological leadership but also create a sustainable barrier to competition, limiting the ability of other market participants to replicate the innovations.

Patent activity is another indicator of innovation activity and technological development in countries. In 2023, the number of patent applications worldwide exceeded 3,55 million. China's Patent Office received approximately 1,64 million applications. The United States, Japan, the Republic of Korea, and Germany followed suit. China accounted for 46,8 % of the global patent volume [15].

In 2024, about 273,900 international applications for Patent Cooperation Treaties (PCTs) were filed, which is 0,5 % more than in 2023. The top 10 countries accounted for 88,1 % of all applications in 2024. Candidates from China and the United States filed applications primarily in the field of computer technology. Japan filed applications primarily for electrical equipment, while the Republic of Korea filed applications for digital communications [16]. There are no data on the Republic of Belarus in the report on Patent Cooperation Treaties (PCT).

One of the promising areas of innovative development in foreign regions is the cluster approach. The economy formed within the framework of the cluster approach is a new model of innovative socio-economic development [17, p. 253]. A regional innovation cluster is a set of economic entities of various forms of ownership located in the region that create and disseminate new knowledge, products, and technologies, as well as the organizational and legal conditions for their business operations, which are formed through the implementation of regional science and innovation policies. Clusters involve the synergy of the entrepreneurial sector, education, and research centers to share knowledge, reduce transaction costs, develop joint innovation projects, and access human resources. The experience of leading countries in innovative development (the United States, Japan, China, Germany, etc.) suggests that cluster mechanisms can provide the necessary foundation for transitioning to an innovative economy through the synergistic effects of their operation.

Innovative clusters in the field of education: Stanford University, Cambridge University, Harvard, Oxford, etc. They produce more scientific publications and attract venture capital investments.

Innovative clusters in the economy: Huawei (Digital Communications) China, Mitsubishi Electric (Computer Technology) Japan, Google (Computer Technology) USA, BOE Technology (Digital Communications) China, Samsung Electronics (Digital Communications) South Korea, Panasonic Startup (Electric Machines, Appliances, and Power) Japan, Z-Park Boston Innovation Center (Medical Technology) USA [18].

Among the top 100 science and technology clusters, the Tokyo – Yokohama cluster (Japan) is leading. It is followed by the Shenzhen – Hong Kong – Guangzhou cluster (China and Hong Kong, China). Both clusters are ranked first and second.

In China, the Shenzhen – Hong Kong – Guangzhou cluster is one of the world's leading centers of scientific and technological innovation, located in the Greater Bay Area of Guangdong – Hong Kong – Macau (GBA). According to the World Intellectual Property Organization (WIPO) for 2024, this cluster ranks second in the world in terms of the concentration of scientific and technological achievements. This cluster is a prime example of the synergy between high-tech manufacturing, science, startup culture, and cross-border cooperation [18].

Shenzhen is rightfully called the "Silicon Valley" of China. This city is a hub for startups and tech giants, home to companies such as Huawei (telecommunications, AI, chips), ZTE (telecommunications), DJI (leader in drones), BYD (electric vehicles, batteries) [18].

Hong Kong is an international financial center with a focus on logistics, medicine, biotechnology, and scientific research. Guangzhou is an industrial and logistics hub that is developing in the fields of biomedicine, AI, and new materials.

In China, the knowledge economy is officially recognized as a national development strategy based on strong education. The number of Chinese students is growing in the world's top universities, and the country is establishing a national system for promoting scientific and technological innovation, which is the natural foundation of the knowledge economy [19].

The government has decided to strengthen its role in the development of the knowledge economy. China aims to encourage increased spending on research and development, promote intellectual property development, and expand the digital economy [19].

The plan includes development in priority areas of science and technology, growth of research projects, support for science-intensive business, effective regulation of the sphere of intellectual property, provision of tax benefits for companies engaged in scientific research and development, and also the stimulation of researchers to work. Presumably, the effect can be given by attracting scientists from all over the world to global innovation centers in Beijing, Shanghai, Hong Kong.

An important aspect of the policy on the development and popularization of the knowledge economy is to increase scientific literacy in society, allow for the development of various forms of employment, focus on the creative development of society, and create conditions for creative professions and non-standard teaching methods [20].

One of the most prominent initiatives is the "Made in China" strategy, which aims to modernize China's manufacturing base by automating processes, using artificial intelligence, and adopting green technologies [19].

As part of its strategy, China is using supportive financial policies. The government is committed to improving transportation, energy, and digital infrastructure. The Belt and Road Initiative is an example of this.

China is a globally competitive producer of technologically complex goods, such as telecommunications equipment, machinery, computers, solar panels, high-speed railways, ships, drones, satellites, heavy equipment, and pharmaceuticals. In all of these industries, China has gained a significant share of the global market, and it is rapidly expanding into new sectors such as robotics, AI, quantum computing, and biotechnology [19].

Taking into account China's experience and the specifics of its development within the framework of the knowledge economy, the Republic of Belarus can learn from China's best practices and identify areas for its own development, as well as key factors that have enabled China to effectively leverage its opportunities in the transition to a knowledge-based economy through the synergy of education, science, and innovation.

**Conclusion**

Thus, the government's policy towards the formation of a knowledge-based economy sets the government's objectives to improve all processes that will enhance the country's overall competitiveness. The chosen vector dictates the specific behavior regarding changes in the vector of financing and production development, allowing countries to maintain leading positions in terms of key indicators and indices that characterize their level of development. Given that education, science, and innovation are the foundation of a knowledge-based economy, leading countries are increasing their investments in these areas, improving their performance in international rankings, and confirming their chosen vector of development. The Republic of Belarus is also improving its policy on the formation of a knowledge economy, taking into account the achievements of foreign experience and its own strengths.

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# METHODOLOGY FOR FORECASTING LABOR RESOURCE REQUIREMENTS IN A CONSTRUCTION ORGANIZATION

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**Abstract**

With the construction industry in the Republic of Belarus developing rapidly, a systematic approach to human resource management is becoming increasingly important, particularly in the context of implementing large-scale infrastructure projects and introducing innovative technologies. The construction sector has a multiplier effect on the national economy, stimulating the growth of related industries and generating a stable demand for qualified personnel. Consequently, forecasting labor demand has become a critical task, ensuring that construction organizations maintain the required number of specialists with appropriate qualifications.

The article discusses the methodological foundations of forecasting the personnel needs of construction organizations, including the development and application of specialized coefficients that reflect the specifics of activities, the complexity of facilities, the internal resources of the enterprise, and the dynamics of personnel movement. An algorithm for calculation is proposed, which covers the entire cycle of personnel planning: from collecting initial data and analyzing the current staff composition to modeling the future need for specialists. Its structure includes mechanisms for accounting for the dynamics of labor resources, including turnover, age-related attrition, and staff replacements, as well as the projected volume of construction work, which allows for an accurate determination of the number and type of specialists required to complete projects within the specified timeframe.

Taking these factors into account allows not only to identify potential personnel risks, but also to form a balanced HR management strategy focused on the sustainable development of the organization. This approach enables timely response to changes in the staff composition, optimization of the recruitment and adaptation of new employees, and improving the efficiency of the existing labor potential. The use of these tools is particularly important for construction organizations operating under conditions of high project load, seasonality, and technological changes, where personnel stability directly affects the quality and timing of work.

**Keywords:** turnover rate, replacement rate, age-related attrition, construction site characteristics, types of construction work, personnel requirements, additional personnel needs.

## МЕТОДИКА ПРОГНОЗИРОВАНИЯ ПОТРЕБНОСТИ В КАДРАХ ДЛЯ СТРОИТЕЛЬНОЙ ОРГАНИЗАЦИИ

**Ю. А. Баканова**

**Реферат**

В условиях активного развития строительного комплекса Республики Беларусь возрастает значимость системного подхода к управлению трудовыми ресурсами, особенно в контексте реализации масштабных инфраструктурных проектов и внедрения инновационных технологий. Строительный комплекс оказывает мультипликативное влияние на экономику, стимулируя развитие смежных отраслей и формируя устойчивый спрос на квалифицированные кадры. В связи с этим актуальной задачей становится прогнозирование потребности в трудовых ресурсах, позволяющее обеспечить строительные организации необходимым количеством специалистов соответствующего уровня квалификации.

В статье рассматриваются методологические основы прогнозирования кадровой потребности строительных организаций, включая разработку и применение специализированных коэффициентов, отражающих специфику видов деятельности, сложности объектов, внутренние ресурсы предприятия и динамику движения персонала. Предложен алгоритм расчета, охватывающий весь цикл кадрового планирования: от сбора исходных данных и анализа текущего состава персонала до моделирования будущей потребности в специалистах. В его структуру заложены механизмы учета динамики трудовых ресурсов, включая текучесть, возрастное выбытие и кадровые замещения, а также прогнозируемые объемы строительных работ, что позволяет точно определить, сколько и каких специалистов потребуется для реализации проектов в заданные сроки.

Учет этих факторов позволяет не только выявить потенциальные кадровые риски, но и сформировать сбалансированную стратегию управления персоналом, ориентированную на устойчивое развитие организации. Такой подход обеспечивает возможность своевременного реагирования на изменения в кадровом составе, оптимизации процессов найма и адаптации новых сотрудников, а также повышения эффективности использования имеющегося трудового потенциала. Применение данных инструментов особенно важно для строительных организаций, работающих в условиях высокой проектной нагрузки, сезонности и технологических изменений, где кадровая стабильность напрямую влияет на качество и сроки выполнения работ.

**Ключевые слова:** коэффициент текучести, коэффициент замещения, возрастное выбытие, характеристика объекта строительства, виды строительных работ, потребность в кадрах, дополнительная потребность в кадрах.

### Introduction

The development of the construction industry is an essential element of sustainable economic growth, not only providing the material foundation for infrastructure, but also setting the pace for the modernization of related sectors. In the context of technological transformations and the digitalization of the economy, there is an increasing need for precise staffing planning, particularly in sectors where labor resources play a crucial role in the implementation of complex projects.

Construction organizations face challenges related to changes in employment patterns, increased requirements for staff qualifications, and the need to adapt to new management practices. In this regard, the development of effective tools for forecasting labor requirements, which take into account the specifics of the industry, the dynamics of projects, and the internal characteristics of enterprises, is particularly relevant.

### Methodology for Forecasting the Demand for Labor Resources

The construction industry traditionally occupies a key position in the national economy of the Republic of Belarus, functioning not only as a production sector but also as a strategic driver of economic growth. As A. V. Kapustkina notes, "Investment and construction activities represent a key sector of the economy that significantly contributes to infrastructure development, job creation, and the improvement of people's quality of life" [1].

Under modern conditions, the construction sector exerts a multiplicative effect on the development of related industries, including the production of building materials, transport logistics, mechanical engineering, architectural and design services, and activities associated with the operation of real estate assets. "The construction sector encompasses diverse areas – social, municipal, transport, industrial, agricultural, energy, and others – the functioning of which directly influences the capacity to improve citizens' well-being" [2].

The investment attractiveness of the construction industry remains consistently high, owing to its substantial contribution to the implementation of state infrastructure programs, housing development, and the modernization of production facilities. The adoption of innovative technologies, digital solutions, and advanced building materials enables the execution of complex tasks that meet contemporary standards of quality, energy efficiency, and environmental safety. This, in turn, "determines the industry's demand for qualified specialists equipped with skills in digital construction management, design, and the erection of buildings and structures using new technologies based on digital methods" [3].

Against the backdrop of the industry's dynamic development, the demand for qualified labor resources capable of adapting to technological change and effectively addressing professional challenges is steadily increasing. Ensuring that construction organizations are staffed with competent specialists is a priority of the government's personnel policy. As V. A. Praslov emphasizes, "The effective development of industries and production complexes is closely dependent on their human resources" [4].

Particular attention today is devoted to forecasting the economy's demand for labor resources. This issue has been addressed in the works of Doctor of Economics, Professor T. N. Leonova, Doctor of Economics, Professor O. V. Zabelina, Candidate of Sociological Sciences, Associate Professor O. A. Volovik, Doctor of Economics, Professor P. P. Lutovinov, Candidate of Economics P. G. Abdulmanapov, Doctor of Physical and Mathematical Sciences, Professor V. A. Gurtov, Doctor of Technical Sciences, Professor E. A. Pitukhin. Doctor of Economics, Professor E. A. Varshavsky. Doctor of Economics I. I. Akulova, Doctor of Technical Sciences, Academician of RAASN E. M. Chernyshov, Candidate of Economics, Associate Professor L. V. Pankova, and many others [5–13].

In order to address this issue systematically, the Republic of Belarus is developing and implementing methods for forecasting labor resource requirements, covering both the economy as a whole and the construction sector in particular. These methods are based on the analysis of current and planned projects, the assessment of labor intensity, and consideration of the demographic and professional characteristics of the workforce.

It should be emphasized that the construction industry, while sharing certain features with other sectors of the economy, possesses a number of specific characteristics. These include a high degree of project individualization, seasonal production cycles, a significant share of manual labor, and the necessity of strict compliance with construction standards and regulations.

The methodology for forecasting labor requirements in construction organizations relies on a comprehensive analysis of the workload associated with the implementation of current and future projects. It takes into account parameters such as task complexity, project scale, and the technological specifics of the methods and materials employed. As A. V. Kashepov observes, "the traditional interdisciplinary economic, demographic, and macroeconomic approach to forming a labor force balance remains effective under current conditions" [14].

The purpose of this methodology is to ensure that organizations have the required number of qualified labor resources at the right time and in the right place, thereby supporting the effective implementation of production plans and reducing risks associated with staff shortages.

When forecasting labor resource requirements for a construction organization, the following key indicators should be considered.

**1. Types of construction activities.** It is essential to determine which types of construction are being undertaken – housing, industrial, civil, infrastructure, and others. Each type has its own requirements for worker qualifications and the specifics of technological processes. For example, reports of the Ministry of Education and Science of the Russian Federation emphasize that "the calculation of the planned volume of construction and installation work should take into account the output per worker and the number of teams" [15].

In the Republic of Belarus, Resolution of the Ministry of Architecture and Construction dated June 30, 2022, No. 66 "On Approval of the Instructions on the Procedure for Determining the Type of Construction Activity and the Name of the Construction Project" [16], together with the Code on Architectural, Urban Planning, and Construction Activities, defines the following types of construction activities:

- Construction of a facility;
- Reconstruction of a facility;
- Modernization of a facility;
- Technical modernization of a facility;
- Major repair of a facility;
- Demolition of a facility;
- Repair and restoration work performed on material historical and cultural assets;
- Installation of all types of equipment;
- Preservation of an unfinished construction facility.

To forecast labor resource requirements for a construction organization, we introduce the **coefficient of personnel requirements by type of construction activity (Kca)**.

**2. Types of construction work.** Specific types of construction work are analyzed – earthworks, concrete, installation, finishing, and others. Each type requires specialists of a particular profile, which affects both the structure and the number of personnel. The construction work classifier [17], developed on the basis of SN 1.03.04-2020 – Organization of Construction Production; TKP 45-1.03-161-2009 – General Requirements for Construction Work; TKP 45-1.03-298-2014 – Procedure for Acceptance of Completed Construction and Special Works; TKP 45-1.03-307-2017 – Quality Control of Construction Work, defines the following types of construction work:

- Earthworks;
- Foundation works;
- Installation works;
- Masonry works;
- Concrete and reinforced concrete works;
- Roofing works;
- Finishing works;
- Carpentry and joinery works;
- Plumbing works;
- Electrical installation works;
- Thermal insulation works;
- Facade works;
- Landscaping;
- Low-voltage systems.

To forecast labor resource requirements for a construction organization, we introduce the **coefficient of staffing for construction work (Kcw)**.

**3. Characteristics of a Construction Project.** The characteristics of a construction project represent a set of parameters that define its structural, spatial, technological, and operational features. These parameters have a direct impact on the organization of the construction process, the choice of technological solutions, the volume of required resources, and the measures necessary to ensure occupational safety. Key characteristics include: the type of structural system, the number of floors, building density, geographical location, functional purpose of the facility, as well as engineering-geological and climatic conditions.

As emphasized by A. V. Ishchenko and co-authors, "when forming the production program of a construction organization, it is necessary to take into account the specifics of the project, including its structural features, the complexity of architectural solutions, and the conditions under which the work is performed" [18]. These parameters directly influence the labor intensity of construction processes and, consequently, the calculation of labor resource requirements.

For the quantitative assessment of the impact of project-specific features on labor costs, it is recommended to use the **coefficient of production specificity of the project (Ksp)**, which reflects the degree of complexity and uniqueness of the construction project.

**4. Characteristics of a Construction Organization.** The characteristics of a construction organization encompass a set of organizational, personnel, technical, technological, and financial-economic parameters that determine its ability to effectively implement construction projects in accordance with current legislation, technical standards, and the requirements of a specific facility.

As noted in the article "12 Indicators of Labor Resource Efficiency in Production" published on the Rus-Kvant portal [19], "the analysis of labor resource utilization in an enterprise must take into account the availability of the necessary personnel, labor productivity, the efficiency of working time utilization, the wage system, and workforce mobility."

The importance of a comprehensive assessment of the internal resources of an enterprise is emphasized, including human capital, organizational structure, and management system. This fully corresponds to the criteria embedded in the **coefficient of organizational and technical potential (KotP)**.

**5. Indicators of Workforce Mobility in a Construction Organization.** In modern conditions, the stability of the workforce in construction organizations is a crucial factor determining their production reliability and overall efficiency. A high level of staff turnover leads to significant costs: financial (recruitment and adaptation of new employees), organizational (disruption of process continuity), and social – such as deterioration of the psychological climate within the team, reduced trust, and weakened cohesion.

As economist A. Shkel notes, "frequent staff turnover has a negative impact on the systematic development of production: labor productivity growth slows down, and product quality deteriorates" [20]. This is particularly relevant for the construction industry, where work efficiency directly depends on the coordination of actions and the qualifications of personnel.

To analyze workforce mobility, a number of quantitative indicators are applied.

**5.1 Labor Turnover and Staff Turnover Ratio (Kt).** Labor turnover includes all employees who have left the organization during a given period. However, when calculating the staff turnover ratio, only dismissals not related to production or state necessity are taken into account – for example, resignations at one's own request, dismissals for violation of labor discipline, or termination due to professional incompetence. These cases form what is known as excessive turnover, which reflects internal problems in personnel management.

According to the methodology presented on the Normativka.by portal, "the staff turnover ratio is an important indicator of workforce stability and makes it possible to identify problems in motivation, working conditions, and personnel policy" [21]. Analyzing the dynamics of **Kt** over several years allows forecasting of HR risks and timely adjustment of managerial decisions.

The reasons for dismissals that are not taken into account when calculating staff turnover include:

- Staff reductions or downsizing;
- Enterprise reorganization;
- Change of management and related personnel reshuffling;
- Retirement.

**5.2 Replacement Ratio (Kr).** For a more complete picture of workforce changes, the replacement ratio is used. It reflects the relationship between the number of employees who need to be replaced and the total number of employees who have left the organization. It is calculated using the formula

$$\text{Kr} = \frac{\text{K}_{re}}{\text{K}_{ex}}, \quad (1)$$

where Kr – replacement ratio;

Kre – number of employees to be replaced, i. e., the number of workers whose positions must be filled. They may leave for various reasons, such as resignation, retirement, illness, etc.;

Kex – total number of employees who left the organization during a given period (e. g., within a year).

For example, if 10 employees left the organization during the year and 8 of them need to be replaced to maintain normal operations, then Kr = 8/10 = 0,8.

This means that 80 % of the departed employees must be replaced.

**5.3 Age-Related Attrition Ratio (Kaa).** The age-related attrition ratio reflects the natural causes of employee departure – retirement, disability, and mortality. It is calculated using the formula

$$\text{K}aa = \frac{Number\ of\ deaths\ in\ the\ age\ group}{Average\ number\ of\ employees\ in\ the\ given\ age\ group} * 1000. \quad (2)$$

This indicator makes it possible to account for demographic risks and to plan personnel policy with consideration of the age structure of the workforce.

Based on the statistical yearbooks of the Republic of Belarus for 2012–2018, the age-related attrition ratio was calculated with differentiation by age groups (table 1).

**Table 1** – Age-Related Attrition Ratio by Age Groups

| Age Group | 20–29 | 30–39 | 40–49 | 50–59 | 60–69 | 70 and older |
|---|---|---|---|---|---|---|
| Age-Related Attrition Ratio | 0,7 | 1,8 | 4,3 | 9,4 | 22,2 | 78,4 |

Note – Source: Own development based on [22–24].

Taking all these indicators into account, the algorithm for forecasting labor resource requirements for an individual construction organization will be as follows.

1. Formation of Input Parameters.

At this stage, the number of personnel, their specialties, and qualifications are determined. The staff turnover ratio (**Kt**) is calculated for the study period, followed by extrapolation to forecast this indicator for the next five years. In addition, the replacement ratio is determined for the analyzed period.

2. Determination of Labor Resources in the Forecast Period

$$\text{LR}_t = \frac{\text{V}_t^{\text{c.w.}}}{\text{PT}_t * \text{K}_{\text{ca}} * \text{K}_{\text{cw}} * \text{K}_{\text{sp}} * \text{K}_{\text{otp}}}, \quad (3)$$

where $\text{LR}_t$ – number of labor resources in the tt-th forecast year, persons;

$\text{V}_t^{\text{c.w.}}$ – volume of contract work in the tt-th forecast year, rubles;

$\text{PT}_t$ – labor productivity in the organization in the tt-th forecast year, rubles per person;

$\text{K}_{\text{ca}}$ – coefficient of personnel requirements by type of construction activity;

$\text{K}_{\text{cw}}$ – coefficient of staffing for construction work;

$\text{K}_{\text{sp}}$ – coefficient of production specificity of the project;

$\text{K}_{\text{otp}}$ – coefficient of organizational and technical potential of the organizatio.

3. Determination of Labor Resources in the Current Period Considering the Age-Related Attrition Ratio (Kaa)

$$\text{LR}_t^{\text{Kaa}} = \sum_{i=1}^{n} \text{LR}_{t-1} * \text{Kaa}, \quad (4)$$

where $\text{LR}_t^{\text{Kaa}}$ – number of labor resources in the current period considering the age-related attrition ratio;

$\text{LR}_{t-1}$ – number of labor resources in the previous year, person;

Kaa – age-related attrition rati;

i – age group;

n – number of age groups.

4. Determination of the Number of Additional Employees Required for a New Project or Increased Work Volume

$$ARt=La+Lc, \quad (5)$$

$$La=LR_t^{Kaa} * Kt * Kr, \quad (6)$$

$$Lc=LR_t - LR_t^{Kaa}, \quad (7)$$

where $AR_t$ – annual additional need for labor resources in the tt–th forecast year, person;

La – attrition-related demand in construction in the tt–th forecast year, persons;

Lc – creation-related demand in the tt–th forecast year, persons;

Kr – replacement ratio;

Kt – staff turnover ratio.

The additional demand for personnel or labor surplus is usually calculated separately for each category of workers, taking into account their profession, qualification (grade), and other factors.

In construction, a significant proportion of workers typically possess multiple related professions. Therefore, when forecasting labor resource requirements, it is necessary to consider the professional mobility of workers, since this determines which specific professions require the recruitment of new employees.

**Conclusion**

An important tool of strategic planning in a construction organization is the methodology for forecasting labor resource requirements. The proposed methodology takes into account a wide range of factors: types of construction activities and works, characteristics of projects and organizations, as well as demographic and workforce indicators. The introduced coefficients make it possible to adapt calculations to the specifics of particular projects and organizations. The forecasting algorithm covers both current and future periods, ensuring flexibility and accuracy in planning.

The application of this methodology will allow for the development of a sustainable personnel policy, reducing the risks associated with staff shortages, improving the efficiency of construction projects, and optimizing the costs of staff recruitment and training.

Thus, the developed methodology is an integral part of the modern labor management system in a construction organization and serves as a basis for making informed management decisions.

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# ANALYSIS AND FINANCIAL CONDITION OF THE REGIONAL ENTERPRISE

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**Abstract**

The relevance of the study is confirmed by the fact that in the context of a dynamically developing economy, where enterprises are faced with many factors that can affect their financial condition, the issue of assessing and forecasting the risk of financial insolvency becomes especially significant. In the process in the course of its activities, every enterprise enters into relationships with suppliers, contractors, customers, various credit companies, government control bodies, investors, and others, in relations with whom the organization has certain obligations.

For Russian enterprises and organizations, the issue of financial stability is a priority in socio-economic policy, on par with national defense and law enforcement.

The subject of the study was a regional enterprise, Rusagro Group LLC. The objective of the study was to analyze the company's financial condition over the five-year period from 2020 to 2024, as well as to develop priority areas for ensuring long-term stability and successful development.

The following objectives were identified during the study:

first, to analyze the financial statements of the enterprise under study;

second, to study the potential risks and factors influencing the enterprise's financial insolvency during the study period;

third, to develop priority areas for the stable and successful development of the enterprise.

The study utilized methods such as entity analysis, transition from the specific to the general, system-functional and comparative analysis, scientific abstraction, and the economic-statistical method.

As a result of the research on the stated topic, priority directions for their solution and development within the framework of the stated research objectives were identified.

**Keywords:** analysis, financial condition, risks and factors, financial insolvency, capabilities of a regional enterprise, agro-industrial complex.

## АНАЛИЗ И ФИНАНСОВОЕ СОСТОЯНИЕ РЕГИОНАЛЬНОГО ПРЕДПРИЯТИЯ

**О. В. Бондарская, Е. А. Белова**

**Реферат**

Актуальность исследования подтверждается тем, что в условиях динамично развивающейся экономики, где предприятия сталкиваются с множеством факторов, способных оказать влияние на их финансовое состояние, где вопрос оценки и прогнозирования риска финансовой несостоятельности становится особенно значимым. В процессе своей деятельности каждое предприятие вступает в отношения с поставщиками, подрядчиками, заказчиками, различными кредитными компаниями, органами государственного контроля, инвесторами и прочими, в отношениях с которыми у организации возникают определенные обязательства. Для российских предприятий и организаций вопрос финансовой стабильности является одним из приоритетных в социально-экономической политике, наравне с национальной обороной и обеспечением правопорядка.

Объектом исследования было определено предприятие региона – ООО ГК «Русагро». Целью исследования стал анализ финансового состояния предприятия за исследуемый пятилетний период с 2020 по 2024 годы, а также выработка приоритетных направлений для обеспечения долгосрочной стабильности и успешного развития предприятия.

В ходе исследования были определены следующие задачи: во-первых, проанализировать отчётность исследуемого предприятия; во-вторых, изучить финансовое состояние организации, возможные риски и факторы, влияющие на финансовую несостоятельность предприятия за исследуемый период; в-третьих, выработать приоритетные направления для стабильного и успешного развития предприятия.

В рамках исследования использовались такие методы, как: сущностный анализ, переход от частного к общему, методы системно-функционального, сравнительного анализа, научной абстракции и экономико-статистический метод.

Как результат исследования по заявленной теме определены приоритетные направления их решения и развития в рамках поставленных задач исследования.

**Ключевые слова:** анализ, финансовое состояние, риски и факторы, финансовая несостоятельность, возможности регионального предприятия, АПК.

### Introduction

In a market economy, the principle of enterprise responsibility for the results of financial and economic activity is implemented in the event of losses, the inability of the enterprise to satisfy the demands of creditors for payment for goods (works, services) and to ensure financing of the production process, i. e. in the event of bankruptcy of the enterprise [1].

In a market economy, a stable enterprise may suddenly, for various reasons, become insolvent, entering the unreliable partner zone and finding itself on the brink of bankruptcy. The number of bankruptcies has been increasing for quite some time, but it also depends largely on the current economic situation, crisis, sanctions, and other factors [14, 15, 17, 19].

The greatest attention in modern bankruptcy studies has been paid to the causes of occurrence, the probability of occurrence, methods and approaches to assessing the probability of bankruptcy, issues of regulating the bankruptcy of business entities, and anti-crisis management of business entities [2, 5, 12].

It should be noted that the reasons for the emergence of enterprise bankruptcy are the basis for the type of bankruptcy, which is an important point in the process of the enterprise's activities and should be taken into account, when developing an anti-crisis management program in the event of bankruptcy.

Traditional risk assessment methods may be inaccurate or outdated. Modern insolvency risk forecasting tools can analyze a greater number of factors, which directly impacts forecast accuracy. To make appropriate decisions to prevent insolvency risk, both companies and investors need to assess and forecast its likelihood.

**Research materials and methods**

Rusagro is a vertically integrated agricultural holding company that unites numerous enterprises operating in agriculture and food production [10]. It is one of the largest such groups in Russia, owning assets in pig farming, sugar production, crop production, and the oil and fats business [3, 4].

Currently, Rusagro Group LLC is successfully developing, increasing production volumes and pursuing an active investment policy aimed at expanding its material and technical base. The company has established markets and distribution channels for its products and services.

Rusagro's sales geography is constantly expanding. Currently, the Company sells its products in more than 80 regions of Russia and more than 49 countries worldwide.

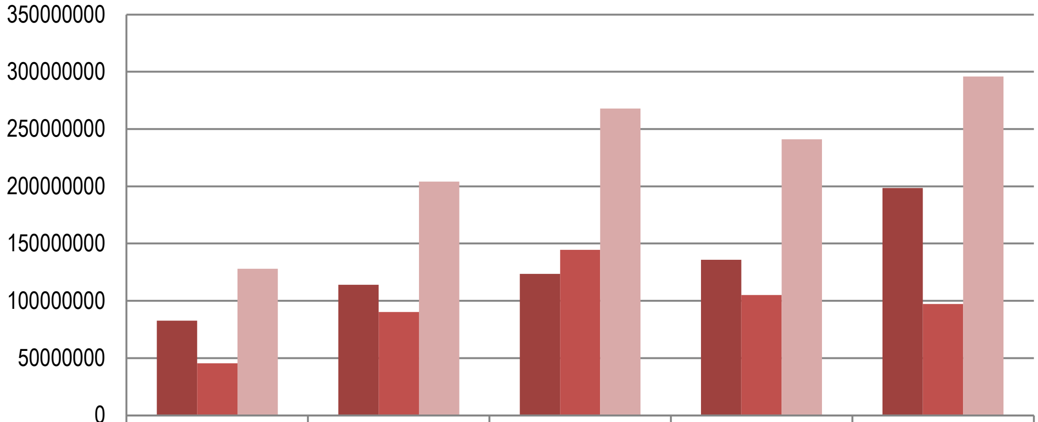
The company's profit for 2024 is RUB 2,394,889,000, revenue for 2024 is RUB 3,964,011,000. The authorized capital of Rusagro Group of Companies LLC is RUB 2,396,874,000.00.

Cost of sales for 2024: RUB 3,886,285,000. Gross profit at the end of 2024: RUB 77,726,000. Total income from current operations for 2024: RUB 6,357,879,000.

Rusagro holds leading positions in sugar production, pig farming, crop production, and the oil and fats business. The Group's land bank covers 685,000 hectares. The Company's depositary receipts are traded on the Astana (AIX) and Moscow (MOEX) stock exchanges.

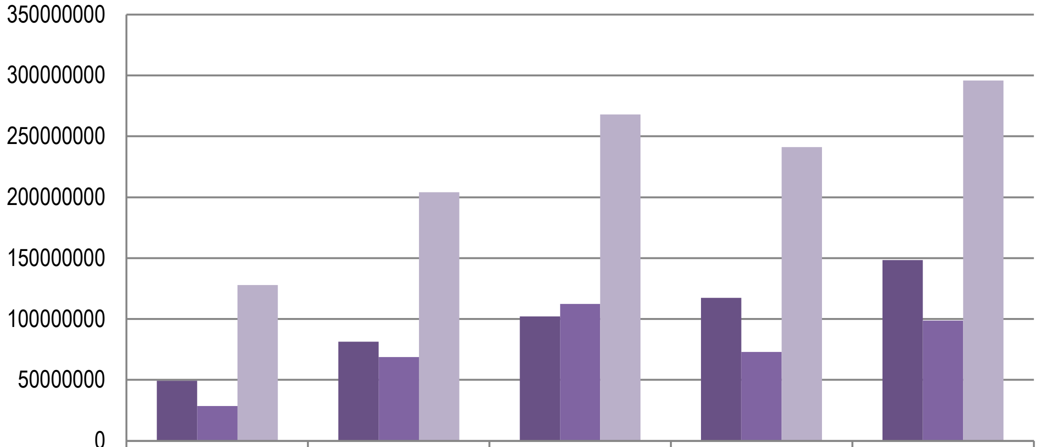
Constructing a horizontal and vertical analysis based on the balance sheet is an important aspect of economic analysis, which allows identifying production and financial risks and forecasting the impact of decisions on the company's performance (Figure 1). Based on open sources and available data, we note that the total value of property in 2024 compared to 2020 increased by 131,18 %, which in absolute terms amounts to RUB 167,843,523 thousand, with non-current assets growing by RUB 115,842,517 thousand or 140,24 %, and current assets increasing by RUB 52,001,006 thousand or 114,69 %. It should be noted that there is an outpacing trend in non-current assets. Such dynamics in the growth of the enterprise's assets is explained by the nature of the analyzed enterprise's activities.

The following changes are observed in the composition of funding sources: equity capital increased by RUB 98,932,359 thousand, or 200,55 %, from 2020 to 2024, while current liabilities increased by RUB 70,333,281 thousand, or 246,91 %. This means that the company is increasing its operating funds through borrowed funds, which, all other things being equal, negatively impacts the company's financial stability (Figure 2).




| | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|
| Total non-current assets | 82604271 | 114005127 | 123432366 | 135872427 | 198446788 |
| Total current assets | 45340145 | 90154534 | 144401600 | 105147913 | 97341151 |
| Total assets of the enterprise | 127944416 | 204159661 | 267833966 | 241020340 | 295787939 |

**Figure 1** – Impact of changes in the organization's assets on the balance sheet total for 2020–2024, thousand rubles [6, 7]




| | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|
| Total equity | 49331263 | 81263282 | 102190465 | 117366464 | 148263622 |
| Total current liabilities | 28484981 | 68649812 | 112504105 | 72880215 | 98818262 |
| Total assets of the enterprise | 127944416 | 204159661 | 267833966 | 241020340 | 295787939 |

**Figure 2** – Structure of liabilities of Rusagro Group LLC for 2020–2024, thousand rubles



https://doi.org/10.36773/1818-1112-2025-138-3-173-178

The entire increase in equity was provided by retained earnings. It increased over the analyzed period by 98,932,359 thousand rubles, or 108,01 %. Accounts payable increased by 53,229,183 thousand rubles, or 2692,4 %. At the same time, deferred income increased by 536,000 thousand rubles, leading to an overall decrease in current liabilities.

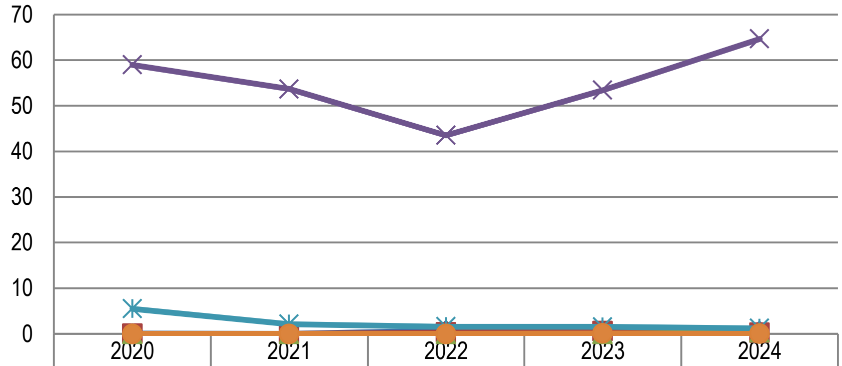
Rusagro Group LLC for 2020–2024, which helps determine what share each category of assets, liabilities and capital makes up in the overall balance sheet structure, which can be useful for identifying trends, analyzing the degree of liquidity and financial stability of the organization [9, 10] (Figure 3).

At the end of 2024, non-current assets accounted for 67,09 %, while current assets accounted for 32,91 %. The share of current assets decreased by 2,53 % from 2020 to 2024, while the share of non-current assets increased by the same amount. The increase in non-current assets was due to an increase in financial investments, which grew by 5,68 %.

Financial investments account for the largest share of current assets (Figure 4). At the end of 2024, their share was 9,15 %, a decrease of 16,38 % compared to 2020. The share of accounts receivable was 13,84 % in 2024, an increase of 8,41 % compared to 2020.

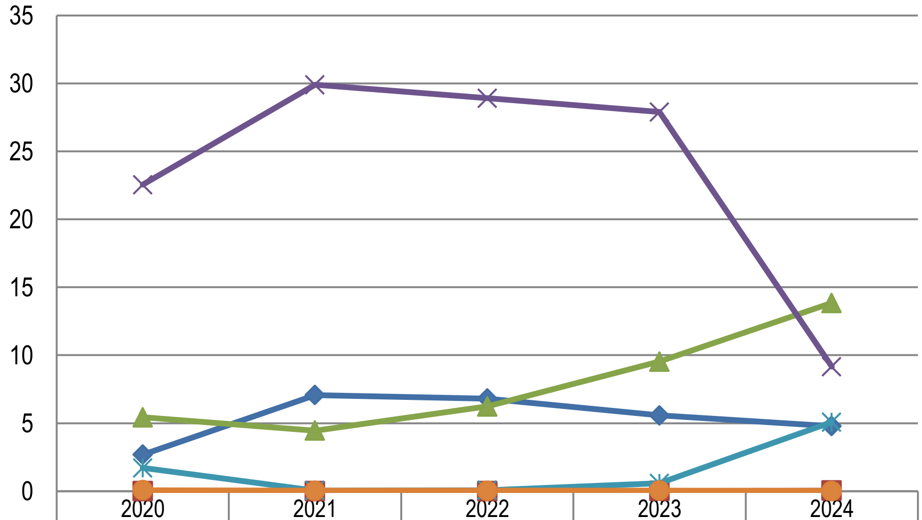
Based on the comparative analytical balance sheet data, conclusions can be drawn about the structure of the enterprise's asset value [8, 13]. It shows the share of each element in assets and the ratio of borrowed and equity funds covering them in liabilities.

Over the period under review, the value of the company's assets increased by 0,23 %. Non-current assets account for the largest share, accounting for 67,09 %; in 2022, this share was 56,37 %. Current assets accounted for 32,91 % at the end of the period.




| | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|
| Intangible assets | 0,05 | 0 | 0,73 | 0,7 | 0,64 |
| Fixed assets | 0,04 | 0,02 | 0,3 | 0,62 | 0,26 |
| Profitable investments and material assets | 0 | 0 | 0 | 0 | 0,32 |
| Financial investments | 58,96 | 53,67 | 43,5 | 53,4 | 64,64 |
| Deferred tax assets | 5,51 | 2,14 | 1,56 | 1,55 | 1,22 |
| Other non-current assets | 0,01 | 0,01 | 0 | 0,11 | 0,02 |

**Figure 3** – Structure of non-current assets of Rusagro Group LLC for 2020–2024, % of total asset value [6, 7]




| | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|
| Reserves | 2,69 | 7,07 | 6,81 | 5,57 | 4,78 |
| VAT on purchased items | 0,01 | 0,01 | 0,01 | 0,02 | 0,05 |
| Accounts receivable | 5,43 | 4,45 | 6,23 | 9,53 | 13,84 |
| Financial investments | 22,54 | 29,9 | 28,9 | 27,89 | 9,15 |
| Finance | 1,71 | 0,04 | 0,07 | 0,57 | 5,08 |
| Other current assets | 0,07 | 0,03 | 0,03 | 0,05 | 0,01 |

**Figure 4** – Rusagro Group LLC for 2020–2024, % of total asset value [6, 7]

An increase in the amount under the "Inventories" item indicates the expansion of the commercial and production activities of the enterprise, which has increased the purchase or production of goods for subsequent sale. An increase in accounts receivable may also indicate an increase in production and sales turnover. However, an increase in accounts receivable is considered a negative fact (Figure 5). In the composition of the enterprise's source of funds, the "Capital and Reserves" section occupies the largest share and amounts to 50,13 % at the end of the period, and 48,7 % at the beginning of the year. The share of long-term liabilities at the end of the period accounts for 16,47 %, and at the beginning of the period – 21,07 %. The share of current liabilities at the end of the period is 33.41%, and at the beginning of the period – 30,24 %. Long-term borrowed funds in 2024 compared to 2020 decreased by 2,067,606 thousand rubles or by 0,04 %. Short-term borrowings in 2024 increased by RUB 25,938,047 thousand or 0,36 % compared to 2020.

The enterprise under analysis is experiencing an increase in accounts payable – this is a negative fact in the enterprise's operations and indicates a deterioration in the financial situation within the organization.

Income statement analysis is the process of examining and evaluating the information contained in a company's financial statements to understand its financial condition, operating performance, and potential future growth.

When analyzing a financial statement, metrics such as revenue, net profit, profitability, asset turnover, and others are typically considered. Analysts and investors can use these results to make decisions about further investments in the company, assess its competitiveness, and forecast future financial performance.

In general, analyzing the financial performance report helps to reveal important financial characteristics of a company and make more informed conclusions about its activities [18–20].

We will analyze the financial results of Rusagro Group LLC for 2020–2024.

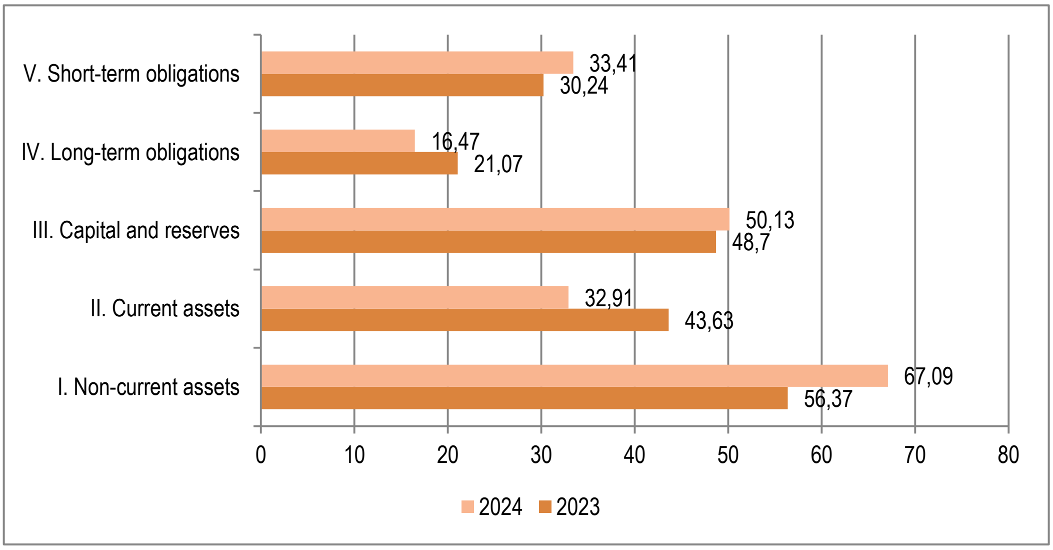
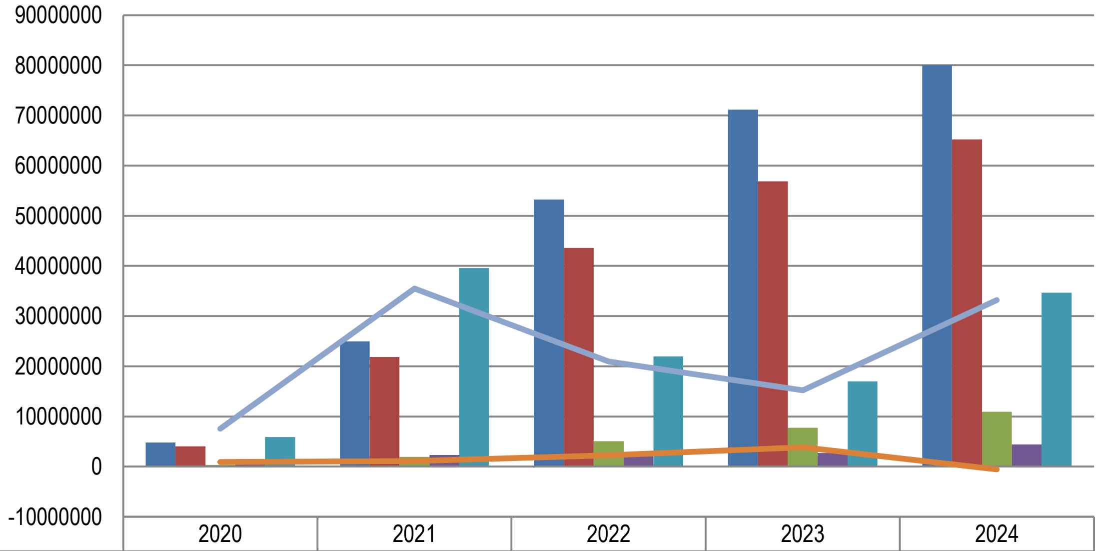



**Figure 5** – Dynamics of the relative values of the asset and liability sections of the balance sheet of Rusagro Group LLC for 2023-2024, % [6, 7]




| | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|
| Proceeds | 4834833 | 24961328 | 53250536 | 71161174 | 80045985 |
| Cost of sales | 4058381 | 21821505 | 43616732 | 56844835 | 65240582 |
| Commercial expenses | 350779 | 1940081 | 5036134 | 7747502 | 10940837 |
| Management expenses | 1313632 | 2307781 | 2371076 | 2695859 | 4437985 |
| Profit (loss) before tax | 5898576 | 39608429 | 21993548 | 16978857 | 34644943 |
| Profit (loss) from sales | 887959 | 1108039 | 2226594 | 3872978 | -573419 |
| Net profit (loss) | 7524139 | 35484519 | 20919037 | 15175999 | 33215212 |

**Figure 6** – Dynamics of the financial results report of Rusagro Group for 2020–2024, thousand rubles

The analysis shows that key financial performance indicators improved during the reporting period. Revenue increased by 25,14 %. Cost of goods sold increased by 27,23 %, meaning revenue is growing at a slower rate than cost of goods sold. However, commercial expenses increased by 14,53 %, and administrative expenses by 22,4 %. Net profit increased by 84,18 % from 2020 to 2024.

**Conclusion**

Thus, the analysis of balance sheet dynamics revealed, on the one hand, an increase in the company's assets. However, non-current assets are growing at a faster rate than current assets. A positive trend is also observed in the composition of the company's asset financing sources.

Summarizing all of the above, we can conclude that the financial position of the enterprise LLC GC Rusagro is reliable, in order to improve its financial position and create stability and reliability, the enterprise needs to develop and implement certain measures for the stable and confident development of the enterprise.

Currently, Rusagro Group of Companies LLC demonstrates relatively stable financial results. Revenue has grown in recent years, indicating increased sales volumes and market expansion. However, despite this positive trend, it is necessary to consider potential risks associated with changing market conditions, fluctuations in raw material and final product prices, and the influence of external economic factors such as sanctions and legislative changes [15].

Rusagro Group recognizes the importance of a responsible approach to risk management, which is inextricably linked to the Strategic Plan and reflects the priorities set by the Group's management. The Company devotes significant resources to identifying, assessing, and incorporating risks into business decision-making.

In 2024, the Company identifies 19 risks that may have a significant impact on its operating results.

In particular, for 2025, the Risk Management System notes the high significance of political and financial risks and draws the attention of the Group's management to managing them and improving practices in relation to them.

In today's reality, continuing the stated topic, the topic of bankruptcy at an enterprise (organization) will also be of interest.

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# IMPLEMENTATION AND FEATURES OF SOCIAL PROJECTS IN THE REGION'S MUNICIPALITIES


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**Abstract**

The socio-economic development of territories is a multifaceted process that includes the interaction of various factors influencing the quality of life of the population, the sustainability of the economy and the sustainability of the environmental situation. Social projects and initiatives are a key tool for the sustainable development of cities and regions, improving people's lives, and solving pressing social problems. In modern Russia, where regions face population decline, uneven distribution of resources, and the need to upgrade social infrastructure, their role is especially important.

The purpose of the study was to analyze existing social projects in urban municipal centers of the Tambov region and identify key factors influencing their success and complete implementation, as an important vector in the development of high-quality services for the region's population.

The objectives of the study were, firstly, to analyze existing social projects in the region's urban municipal centers; secondly, to identify the causes and problems associated with their complete failure to implement.

Thirdly, to develop recommendations for improving the mechanisms for implementing social projects in municipalities.

To achieve the stated goal, the objects of the study were selected municipal urban territories of the Tambov region. This is the regional center of the region – Tambov, as well as the Science City of the region – Michurinsk and the historical center – a small town of the region – the city of Morshansk.

Studying these projects allows us to evaluate their effectiveness, highlight successful examples, and identify factors that hinder their effective implementation. Particular attention will be paid to the specifics of the social sphere in the municipalities of the Tambov region, priority areas for its development, and problems arising in the implementation of social initiatives.

Based on the data obtained, recommendations will be developed to improve existing programs and create new strategies for the social development of cities in the region.


**Keywords:** Tambov Oblast, municipal urban territories, social projects, realities and prospects.

## РЕАЛИЗАЦИЯ И ОСОБЕННОСТИ СОЦИАЛЬНЫХ ПРОЕКТОВ В МУНИЦИПАЛЬНЫХ ОБРАЗОВАНИЯХ РЕГИОНА

**Т. А. Бондарская**


**Реферат**

Социально-экономическое развитие территорий представляет собой многогранный процесс, включающий в себя взаимодействие различных факторов, влияющих на качество жизни населения, устойчивость экономики и устойчивость экологической ситуации.

Социальные проекты и инициативы – ключевой инструмент для устойчивого развития городов и районов, улучшения жизни людей и решения насущных социальных проблем. В современной России, где регионы сталкиваются с сокращением населения, неравномерным распределением ресурсов и необходимостью обновления социальной инфраструктуры, их роль особенно важна.

Цель исследования: проанализировать действующие социальные проекты в городских муниципальных центрах Тамбовской области и определить ключевые факторы, влияющие на их успешность и полноту реализации, как важного вектора в развитии качественных услуг для населения региона.

Задачами исследования стали, во-первых, анализ действующих социальных проектов в городских муниципальных центрах региона; во-вторых, уточнение причин и проблем, связанные с их неполной реализацией; в-третьих, определение приоритетов муниципальной власти в развитии социальной сферы муниципальных территорий; в-четвертых, выработка рекомендаций по улучшению механизмов реализации социальных проектов в исследуемых муниципальных образованиях.

Для реализации поставленной цели, объектами исследования были выбраны муниципальные городские территории Тамбовской области. Это областной центр региона – Тамбов, Наукоград региона – Мичуринск и исторический центр – малый город региона – город Моршанск.

Изучение этих проектов позволяет оценить их действенность, выделить успешные примеры и выявить факторы, препятствующие их эффективному осуществлению. Особое внимание будет уделено специфике социальной сферы в муниципалитетах Тамбовской области, приоритетным направлениям ее развития и проблемам, возникающим при реализации социальных инициатив. На основе полученных данных будут разработаны рекомендации по улучшению существующих программ и созданию новых стратегий социального развития городов региона.


**Ключевые слова:** Тамбовская область, муниципальные городские территории, социальные проекты, реалии и перспективы.

### Introduction

In the context of constant social, economic, and environmental change, the relevance of studying regional socioeconomic development strategies is growing. A strategic approach to the formulation and implementation of regional development programs allows not only to identify priority areas but also to effectively allocate resources to achieve these goals [1].

In the Tambov region, where urban municipal centers are key focal points for social activity and management resources, studying successful practices and challenges in implementing social projects is a pressing and crucial task.

The Tambov region, located in the center of European Russia, possesses significant economic potential, a rich history, and cultural heritage. However, the specifics of its socioeconomic development require targeted analysis and assessment, both of its current status and prospects. A study of the substantive approach to formulating a regional socioeconomic development strategy, as an important element of state social and regional policy, allows us to identify key mechanisms for improving quality of life and the sustainability of the local economy.

### Materials and methods

A significant contribution to the development of the theory and practice of regional management of the national economy and its territorial complexes was made by such scientists as S. S. Artobolevsky, M. K. Bandman, T. A. Bondarskaya, O. V. Bondarskaya, P. I. Burak,

L. B. Vardomsky, O. A. Zolotareva, M. G. Ganopolsky, A. L. Gaponenko, S. Yu. Glazyev, A. G. Granberg, V. A. Tsvetkov, A. A. Khachaturyan and others [8, 25].

In solving theoretical and applied problems in the study, general scientific methods of system and comparative analysis, descriptive statistics, economic and mathematical methods, methods of strategic planning and management, and others were used.

The research information base contains federal and regional regulatory legal acts, analytical and statistical materials presented in open official Internet resources of the Government of the Russian Federation and the Government of the Tambov Region, strategies for the socio-economic development of municipalities, national projects of the country and municipal projects of the region.

Many scientific papers have summarized existing experience, but these methods for organizing and conducting analytical analysis require adaptation to Russian realities [2]. This suggests that the research potential of the topic defined by the dissertation has not yet been fully exhausted, providing an opportunity to conduct research on the stated topic in municipal areas of our great country.

**Research results**

Tambov Oblast, as one of the central regions, has accumulated significant experience in implementing social programs at various levels [18, 20].

Currently, it is important to note the regional government's important role in developing the social sphere in the Tambov Region, which involves developing and implementing a set of measures aimed at improving the quality of life of the region's residents. The fundamental document for this purpose is the Strategy for Socioeconomic Development of the Tambov Region until 2035 [14]. It includes programs for the development of education, healthcare, culture, housing construction, mass physical education and sports, the labor market, family support, and other areas. The key areas of focus include: stabilizing the population and reducing the rate of natural decline; ensuring migration influx; and improving the quality of life for all residents of the region.

For our study, we identified three municipal centers of the Tambov region: Morshansk, Michurinsk and Tambov.

In collaboration with the Administration, representatives of business, the public, and the expert community of the Sreda Urban Technologies Academy, key priorities for the city of Tambov were identified: human capital development and conditions for personal growth; a harmonious and safe urban environment; modern engineering infrastructure and comfortable housing; an adaptive economy; and effective administrative technologies.

Let us highlight the key areas of social development for the city of Morshansk in the Tambov Region. Based on the results of a strategic analysis and taking into account the stated strategic goals, the key priority areas for the city's socio-economic development have been identified. These include: a new quality of life and demographic development encompassing such areas as education, culture, sports, housing and utilities, demography, and others; innovative development and modernization of the economy encompassing such areas as economics, entrepreneurship, transport and road infrastructure, energy conservation, and the provision of municipal services; and effective municipal governance aimed at addressing issues of budget policy, effective management and disposal of municipal property, and the implementation of mechanisms for information openness, transparency, and digitalization of local government bodies [3–5].

We would also like to highlight the key areas of social development for the municipality of Michurinsk in Tambov Oblast, outlined in the action plan based on the regional socioeconomic development strategy until 2030. The district's strategic development priorities include: improving the standard of living and quality of life; advancing the development of the agro-industrial complex, industrial, and processing industries; preserving cultural and historical heritage and realizing tourism and recreational potential; and achieving balanced spatial development [11].

Sector priorities, it is necessary to highlight the key areas in each of the territories under study, namely, the city of Morshansk. The stated priorities are: creating conditions for improving citizens' well-being; maintaining and improving children's health; creating favorable conditions for children's rest and recreation; and creating a comprehensive system of temporary employment and additional financial support for minors aged 14 to 18 during their free time during the summer holidays.

In reviewing the key priorities of the Science City in Michurinsk within the framework of the socio-economic development strategy until 2030, we highlight key priorities, including: modernization of enterprises and infrastructure renovation; reconstruction of social facilities; digitalization of the city and building effective feedback with the population [10]. The key areas of social development have been identified as poverty reduction through the development of targeted forms of social support for families and individuals with incomes below the established subsistence minimum; creating conditions for the participation of socially vulnerable citizens in the life of the city and society as a whole; supporting senior citizens in solving life's problems, realizing their own potential to overcome difficult life situations, and meeting their needs for leisure activities.

As part of our research, we identified some very interesting social initiatives being implemented in the Tambov region [7, 9, 12, 17].

1. "Routes to the Future" is a project by Pigment JSC that introduces visitors to the region to the company's history. One of the former workshops now houses an exhibition hall, a panoramic cinema, chemical laboratories, an experimental space, and other areas.
2. "I'm in Agro." A project by JSC Rosselkhozbank that helps students from agricultural colleges and universities find advanced training programs, internships, and jobs in the agricultural industry.
3. "Chemistry Olympiad. Modern Materials and Technologies." The project was organized by JSC Pigment. Every year, schoolchildren from the Tambov Region participate in the Olympiad, solving problems related to real-life production processes.
4. The creation of a community of mothers of SVO participants, "SVOi Consultants," and a school for social coordinators. These projects aim to improve the quality of life of the population, with a focus on supporting SVO participants and their families.
5. Establishing a "Social Taxi" service for transporting bedridden disabled people. A project by Dina Zhelnovakova, the regional service commissioner for the Tambov region. Took second place based on the expert assessment.

Interesting social initiatives implemented in the municipal areas we identified as study sites, such as the city of Morshansk in the Tambov Region, include the installation of playground equipment in the city park. Swings, a carousel, a slide, and a sandbox were installed, along with trash cans and benches, and the trees were tidied up. New bus shelters were installed, and the Pushkin City Garden was restored. Pedestrian areas were created in the garden, along with hardscape elements, and much more was added to enhance the quality of life for residents.

For comparison, consider social initiatives implemented in the city of Michurinsk in the Tambov Region, such as the creation of a landscaped embankment park [15, 16, 19]. The project was completed in 2022, with a total cost of 270,7 million rubles. This was a victory in the All-Russian Competition of Urban Development Strategies. In 2022, the Michurinsk development project won the "Best Flagship Project" category.

Implementation of national projects. Michurinsk implemented projects in the areas of education, culture, healthcare, demography, housing and urban environment, small and medium-sized businesses and support for individual entrepreneurship, and road safety. This included participation in the federal project "Cultural Environment." The city's Literary and Musical Museum received new museum, exhibition, and interactive equipment. This also included participation in the national project "Road Safety." Michurinsk installed and replaced road signs, applied road markings, and carried out pothole repairs.

To effectively manage cities and improve living standards, it is necessary to carefully analyze socioeconomic indicators. They reflect the state of the economy, the social sphere, and the overall well-being of residents. In this chapter, we will conduct a detailed study of the socioeconomic status of Tambov, Morshansk, and Michurinsk, three cities in the Tambov region with different economic structures and potential. This comparative analysis will help identify common challenges and opportunities, as well as develop practical recommendations for improving the governance of these municipalities, developing their economies, and enhancing the quality of life.

Let us analyze the main socio-economic indicators of the standard of living of the population of the Tambov region.

**Table 1** – Main socio-economic indicators of the standard of living of the population of the Tambov region [22–24]

| | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|
| Average per capita cash income (per month), rubles | 27924 | 30290 | 34783 | 39229 | 46133 |
| Real cash income, as a % of the previous year | 94,3 | 99,1 | 98,7 | 104,7 | 113,3 |
| Average monthly nominal accrued wages per employee, rubles | 31062,7 | 34437,8 | 39345,7 | 45742,1 | 54130,1 |
| Real accrued wages per employee, in % previous year | 104,1 | 102,7 | 99,5 | 109,5 | 110,2 |
| Average size of assigned monthly pensions, rubles | 14136,90 | 15169,45 | 17362,77 | 17497,1 | 18769,6 |
| Real pension size, as a percentage of the previous year | 99,2 | 97,4 | 101,6 | 103,0 | 100,1 |

An analysis of key socioeconomic indicators of living standards in the Tambov Region indicates that, despite some success in increasing wages and pensions, the socioeconomic situation in the Tambov Region remains ambiguous. Unemployment (Figure 1) and significant income inequality have the potential to negatively impact the lives of the population.

Let's consider the average monthly salary of employees of large and medium-sized enterprises in the municipal territories of the Tambov region.

An analysis of average monthly nominal wages of employees at large and medium-sized enterprises in the Tambov Region (Tambov, Morshansk, and Michurinsk) for the period 2020–2024 reveals significant differences. Tambov has the highest wages, which correlates with a more developed industrial sector. Lower rates in Morshansk and Michurinsk are likely due to economic structure and limited job supply. Despite the overall upward trend in wages, achieving a more balanced income distribution requires targeted support for economic development and job creation in less developed municipalities.

We will assess the level of officially registered unemployment in the cities of Tambov, Morshansk and Michurinsk.

An analysis of registered unemployment trends in the urban districts of Tambov Oblast (Tambov, Morshansk, and Michurinsk) from 2020 to 2024 allows us to assess the state and resilience of their labor markets. Minor differences were identified: Tambov and Morshansk exhibit higher unemployment rates, which may indicate limited employment opportunities and structural problems. In contrast, Michurinsk's more developed economy and diversified employment structure contribute to maintaining low unemployment. Despite the short-term negative impact of economic crises and the COVID-19 pandemic, the overall trend during the study period is a decline in unemployment in most cities, indicating economic recovery.

We will analyze the provision of educational institutions in the urban districts of the Tambov region, with a particular focus on the cities of Tambov, Morshansk and Michurinsk.

**Table 2** – Average monthly nominal wages of employees of large and medium-sized enterprises in the cities of Tambov, Morshansk and Michurinsk [6, 22, 23]

| | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|
| Total for the region (thousand rubles) | 33321,5 | 36360,3 | 41106,4 | 47624,3 | 56900,3 |
| Tambov | 35998,3 | 39557,1 | 43565,1 | 44706,0 | 64709,7 |
| Morshansk | 30305,4 | 33086,5 | 39753,6 | 41757,0 | 58097,5 |
| Michurinsk | 32956,9 | 35585,2 | 41473,4 | 51947,0 | 61100,8 |

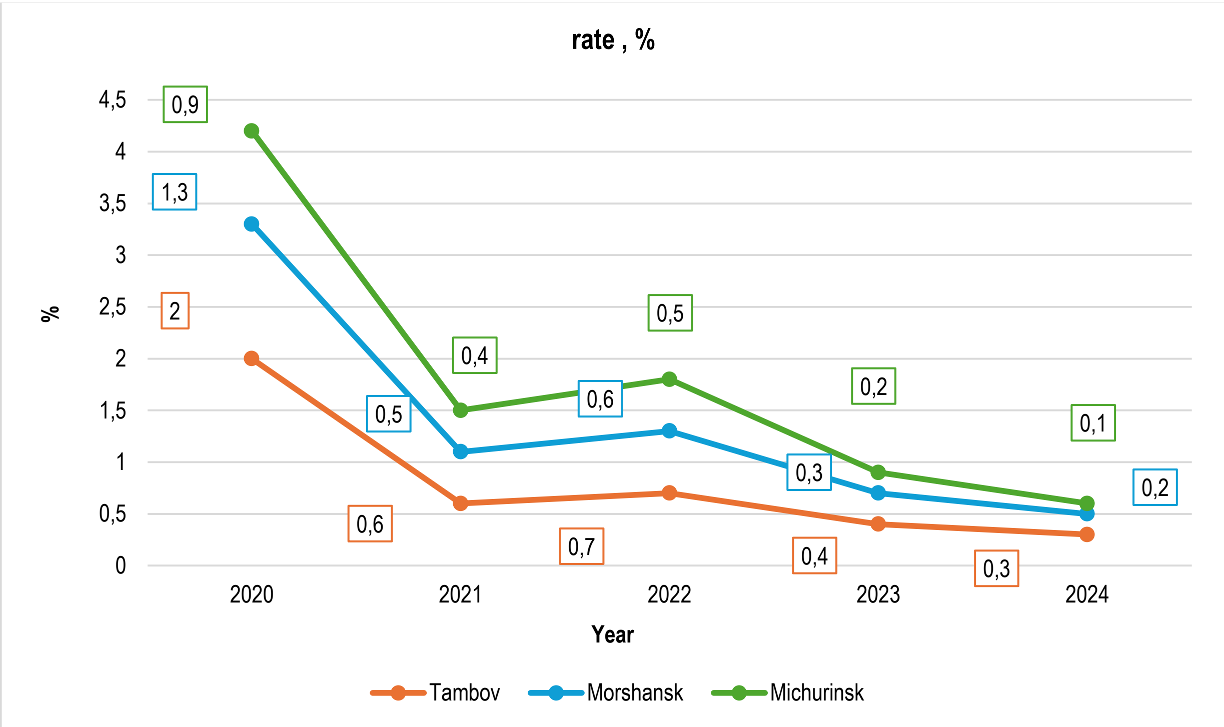
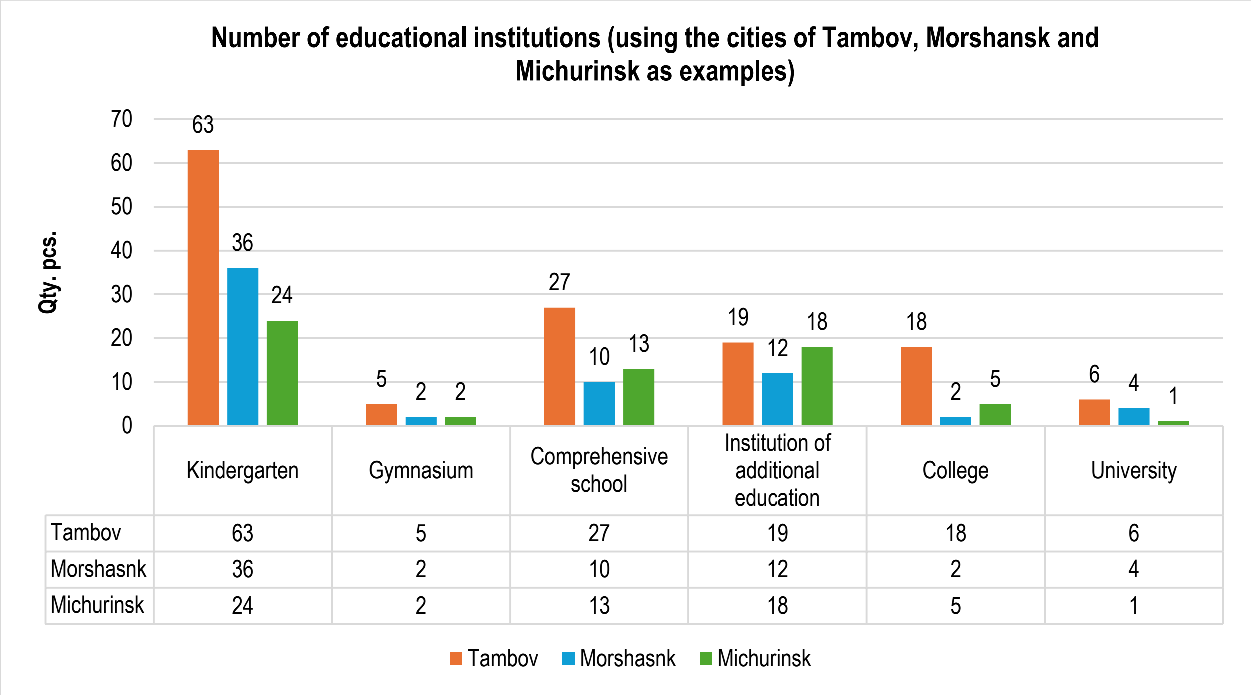



**Figure 1** – The level of officially registered unemployment in urban districts of the Tambov region (using the example of the city of Tambov, Morshansk and Michurinsk) for 2020–2024 [22]

A study of the educational infrastructure of urban districts in the Tambov Region (using Tambov, Morshansk and Michurinsk as examples) identified the presence of a variety of educational institutions (schools, gymnasiums, colleges, and universities) in each of the cities [13]. Tambov's numerical superiority stems from its status as the administrative center and its more developed infrastructure. Morshansk and Michurinsk, despite having fewer institutions, provide access to high-quality education for the local population. The presented data confirm the importance of educational infrastructure for regional development and demonstrate the spatial distribution of institutions, which can be used as a basis for further research in education and social policy.

Let's look at the main healthcare indicators using the Tambov region as an example.

Tambov Oblast is participating in the federal project "Development of the Primary Health Care System" and currently there are results (Table 3).




| | Kindergarten | Gymnasium | Comprehensive school | Institution of additional education | College | University |
|---|---|---|---|---|---|---|
| Tambov | 63 | 5 | 27 | 19 | 18 | 6 |
| Morshasnk | 36 | 2 | 10 | 12 | 2 | 4 |
| Michurinsk | 24 | 2 | 13 | 18 | 5 | 1 |

**Figure 2** – Number of educational institutions in urban districts of the Tambov region (using the example of the city of Tambov, Morshansk and Michurinsk) [21, 22]

**Table 3** – Participation of the Tambov region in the federal project "Development of the primary health care system" [26]

| Main events | Expected results | | Implementation deadlines |
|---|---|---|---|
| | across the Russian Federation | in the Tambov region | |
| Creation of new feldsher, feldsher-midwife stations, and medical outpatient clinics | 350 objects | 3 objects | 2018–2019 |
| Replacement of feldsher, feldsher-midwife stations, and medical outpatient clinics | 1200 objects | 31 objects | December 31, 2020 |
| Purchase of mobile medical units | 1300 | 12 | December 31, 2020 |
| Participation in the creation and dissemination of the "New Model of a Medical Organization Providing Primary Health Care" | 54,5 % honey. organizations | 65 % honey. organizations | 2019–2024 |
| Development of a regional strategy for the development of air ambulance services | + | + | July 1, 2020 |
| Construction of helipads | 78 | 5 | November 27,2020 |
| Carrying out air ambulance flights | 12500 departures | 1000 hours | 2020–2024 |

The Tambov Region's participation in the federal project "Development of the Primary Health Care System" is improving the accessibility and quality of medical services in the region. The project is implementing important initiatives, including the development of air ambulance services and the modernization of the primary healthcare network (paramedic stations, outpatient clinics). As a result, residents of the Tambov Region receive higher-quality and more accessible medical care.

**Conclusion**

To summarize the analysis, we note that the regional executive authorities are making significant progress in implementing social projects, in each individual municipality.

However, there are common problems and obstacles that we would like to highlight.

– Financial constraints. A lack of public funds and difficulties in attracting private capital and sponsorship. The city budget cannot always cover all needs, so projects are forced to seek additional funding sources, including through non-profit organizations. This makes social initiatives dependent on volunteer work, which negatively impacts their quality and sustainability.

– Management and control issues. Non-transparent use of resources and a lack of proper oversight of budget expenditures create fertile ground for corruption.

– A talent shortage. A shortage of specialists with experience in social sciences, project management, and social initiative design. Many projects require social service specialists capable of effectively managing programs and interacting with the public. The lack of such specialists leads to a decline in the quality of project implementation and, consequently, to citizen dissatisfaction.

– Weak public relations. Insufficient citizen engagement in the discussion and development of social projects, which reduces their relevance and support. Low awareness. Another serious problem is the lack of public awareness of existing social projects. It is necessary to raise public awareness using various communication channels, such as social media, local media, and public events, to encourage civic participation.

– Cooperation issues. Cooperation between government agencies and non-profit organizations leaves much to be desired, which also hinders the implementation of social projects. Clear coordination is often lacking, leading to duplication of efforts and blurred responsibilities. For example, projects developed and implemented by NGOs may be ignored by local authorities, as was the case with a social rehabilitation project for people with addictions, which received no support from the city administration.

– Lack of coordination. Another major problem is the lack of clear coordination between various agencies and organizations involved in the social sector. Duplication of efforts is often observed, with several organizations developing similar projects without taking existing initiatives into account. This leads to bureaucratic complications and inefficient use of resources.

Thus, the successful implementation of these initiatives requires a comprehensive approach that includes improved cooperation, active citizen engagement and the development of effective financing mechanisms.

The implementation of social projects in urban municipal centers plays a vital role in the region's development, contributing to improved quality of life, infrastructure development, and social support, all of which enables residents to live comfortably in their beloved homelands.

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# THE USE OF ARTIFICIAL INTELLIGENCE IN THE ORGANIZATION OF TOURIST ROUTES ON THE EXAMPLE OF ENOTOURISM

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**Abstract**

The article examines the theoretical and applied aspects of the use of artificial intelligence technologies in the formation and optimization of tourist routes in the field of enotourism under the conditions of the digital transformation of the industry. The relevance of the study is determined by the growing demand for personalized tourist products, the development of the smart tourism concept, and the necessity of introducing intelligent mechanisms for managing tourist flows in the cultural and gastronomic segment.

The purpose of the study is to identify the possibilities, advantages, and practical effects of applying artificial intelligence in the organization of enotourism routes, as well as to conduct their empirical assessment using international examples. The methodological basis includes methods of systems analysis, clustering, correlation analysis, machine learning algorithms, hybrid recommender systems, route optimization methods, and big data processing tools. The empirical base comprises information on more than 4,000 enotourism sites in Italy, France, Portugal, the United States, Russia and Georgia.

The role of artificial intelligence as a key element of the digital ecosystem of enotourism is demonstrated. The developed multi-level model of intelligent routing ensures the transition from static routes to adaptive personalized trajectories that take into account tourists' preferences, seasonality, and logistical constraints.

Empirical results revealed a strong positive correlation between the level of digitalization of destinations and tourist satisfaction with AI-generated routes, as well as a relationship between the reduction of planning time and the increase in the profitability of wineries. A comparison with traditional and agency-based routes confirmed the advantages of AI in terms of personalization, optimality, cultural richness and economic efficiency.

**Keywords:** artificial intelligence, enotourism, tourist routes, personalization, smart tourism, digitalization of tourism, Big Data, AR/VR technologies, Internet of Things (IoT), recommender systems, sustainable territorial development.

## ИСПОЛЬЗОВАНИЕ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА В ОРГАНИЗАЦИИ ТУРИСТИЧЕСКИХ МАРШРУТОВ НА ПРИМЕРЕ ЭНОТУРИЗМА

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**Реферат**

В статье рассматриваются теоретические и прикладные аспекты применения технологий искусственного интеллекта при формировании и оптимизации туристских маршрутов в сфере энотуризма в условиях цифровой трансформации индустрии. Актуальность исследования определяется ростом спроса на персонализированные туристские продукты, развитием концепции smart tourism и необходимостью внедрения интеллектуальных механизмов управления туристскими потоками в культурно-гастрономическом сегменте.

Цель работы заключается в выявлении возможностей, преимуществ и практических эффектов применения искусственного интеллекта при организации энотуристических маршрутов и в проведении их эмпирической оценки на международных примерах. Методологическую основу составили методы системного анализа, кластеризации, корреляционного анализа, алгоритмы машинного обучения, гибридные рекомендательные системы, методы оптимизации маршрутов и инструменты обработки больших данных. Эмпирическая база включает сведения о более чем 4000 объектах энотуризма в Италии, Франции, Португалии, США, России и Грузии.

Показана роль искусственного интеллекта как ключевого элемента цифровой экосистемы энотуризма. Разработанная многоуровневая модель интеллектуальной маршрутизации обеспечивает переход от статичных маршрутов к адаптивным персонализированным траекториям с учетом предпочтений туристов, сезонности и логистических ограничений.

Эмпирические результаты выявили высокую положительную корреляцию между уровнем цифровизации дестинаций и удовлетворенностью туристов ИИ-маршрутами, а также связь между сокращением времени планирования и ростом доходности винодельческих хозяйств. Сравнение с традиционными и агентскими маршрутами подтвердило преимущества ИИ по персонализации, оптимальности, культурной насыщенности и экономической эффективности.

**Ключевые слова:** искусственный интеллект, энотуризм, туристские маршруты, персонализация, умный туризм (smart tourism), цифровизация туризма, большие данные (Big Data), технологии AR/VR, интернет вещей (IoT), рекомендательные системы, устойчивое развитие территорий.

### Introduction

Wine tourism (enotourism) has in recent years become one of the most dynamically developing areas of cultural and gastronomic tourism, integrating tasting experiences, regional identity, and principles of sustainable territorial development. According to UNWTO data, the share of tourists choosing trips with a pronounced wine-gastronomic component exceeds 25 % in the structure of international travel and demonstrates a stable positive trend [1]. The growing interest in enotourism is accompanied by increasing demand for personalized routes and digital services that make it possible to enhance the quality of the tourist experience and to optimize the management of tourist flows at the destination level [2, 3].

In the context of the rapid digitalization of the tourism industry, the requirements for the implementation of intelligent technologies–ensuring deep analysis of tourist preferences, demand forecasting, and real-time route adaptation–are increasing. In this regard, artificial intelligence (AI) becomes a key element of the smart tourism concept, shaping new approaches to the design and management of tourist trajectories [4–6]. This determines the relevance of the present study, aimed at a systematic examination of AI capabilities in the formation and optimization of enotourism routes [7–9].

The purpose of the study is to identify the possibilities, advantages, and outcomes of applying artificial intelligence technologies in the organization and optimization of tourist routes in the field of enotourism, as well as to conduct their model-empirical assessment using examples of countries with different levels of digital maturity.

To achieve this goal, the study addresses the following tasks:

- to analyze modern AI technologies used in tourism;
- to determine the characteristics of enotourism as an object of intelligent routing;
- to assess the effectiveness of AI for personalization and optimization of tourist routes;
- to develop and test an intelligent routing model using the example of six countries with different levels of digital maturity.

The object of the study comprises the processes of organizing and personalizing tourist routes in enotourism. The subject of the study is artificial intelligence technologies applied in the formation and optimization of enotourism routes.

The scientific novelty lies in the development of a comprehensive model for applying AI to the construction of enotourism routes based on machine learning algorithms, clustering, and big data analysis [10–12]. The model was tested using the examples of Italy, France, Portugal, the United States, Russia and Georgia.

**Intelligent Technologies in the Formation and Optimization of Enotourism Routes**

Contemporary research in the field of enotourism underscores its interdisciplinary character, integrating aspects of cultural studies, marketing, geography, and the digital economy. Enotourism is regarded not only as a form of specialized leisure but also as an important instrument of territorial branding that contributes to the preservation of cultural heritage, the development of rural territories, and the formation of sustainable tourist clusters [3, 7, 8].

The development of enotourism in recent decades is directly associated with the digitalization of the tourism industry. Geographic information systems, online booking, recommendation services, mobile applications, and big data analytics form the foundation for the transition from standard routes to intelligently managed, adaptive tourist trajectories [13–15]. The use of artificial intelligence technologies reinforces this process: AI enables the creation of dynamic routes that take into account seasonality, site congestion, tourist preferences, and logistical constraints. Since the creation of such adaptive routes requires precise analysis of user characteristics and the identification of hidden patterns within large data sets, personalization tools acquire particular significance. The scientific literature emphasizes the role of hybrid recommendation systems and clustering algorithms as key mechanisms for shaping individualized tourist experiences [6, 16, 18].

At the same time, the practical implementation of digital and intelligent technologies in enotourism varies considerably across countries, as their effectiveness is determined by the level of digital maturity of tourism ecosystems. Research shows that the pace of digitalization depends not only on technological infrastructure but also on cultural characteristics of tourist experience perception, institutional environments, and the degree of development of regional clusters [7, 9, 16, 19]. These factors define the unequal readiness of countries to integrate intelligent technologies and predetermine differences in the expected effects of their application. In this regard, comparing the digital maturity level of countries with the characteristics of their wine tourism makes it possible to identify regional contexts in which the implementation of AI has the greatest potential.

As comparative analysis demonstrates, the development of digital infrastructure and the breadth of digital platform usage directly determine the possibilities for integrating intelligent technologies and the extent of their influence on the quality of the wine experience (Table 1) [3, 9, 10, 12].

**Table 1 –** Comparison of Digital Maturity and Readiness for AI Implementation in Enotourism by Country

| Country | Main Sources and Digital Platforms | Level of Digitalization, % | Readiness for AI Implementation | Features of the Digital Ecosystem |
|---|---|---|---|---|
| Italy | Enoteca Italiana, WineTourism.com, regional registries, Italian Wine Lover, Eataly | 88 | High | Advanced recommendation systems and integration of smart tourism (Tuscany, Piedmont) |
| France | OpenWineData, TripAdvisor, Google Places, state wine registries | 90 | Very high | State-supported digitalization, AI in destination management (Bordeaux, Burgundy) |
| Portugal | Turismo de Portugal DataHub, WineTourism.com | 82 | High | Development of national AI platforms and integration of regional data |
| USA | Yelp, Google, OpenStreetMap, Napa Big Data Initiative | 92 | Maximum | Full integration of Big Data and AI, leading investor in automation |
| Russia | VisitKuban, regional registries, Google Maps | 62 | Medium | Partial digitalization, pilot AI projects in Krasnodar Krai |
| Georgia | Georgia.travel, wine associations, OpenStreetMap | 58 | Low–medium | Early stage of digitalization, high growth potential in Kakheti |

Note – Source: Compiled by the author based on data from OECD, WEF, the World Bank and national tourism platforms [3, 8–10, 12, 20, 24–29].

Interpretation of the presented data makes it possible to identify differences among national models of enotourism. In countries with a well-developed wine tourism culture – Italy, France, the United States and Portugal – a high level of digitalization ensures the widespread application of AI for creating emotionally rich, personalized routes and interactive services [8, 9, 21, 22–26]. In regions where wine tourism retains a predominantly traditional or event-driven character (Russia, Georgia), digital infrastructure remains limited, which results in the use of AI primarily for navigational and informational purposes [27–29].

Against the background of the identified differences, it becomes evident that the potential for introducing intelligent technologies into enotourism is determined by a combination of national and regional conditions. This necessitates a shift from macro-level analysis of digitalization to the examination of specific areas of AI application within the sector. A key domain in which AI possesses the most significant practical potential is the organization of tourist routes. The main possibilities for applying AI in the construction of wine routes may be conventionally grouped into five categories:

***1. Personalization.*** Personalization of routes in enotourism is based on machine learning methods, recommendation systems, and predictive analytics, which make it possible to account for multidimensional data about tourists: taste preferences (wine varieties and styles, price categories), socio-demographic characteristics, travel and booking history, geolocation trajectories, digital traces on tourism platforms, textual reviews, and sentiment analysis results [9, 13, 16, 30]. The use of these technologies enables the formation of a detailed tourist profile and the construction of routes that most accurately correspond to individually defined interests.



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The transition from static to dynamic adaptive routes is a direct consequence of AI implementation: the system becomes capable of adjusting the route in real time. When weather conditions, winery congestion, transportation situations, or the tourist's current preferences change, the algorithm automatically proposes alternative sites to visit, modifies the sequence of tastings, or supplements the route with cultural and gastronomic activities [15, 17, 28], thereby enhancing route flexibility and the overall quality of the travel experience.

The functional advantages of personalized routes create prerequisites for economic effects. Personalization contributes to increased booking conversion, longer trip duration, and higher average spending due to more accurate alignment of the tourism product with consumer expectations [7, 9]. For wine-producing regions, this entails a more even distribution of tourist flows, reduced pressure on the most visited sites, and broader involvement of small wineries in the tourism economy [13, 15, 18].

In addition to economic outcomes, personalization has a significant impact on the sustainable development of territories. Individualized routes make it possible to consider environmental constraints, the carrying capacity of sites, and the seasonal differentiation of tourist flows, thereby forming mechanisms for balanced management of enotourism destination development [9, 15, 18, 22].

***2. AR/VR Technologies.*** The introduction of augmented reality (AR) and virtual reality (VR) technologies forms a new format of tourist–territory interaction based on the effect of digital immersion. Immersive solutions make it possible to model tasting spaces, wine cellars, vineyards, and technological processes in a 360° format, expanding the accessibility of routes and enhancing the emotional richness of the travel experience [19, 20].

VR technologies are used primarily for preliminary and remote tours, providing virtual tourists with the opportunity to become acquainted with the architecture of wineries, their history, and tasting programs. This approach serves as an effective motivational tool and increases the likelihood of an eventual in-person visit [9, 20, 22].

The expansion of AR/VR functionality at the stage of direct route visitation necessitates consideration of the role of augmented reality. AR technologies are used directly along the route and provide superimposition of digital content onto physical space, visualizing parameters of the terroir, grape varieties, climatic characteristics, and elements of the winemaking cycle [19, 20]. Their integration with AI allows the depth and format of visual accompaniment to be adapted to the tourist's interests–educational, gastronomic, cultural, or architectural [16, 18, 20].

International practice demonstrates that AR/VR solutions perform not only entertainment functions but also serve as tools of territorial marketing, digital branding, and preservation of the cultural heritage of wine-producing regions [9, 22, 29], strengthening their positioning within the global tourism space. A more detailed examination of cross-country differences shows that the highest maturity of AR/VR technologies is observed in Italy, France, and the United States, where they are integrated into smart tourism strategies, whereas in Portugal, Russia, and Georgia their dissemination is predominantly limited to pilot initiatives [9, 17, 22].

Overall, AR/VR technologies simultaneously provide preliminary familiarization with routes and create an immersive tourist experience that enhances the emotional perception of the territory and its competitiveness in the digital economy [9, 20, 22].

***3. Big Data*** constitutes a key element of intelligent management in enotourism routes, ensuring the transition from static planning to dynamically adaptable tourist trajectories [1, 13, 15, 17]. The analytical framework of such systems is formed on the basis of data on tourist movements, bookings, transactions, user digital traces, climatic conditions, infrastructural characteristics, and seasonal activity of territories [15, 30, 34]. Integration of these heterogeneous sources enables the construction of multidimensional models of tourist behavior and significantly increases the accuracy of demand forecasting [7, 15, 17].

Machine learning provides the possibility of anticipatory management of tourist flows: routes are adjusted not only in response to emerging congestion but also on the basis of probabilistic scenarios of its occurrence [13, 15, 17], which is especially important for regions with pronounced seasonality and limited carrying capacity [1, 9, 13, 15].

In addition to temporal parameters, Big Data exerts a substantial influence on the spatial organization of routes. Its use makes it possible to identify zones of tourist concentration, construct logistically rational sequences of visits, and differentiate routes by traveler type [13, 15, 30], which leads to reduced travel time and shorter queues [7, 9].

In the context of sustainable development, Big Data performs the function of balancing tourist load by redistributing flows between primary and peripheral sites and stimulating the involvement of small wineries in the region's tourism ecosystem [1, 9, 15]. Economic effects include increased accuracy of recommendations, longer average tour duration, higher rates of repeat visits, and substantial growth in digital bookings [1, 15, 30], as well as improved effectiveness of marketing campaigns through more precise targeting [7, 9, 17].

Thus, Big Data serves as the foundation for the formation of intelligent tourism ecosystems in which routes, events, tasting programs, and logistical processes are integrated into a unified digital environment for managing the tourist experience [1, 9, 15, 17, 30].

***4. Multisensory Technologies.*** Multisensory technologies emerge at the intersection of digital solutions, cognitive psychology, and the experience economy. They activate visual, auditory, olfactory, and tactile perceptual channels, enhancing emotional engagement, improving route memorability, and forming stable associations with the territory and the wine product [9, 33].

In enotourism destinations, multisensory approaches are implemented through immersive tastings, interactive wine museums, audiovisual installations, and aroma stations that link the perception of wine with the context of terroir, climate, technologies, and cultural traditions [9, 19, 34]. The combination of visual effects, spatial sound, and olfactory stimuli increases the subjective evaluation of tasting quality and stimulates repeat visits [9, 33]. Integration of AI enables the personalization of sensory scenarios–the adaptation of lighting, sound, and aromatic parameters to the tourist's individual profile [9, 16, 18].

In practice, multisensory technologies are also used for spatial structuring of routes: they make it possible to differentiate tasting rooms, educational zones, and cellars, creating a coherent sensory trajectory of the journey. The highest levels of maturity of such technologies are observed in Italy, France, and the United States, where they are integrated into strategies for forming an immersive tourist experience [9, 33], whereas in Portugal, Russia, and Georgia their dissemination remains more limited [23–29, 33].

In combination with AR/VR, multisensory formats enhance the educational and cultural potential of routes, create unique digital assets of territories, and increase their attractiveness [9, 18, 33], while the use of AI enables the identification of the most effective sensory scenarios and improves the economic performance of enotourism projects [9, 18, 33].

***5. Integration with Internet of Things (IoT) Technology.*** The Internet of Things (IoT) forms the technological foundation of "smart" enotourism routes, linking the physical infrastructure of wine-producing regions with digital management platforms [12, 14, 17, 36]. Sensor networks–traffic counters, microclimate sensors, RFID tags, beacons, and load-monitoring systems–ensure continuous real-time data flow.

In this context, within advanced digital ecosystems, IoT is applied not only in the tourism sector but also in winemaking, connecting the processes of "vineyard–winery–route" [17, 37, 38] and enhancing the sustainability and synchronization of service delivery.

Unlike Big Data, which operates primarily at the strategic level, IoT provides route adaptation at the operational level by responding to weather changes, queues, traffic congestion, and mass tourist arrivals [13, 15, 36]. Integration of IoT with mobile applications makes it possible to automatically adjust routes, suggest alternative locations, regulate tasting schedules, and reduce the risk of site overload [12, 14, 17]. Such operational flexibility directly translates into economic advantages, including reduced operating costs, increased throughput without infrastructure expansion, improved planning accuracy, and growth in digital bookings [9, 14, 36].

Given the outlined functional and economic effects of IoT, the degree to which different countries possess the conditions for its practical implementation becomes an important issue–one determined by the level of digital maturity of their tourism ecosystems. The highest level of IoT maturity is observed in Italy, France, and the United States, whereas in Portugal, Russia, and Georgia the development of this technology remains at an emergent stage [28, 23–26, 28, 29].

Overall, IoT is viewed as a key element of the technological transformation of enotourism, ensuring the transition from static routes to adaptive digital ecosystems that account for context, behavior, and the dynamics of tourist flows in real time [9, 12, 14, 217, 36].

Summarizing the examined directions of digital transformation, it may be noted that the combined integration of artificial intelligence technologies, AR/VR, Big Data, multisensory solutions, and IoT forms a qualitatively new model for organizing enotourism routes. This model makes it possible to move from fragmented logistical and excursion practices to a unified intelligent system for managing the tourist experience, oriented toward sustainable territorial development, improved service quality, and enhanced competitiveness of wine-producing regions.

Building on the results of synthesizing theoretical and applied approaches to the use of artificial intelligence in enotourism, as well as on the analysis of the corresponding digital technologies [1, 9, 12–15, 17, 30, 37], a multi-level model for organizing enotourism routes was developed. This model is aimed at forming personalized tourist trajectories optimized with regard to traveler preferences, time constraints, seasonality, and geographic accessibility of sites. The structure of the model includes three interconnected levels integrated into a unified system of intelligent route planning (Figure 1).

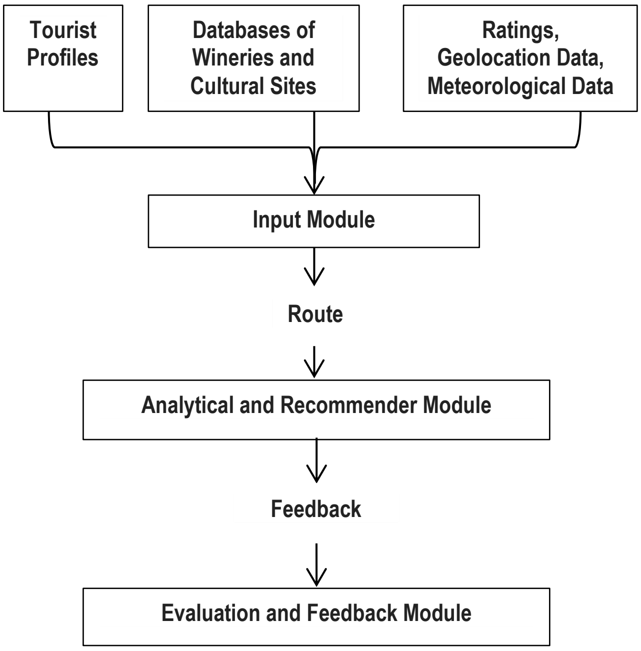


**Figure 1** – Model of Enotourism Route Organization Using Artificial Intelligence

Note – Source: Author's own development based on the concept of smart tourism destinations and digital tourism ecosystems [2, 5, 14, 15, 16, 38].

Transitioning to the description of the functional structure, it should be noted that the first level–the data acquisition module–aggregates information from open sources and API platforms (WineTourism.com, OpenStreetMap, Google Places, TripAdvisor, national registries) [1, 9, 30, 35]. The system receives data on tourists, wineries, schedules, reviews, geolocation, and seasonal constraints. Normalization procedures ensure their comparability and prepare them for subsequent analytical processing.

The second level – the analytical and recommendation module–performs user segmentation based on clustering methods (k-means, DBSCAN) [13, 18, 30] and generates routes using hybrid recommendation algorithms [6, 16]. When generating a route, the system accounts for the relevance of sites to the tourist's interests, transport accessibility, ratings, seasonality, and the event load of the territory. Logistical optimization is carried out using Dijkstra and A* algorithms [15].

The third level–the evaluation and feedback module–collects user assessments, survey results, sentiment analysis of reviews, and data on repeat visits [9, 18, 30]. These inputs are applied for model retraining, refinement of personalization parameters, and improvement of recommendation accuracy.

Taken together, the proposed model ensures real-time route formation, logistics optimization, consideration of seasonal and infrastructural constraints, enhanced safety of tasting tourism, balancing of tourist flows, and increased efficiency of enotourism facilities. Thus, the model functions as a universal intelligent platform supporting the sustainable development of wine-producing territories and the integration of enotourism into the digital ecosystem of smart tourism.

To assess the practical applicability of the proposed model, it was tested using the example of six countries: Italy, France, Portugal, the United States, Russia, and Georgia. The selection of destinations is determined by their significant contribution to the global wine tourism market, as well as by pronounced differences in the digitalization of tourism infrastructure and the extent of AI technology adoption [1, 3, 10, 11, 17].

Routes were generated on the basis of a universal meta-request from a tourist, including preferred trip duration, a combination of popular and authentic sites, temporal and logistical constraints, seasonal parameters, winery load levels, and the need to incorporate tasting, cultural, and natural activities. This approach ensures comparability of results across countries and reflects the typical logic of user interaction with an AI system [12, 16, 18].

He approbation of the model consisted of three interconnected stages.

**At the first stage**, the interpretation of the user request was carried out, and a tourist profile was generated on the basis of aggregated data on preferences, digital traces, route history, and cultural orientations.

**At the second stage**, intelligent filtering of enotourism sites was performed using data from OpenWineData, WineTourism.com, TripAdvisor API, OpenStreetMap, Google Places, and national tourism registries [1, 9, 30, 35], taking into account opening hours, accessibility, congestion levels, climatic, and seasonal factors.

**At the third stage**, the route was generated using hybrid recommendation algorithms and optimized with A* and Dijkstra methods, which made it possible to minimize temporal and transportation costs [15].

The results are presented in Table 2, which contains a list of wineries, route duration, the digital tools employed, and the key effects of AI implementation.

Analysis of the data in the table shows that AI-generated routes in all six countries combine major historical wineries with small family-owned estates. Such a combination expands the cultural richness of the journey and supports a more even distribution of tourist flows. In Tuscany, the three-day circular route reduced planning time by 38 % and yielded an ROI of approximately 23 %. In Burgundy, the application of Big Data and digital wine maps enabled high personalization accuracy (precision = 0,91), whereas in Napa Valley the highest level of automation in traffic and sales forecasting was recorded [9, 13, 16, 17, 37].

In Portugal, routes were optimized according to climatic and seasonal parameters, resulting in a 17 % increase in visitation and a 20 % rise in average tourist spending. In Russia, the VisitKuban AI Route model and IoT sensors increased booking conversion by 21 %. In Georgia, routes became more content-rich and extended tour duration by 18 %, taking into account cultural events in the region [25, 27–29, 31].

The obtained results confirm that the effectiveness of intelligent routing directly depends on the quality of the initial data: completeness, relevance, and coherence of geolocation, rating, temporal, and event parameters. In countries with a developed digital infrastructure, the models demonstrate high adaptability and accuracy, whereas fragmentation or limited availability of data in regions with lower levels of digitalization reduces calculation effectiveness and restricts the scale of AI implementation [10, 11, 17, 30].

To quantitatively confirm the relationship between the level of digitalization of tourist destinations and tourist satisfaction with AI-generated routes, a Pearson correlation analysis was conducted. The analysis was based on a sample of six countries (n = 6) differing in digital maturity. As an indicator of digital maturity, the composite Digital Maturity Index (DMI) was used, based on DESI, the World Economic Forum's Digital Development Index, and World Bank data [3, 10, 11, 17]. Tourist satisfaction was assessed using the Tourist Satisfaction Index (TSI), formed from user ratings, sentiment analysis of reviews, and online surveys (n = 300) [9, 10, 18].

The results presented in Figure 2 indicate a strong positive correlation between the digital maturity index (DMI) and the level of tourist satisfaction with AI-generated routes ($r = 0{,}92$; $p < 0{,}05$). A moderate positive relationship was also identified between the reduction in route planning time and the increase in profitability of wineries ($r = 0{,}71$), which confirms the economic efficiency of intelligent routing [16, 17, 37].

**Table 2 –** Routes Generated by AI for Various Enotourism Regions

| Country / Region | Key Sites (Wineries) | Route Duration, Days | Digital and Intelligent Elements of the Route | Features of the AI-Generated Route |
|---|---|---|---|---|
| **Italy / Tuscany** | Antinori, Castello di Ama, Castello di Brolio, Castello Banfi, Caparzo, Avignonesi | 3 | Hybrid recommendation system; A* and Dijkstra algorithms; integration with IoT monitoring and AR/VR | Circular route; logistical optimization; 38 % reduction in planning time; ROI ≈ 23 % |
| **France / Burgundy** | Château de Pommard, Domaine Roulot, Maison Chanson, Gevrey-Chambertin, Château de Chamirey | **3** | Big Data and review analysis; predictive modeling of visitation; digital tastings | High personalization accuracy (precision = 0,91); integration with the digital wine map system |
| **Portugal / Douro Valley** | Quinta da Pacheca, Quinta do Seixo, Quinta do Bomfim, Quinta da Roêda | 4 | Tourist clustering; adaptive routing based on weather data; NLP-based review analysis | Seasonality and climate optimization; 17 % increase in visitation; 20 % increase in average tourist spending |
| **USA / Napa Valley** | Robert Mondavi Winery, Stag's Leap Wine Cellars, Beringer Vineyards, Castello di Amorosa, Artesa Vineyards & Winery | 3 | Machine learning for demand forecasting; integration with IoT and VR tours | High level of automation; traffic and sales forecasting; ROI ≈ 26 % |
| **Russia / Krasnodar Krai** | Abrau-Durso, Fanagoria, Chateau de Talu, Guy-Kodzor, Kuban-Vino, Lefkadia | 3 | VisitKuban AI Route platform; IoT sensor integration; booking API and geoanalytics | 21 % increase in booking conversion; use of Big Data for flow analysis |
| **Georgia / Kakheti** | Shumi Winery, Tsinandali Estate, Kindzmarauli Corporation, Khareba Winery | 2–3 | SmartWineGeorgia system; hybrid recommendation algorithms; IoT integration | 18 % increase in tour duration; formation of "smart" routes considering cultural events |

Note – Source: compiled by the author based on [1, 3, 9, 10, 13, 14, 16–18, 29, 30].

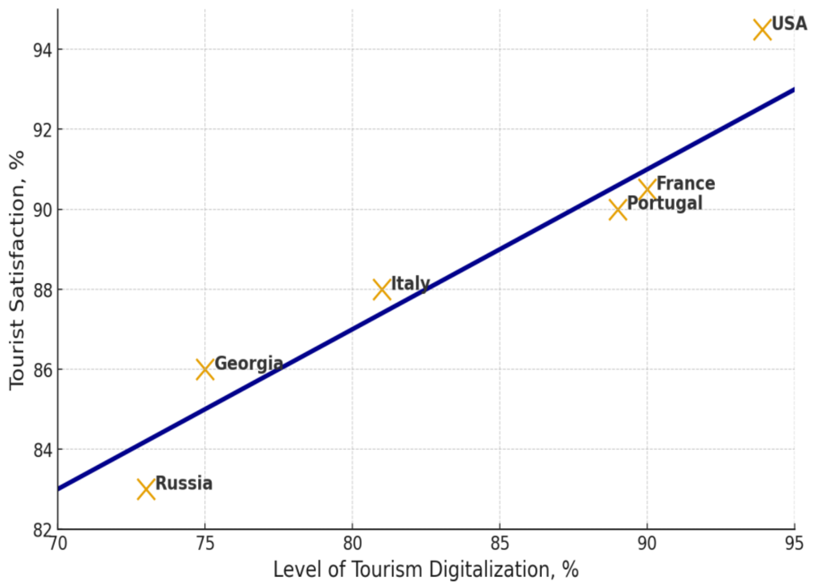


**Figure 2 –** Correlation Dependence between the Level of Digital Maturity of Tourist Destinations (DMI) and the Tourist Satisfaction Index (TSI)

Note – Source: Author's own development based on aggregated data from UNWTO, OECD, the World Economic Forum, the World Bank, and user review platforms [1, 3, 10–12, 17, 30, 37].

According to the graph, a 10 % increase in the level of territorial digitalization correlates with an approximate 3,9 % rise in tourist satisfaction, indicating the significance of digital maturity as a factor in the competitiveness of enotourism destinations. At the same time, the obtained results should be regarded as indicative: the identified relationships reflect stable trends in the digital transformation of enotourism but do not permit strict causal interpretation. This underscores the need to expand the panel sample and conduct more advanced econometric analysis [1, 10, 16, 17].

As an illustrative example of the functioning of the developed AI model, a "Circular Route through Tuscan Wineries" was generated on the basis of a tourist meta-request that included a combination of well-known winery brands and small family estates, optimization of travel time, consideration of seasonality and site congestion, and integration of tasting, gastronomic, and cultural activities. The spatial configuration of the route is presented in Figure 3.

The route unites three key wine-producing zones of the region– Chianti Classico, Montalcino, and Montepulciano – which differ in terroir, grape varieties, technological practices, and historical-cultural context. The set of sites selected for visitation includes both major wineries (Antinori, Castello di Ama, Castello di Brolio, Banfi, Avignonesi) and small estates employing organic and biodynamic practices (Podere le Ripi, Salcheto), thereby ensuring diversification of the wine experience and deeper acquaintance with local traditions [35, 38].

The total length of the route is approximately 285 km, corresponding to a trip duration of 2–3 days. Logistical parameters were calculated using data from OpenStreetMap, the Google Maps Distance Matrix API, and Tuscany's regional road services, while information on wineries and infrastructure was sourced from WineTourism.com, the TripAdvisor API, and the Open Tourism Data Hub Toscana [1, 23, 35, 38]. Optimization of the order of visits was performed using A* and Dijkstra algorithms, which made it possible to minimize transportation costs while maintaining a rich program.

A detailed logistical profile of the route, including distances, travel time, and the functional characteristics of individual segments, is provided in Table 3.


**Figure 3 –** Scheme of the Circular Route through the Wineries of Tuscany

Note – Source: Author's own development based on data from regional digital tourism platforms of Tuscany, intelligent routing algorithms, and tourism aggregators [15, 23, 30, 35].

Analysis of the logistical parameters presented in Table 3 shows that transfers between sites typically take 15–40 minutes, ensuring a comfortable travel pace and reducing transportation-related fatigue for the tourist. The route is structured according to the principle of gradual immersion into the region's wine territories: from large technologically advanced wineries to intimate family estates, and subsequently to premium producers in the Brunello di Montalcino and Vino Nobile di Montepulciano zones. This configuration maintains the internal coherence of the route and provides a diverse wine experience. The longest transfer (65–75 minutes) occurs at the final stage – returning from Montepulciano to Florence. This is due to the geographical characteristics of the region and does not disrupt the overall travel balance thanks to the circular structure of the route.

A significant element in the design of the route was the integration of safe enotourism requirements into the process of intelligent routing, specifically excluding driving after tastings. Special safety time slots were embedded into the routing algorithm, mandating intermediate non-driving activities–gastronomic breaks, cultural stops, and walking segments–as well as recommendations for using alternative transportation. In cases where the tourist prefers individual car travel, the system automatically adjusts the tasting format ("non-driving tastings") or offers the use of transfers, wine road shuttles, or taxis, in accordance with international standards of sustainable and responsible wine tourism [12, 14, 17].

The circular configuration of the route, beginning and ending in Florence, ensures logistical coherence, eliminates duplication of segments, and contributes to an even distribution of tasting activities. Accounting for time constraints, visitation density, and distances between sites made it possible to construct an optimal sequence of winery visits and associated locations, preventing program overload and ensuring a comfortable travel experience.

The spatiotemporal structure of the enotourism route generated by artificial intelligence is characterized by a reduction in the share of logistical costs while maintaining a high level of thematic richness. According to the data in Table 3, the total travel time accounts for 26,8 % of the route's overall duration. The remaining 73,2 % is allocated to thematic components: tastings and production visits (46,2 %), cultural and historical site visits (23,1 %), and gastronomic activities (3,9 %). This proportion confirms the effectiveness of algorithmic optimization, which simultaneously minimizes logistical losses and expands the set of sites included in the route.

The example of the route through the wine-producing territories of Tuscany demonstrates that the application of artificial intelligence not only reduces planning time and rationalizes travel logistics but also promotes deeper integration of family-owned estates into the tourist flow, strengthens the cultural dimension of the route, and supports the principles of safe and sustainable enotourism. The totality of the obtained results confirms the practical viability of the intelligent routing model and its strong potential for replication in other wine-producing regions of the world.

To enhance the analytical substantiation of the study, a comparison was conducted between the AI-generated route through the wineries of Tuscany and the two most widespread models of organizing enotourism travel–the traditional self-planned route and the standard agency route. The comparative characteristics of these formats, presented in Table 4, make it possible to identify their fundamental differences in the degree of personalization, logistical efficiency, level of authenticity and compliance with the requirements of safe and sustainable enotourism.

**Table 3 –** Logistical Profile of the AI-Generated Route through Tuscan Wineries

| Route Stage | Travel Segment | Distance, km | Travel Time, min | Key Characteristic of the Route and the Winery (at Destination) |
|---|---|---|---|---|
| 1 | Florence ⟶ Antinori nel Chianti Classico | 30 | 30 | Departure from the arrival point; Antinori is a large, technologically advanced winery with a well-developed enotourism infrastructure |
| 2 | Antinori ⟶ Castello di Ama | 28 | 35 | Transfer within the Chianti Classico cluster; Castello di Ama is an art-winery combining contemporary art with terroir-driven wines |
| 3 | Castello di Ama ⟶ Castello di Brolio | 20 | 25 | Historic Chianti area; Castello di Brolio is a castle-winery with a pronounced historical and cultural context |
| 4 | Castello di Brolio ⟶ Fattoria La Ripa | 14 | 18 | Transition to a more intimate location; Fattoria La Ripa is a family estate emphasizing local winemaking traditions |
| 5 | Fattoria La Ripa ⟶ Castello Banfi | 32 | 40 | Shift from Chianti to southern Tuscany; Castello Banfi is a major wine resort and enotourism center in the Brunello di Montalcino zone |
| 6 | Castello Banfi ⟶ Podere le Ripi (Montalcino) | 20 | 25 | Short transfer within the Brunello zone; Podere le Ripi is a boutique biodynamic winery |
| 7 | Podere le Ripi ⟶ Caparzo | 10 | 15 | Movement within the Montalcino DOCG; Caparzo is a traditional Brunello winery with a developed tasting infrastructure |
| 8 | Caparzo ⟶ Avignonesi (Montepulciano) | 48 | 50 | Transition from the Brunello zone to the Vino Nobile zone; Avignonesi is one of the key Montepulciano wineries oriented toward organic/biodynamic production |
| 9 | Avignonesi ⟶ Florence (route closure) | 65 | 75 | Return to the starting point; completion of the circular route with a logically structured transition from wine zones to the region's cultural capital |

Note – Source: compiled by the author based on [23].

**Table 4 –** Comparative Characteristics of Traditional, Agency and AI-Generated Enotourism Routes through Tuscan Wineries

| Indicator | Traditional Route (self-planned) | Agency Route (regional tour operators) | AI-Generated Mixed Route |
|---|---|---|---|
| **Degree of personalization** | Low – depends on the tourist's experience and random information selection | Moderate – adaptation possible within template programs | High – formed on the basis of the tourist's profile, preferences, logistical and cultural parameters |
| **Consideration of opening hours, seasonality, site congestion** | Weak | Partial | Full – automatic optimization of schedules, seasonal factors, and traffic |
| **Diversity of wineries** | Limited – mainly large, well-known estates | Limited – wineries adapted for tourism | Maximum – combination of major historical and family wineries (Podere le Ripi, Salcheto, etc.) |
| **Authenticity of experience** | Unstable | Moderate | Very high – integration of artisanal practices and local cultural points |
| **Logistics (route optimality)** | Low – chaotic movements, high transportation costs | Moderate – route constructed without personalized optimization | High – optimization based on A* and Dijkstra algorithms |
| **Average planning time** | 3–5 hours | 1–2 hours | Reduced by 38 % (≈ 18–25 minutes) |
| **Average travel time between points** | 45–90 minutes | 40–70 minutes | 18–45 minutes |
| **Consideration of tasting safety (driving safety)** | Absent | Minimal | Full – "alcohol-sensitive time slots," transfers, non-driving tastings |
| **Integration of cultural sites (Siena, Montepulciano, etc.)** | Inconsistent | Partial | Structured – based on clustering and temporal constraints |
| **Tourist satisfaction (survey n = 300 and sentiment analysis ≥ 0.78)** | 82–84 % | 86–88 % | 92–94 % |
| **Recommendation accuracy (Precision@K)** | – | – | 0,87 – level of mature hybrid recommender systems |
| **ROI of wineries (Return on Investment)** | 0–5 % | 8–12 % | ≈ 23 % due to increased tastings and higher average spending |
| **Key performance indicators of the route (KPI)** | Low – no analytics | Moderate | High – load balancing, logistics optimization, increase in average spending |
| **Accessibility of digital services** | Random | Moderate | Full – integration of WineTourism.com, OpenStreetMap, TripAdvisor |

Note – Source: compiled by the author based on aggregated data from digital tourism platforms, regional statistics, and analytical studies in the field of smart tourism [1, 12, 13, 15, 16–18, 30, 37, 39].

The analysis shows that traditional routes, based on independent search and fragmented digital sources, are characterized by limited diversity of wineries, low personalization, and weak consideration of opening hours, seasonality, and site congestion. This results in increased time costs for planning (3–5 hours), chaotic movements, and reduced tourist satisfaction (82–84 %). Agency routes are more structured and predictable; however, they retain a high level of standardization and are oriented toward an averaged traveler profile. Their flexibility is constrained by template-based programs, which limits the diversity of visited sites and restricts satisfaction levels (86–88 %).

In contrast to these models, the AI-generated route is formed through the integration of the tourist's personal preferences, spatiotemporal parameters, seasonal factors, site load data, and user analytics. This ensures maximal variability of visited wineries–from major historical estates to small family producers–and significantly enhances the authenticity and depth of impressions. A substantial advantage of the AI-based approach lies in the full automation of accounting for opening hours, seasonal constraints, transport accessibility, and tourist traffic intensity–capabilities unavailable in traditional and agency formats.

The AI-generated route fundamentally differs from traditional and agency models of travel organization in its construction mechanism: it integrates data on tourist preferences, seasonality, logistics, site congestion, and user evaluations. Such an approach creates a maximally diverse and balanced set of wineries and enhances the authenticity of visits. Its key advantage is the automatic adjustment of temporal parameters and schedules, ensuring that the route meets the requirements of sustainable and responsible wine tourism.

The logistical efficiency of the AI-generated route is ensured through the application of A* and Dijkstra algorithms, which optimize distances and travel time. According to Table 4, average transfer time is reduced to 18–45 minutes (compared to 45–90 minutes for traditional routes and 40–70 minutes for agency routes), while planning time decreases by 38 %, averaging 18–25 minutes. An important distinction between the AI-generated route and traditional or agency formats is the full consideration of safe enotourism requirements: the system automatically generates safety time windows, adapts tasting formats, or proposes alternative transportation solutions, ensuring compliance with international standards of responsible wine tourism [12, 17, 36].

Comparative analysis of economic efficiency demonstrates the advantages of intelligent routing: winery ROI increases to 23 % due to growth in the number of tastings, higher average spending, and expansion of accompanying services, whereas in traditional routes this indicator is 0–5 % and in agency routes 8–12 %. The AI-generated route is characterized by the highest levels of tourist satisfaction (92–94 %) and recommendation accuracy, corresponding to the performance of mature hybrid recommender systems.

Taken together, the results of the analysis presented in Table 4 show that the AI-generated route provides not only quantitative advantages–reduced planning time, optimized logistics, and increased economic returns–but also a qualitatively different level of personalization, cultural richness, and safety. This confirms the high potential of intelligent routing systems in the development of wine-producing territories and the formation of sustainable digital tourism ecosystems [9, 14, 18, 38].

**Conclusion**

The conducted study has shown that artificial intelligence technologies, at the current stage of tourism industry development, are becoming key instruments for managing enotourism routes. The use of AI enables the transition from static and standardized travel models to adaptive, personalized trajectories that account for individual tourist preferences, seasonal and infrastructural constraints, logistical parameters, and the requirements of safe tasting tourism.

The developed multi-level model of intelligent routing, incorporating an input data module, an analytical–recommendation module, and an evaluation–feedback module, demonstrated practical viability during testing in six countries with different levels of digital maturity in their tourism ecosystems–Italy, France, Portugal, the United States, Russia, and Georgia. The test results confirm the high adaptability of the proposed model to varying destination conditions and reveal its potential for scaling to other wine-producing regions.

The empirical assessment identified a strong positive correlation between the level of digitalization of tourist destinations and tourist satisfaction with AI-generated routes (r = 0,92), as well as a moderate relationship between reduced planning time and increased profitability of wineries (r = 0,71). These findings confirm the pronounced economic effect of implementing intelligent routing systems and their significance for improving the quality of tourist routes.

Comparative analysis of traditional, agency, and AI-generated routes showed that intelligent routing provides a higher level of personalization, logistical optimality, and structural coherence of visit programs, while surpassing alternative approaches in key performance indicators (KPIs) – recommendation accuracy, evenness of tourist flow distribution, average spending, and winery return on investment.

Thus, the use of artificial intelligence in the organization of enotourism routes should be considered a promising tool for the sustainable development of wine-producing territories, for increasing their competitiveness, and for forming digital tourism ecosystems within the framework of smart tourism.

Future research prospects include expanding cross-country samples, advancing predictive modeling methods for tourist demand, deepening IoT integration in the management of enotourism infrastructure, and improving econometric models for evaluating the effectiveness of AI solutions. Additional attention is required for analyzing limitations associated with data heterogeneity and the variability of digital maturity across different regions.

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# LOGISTICS DISPROPORTIONS IN CHINA'S CONSTRUCTION AND THE DIGITAL TOOLS TO NARROW THEM

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**Abstract**

This article reframes China's inland-coastal gap in construction as a logistics disproportions problem and builds a logistics-first digital agenda to address it. First, it defines logistics disproportions as systematic differences in end-to-end lead-time predictability, the transport mode mix for heavy modules, and the stability of payment cycles. It then synthesizes peer-reviewed literature on coastal logistics, Building Information Modeling (BIM) and digital twins, national policy on prefabrication, and international rankings/benchmarks to establish the evidence base and bound plausible effect sizes. Second, it translates that evidence into an operational toolbox: supply-chain BIM (SC-BIM) that models routings and staging; factory-yard-site digital twins for re-sequencing and buffer sizing; standardized e-procurement with product data templates; Internet of Things (IoT) tracking with a transportation management system (TMS); verifiable shipment/installation milestones to align cash with events; artificial-intelligence (AI) risk forecasting; and inland consolidation hubs positioned near railheads. Third, it converts the agenda into a testable plan. A SWOT analysis identifies assets and frictions; a transformation roadmap assigns owners, instruments, and target indicators – on-time delivery, rail/water share of ton-kilometres, re-handling reduction, P90 – P50 delivery-window spread, and days sales outstanding (DSO) – with staged horizons of 9–36 months. Fourth, it specifies governance conditions: shared data schemas, open APIs, and product data templates to ensure interoperability across provinces and portfolios. A brief vignette illustrates how the playbook scales from a single inland project to programs. Finally, it acknowledges limits (secondary data, uneven provincial granularity) and sets a research agenda: open lead-time datasets, PDT-based public-procurement pilots, and causal evaluation of rail-hub deployments. In terms of China's construction logistics, the SWOT configuration in the table revealed precisely these imbalances: strong coastal logistics corridors and mature digital platforms coexist with structurally weaker domestic networks, higher turnaround time volatility, and slower adoption of smart logistics tools. In practice, this means that strengths and opportunities are locally concentrated, while weaknesses and threats accumulate in inland regions and small towns, where construction projects depend on smaller and less sustainable supply routes.

**Keywords:** construction logistics, digitalization, supply-chain BIM, digital twins, e-procurement, IoT tracking, TMS, inland hubs, China.

## ЛОГИСТИЧЕСКИЕ ДИСПРОПОРЦИИ СТРОИТЕЛЬСТВА В КИТАЕ И ЦИФРОВЫЕ ИНСТРУМЕНТЫ ИХ НИВЕЛИРОВАНИЯ

**Н. А. Григорьева, О. С. Голубова, Юйхао Цзян**

**Реферат**

В данной статье переосмысливается внутренний – прибрежный разрыв Китая в строительстве как проблема логистических диспропорций и выстраивается «логистико-центричная» цифровая повестка для его решения. Во-первых, логистические диспропорции определяются как систематические различия в предсказуемости сквозных сроков поставки, в модальном составе перевозок для тяжелых модулей и в стабильности платежных циклов. Затем синтезируется рецензируемая литература по прибрежной логистике, информационному моделированию строительства (Building Information Modeling, BIM) и цифровым двойникам, национальная политика префабрикации, а также международные рейтинги/бенчмарки с тем, чтобы задать доказательную базу и очертить правдоподобные величины эффектов. Во-вторых, эта база переводится в операционный «набор инструментов»: цепочно-поставочный BIM (SC-BIM), моделирующий маршруты и зоны накопления; цифровые двойники связки «фабрика – склад – стройплощадка» для пересеквенирования и задания буферов; стандартизированная электронная закупка с шаблонами продуктовых данных; отслеживание через интернет вещей (Internet of Things, IoT) вместе с системой управления перевозками (Transportation Management System, TMS); верифицируемые вехи отгрузки/монтажа для привязки денег к событиям; прогнозирование рисков на базе искусственного интеллекта (Artificial Intelligence, AI); и внутренние хабы консолидации, размещенные у железнодорожных узлов. В-третьих, повестка превращается в проверяемый план. SWOT-анализ выявляет активы и трения; «дорожная карта» закрепляет ответственных, инструменты и целевые индикаторы – поставки в срок, доля ж/д и водных тонно-километров, сокращение перегрузок, разброс окон поставок P90 – P50 и дни дебиторской задолженности к погашению (Days Sales Outstanding, DSO) – с поэтапными горизонтами 9–36 месяцев. В-четвертых, задаются условия управления данными: общие схемы данных, открытые API и шаблоны продуктовых данных для обеспечения межрегиональной и межпортфельной совместимости. Краткая виньетка демонстрирует масштабирование «плейбука» от одного внутреннего проекта к программам. В заключении оговариваются ограничения (вторичные данные, неоднородная детализация по провинциям) и формируется исследовательская повестка: открытые наборы по срокам, пилоты госзакупок на базе PDT и причинная оценка внедрения ж/д-хабов. С точки зрения строительной логистики Китая, конфигурация SWOT в таблице выявила именно эти диспропорции: сильные прибрежные логистические коридоры и зрелые цифровые платформы сосуществуют со структурно более слабыми внутренними сетями, более высокой волатильностью времени выполнения заказов и более медленным распространением интеллектуальных логистических инструментов. На практике это означает, что сильные стороны и возможности локационно сконцентрированы, в то время как слабости и угрозы накапливаются во внутренних регионах и небольших городах, где строительные проекты зависят от все меньшего и менее устойчивых маршрутов поставок.

**Ключевые слова:** логистика строительства, цифровизация, BIM, цифровые двойники, электронные закупки, IoT, TMS, консолидационные хабы, Китай.

### Introduction

China's construction sector has achieved global visibility, with Chinese firms consistently ranked among the world's largest international contractors; yet this outward success coexists with uneven domestic capabilities and benefits [1]. A growing body of work on coastal logistics shows why the advantage concentrates at the seaboard: dense port-rail systems, thicker supplier networks and more stable flows, while inland corridors remain more road-dependent and variable [2]. Political-economy studies add that "logistical fixes" have historically favored coastal nodes, reinforcing a spatial divide that outlives individual projects [3]. At the same time, international benchmarks underline that logistics performance-reliability, speed, predictability-shapes lead times and competitiveness in ways that are highly consequential for construction scheduling and cost [4].

The definition of "logistics disproportions" is refered to systematic inland-coastal gaps in (i) end-to-end lead-time predictability, (ii) mode mix (rail/water vs. road) for heavy modules, and (iii) the stability of payment cycles. Operationally, the coefficient of variation for door-to-door lead times is tracked, the rail/water share of ton-kilometers for prefabricated elements, the P90 – P50 gap for delivery windows, and DSO days along the supply chain. These indicators map directly to project risk and working-capital costs and can be audited at monthly cadence.

Since 2016, national guidance has promoted prefabrication and industrialized methods, creating a supportive frame for logistics-aware delivery [5]. Reviews of Chinese prefabrication policy document a large and coherent corpus of measures and link them to measurable outcomes – higher labor productivity, lower material intensity and tangible environmental gains [6–8]. By 2021, the prefabricated share of new floor area reportedly approached a quarter of national additions, signaling that scale effects are possible when policy, industry capacity and logistics align [9].

Digitalization cuts across this terrain but diffuses unevenly. Empirical studies describe persistent heterogeneity in BIM capabilities and collaboration practices within China's AEC ecosystem, with adoption patterns diverging from overseas models [10], even as comparative work finds acceleration post-2016 and broader use in complex public works [11]. Meanwhile, case-based and review literature shows that digital twins linking factory, yard and site can reduce variability by aligning buffers, crane windows and delivery slots; these effects matter most on long in land chains [12–13].

The problem this article addresses is therefore not a lack of technology per se, but logistics disproportions that raise variability inland and blunt the returns to digital tools. The task for the main part is threefold: first, to formalize the inland-coastal gap as a logistics problem grounded in evidence [2–4,10–13]; second, to specify a logistics-first digital agenda-supply-chain BIM, factory-yard-site twins, standardized e-procurement with product-data templates, IoT/TMS visibility, and verifiable payment milestones – drawing on recent research and practice [14–18]; third, to set out a transformation roadmap with operational indicators that owners, contractors and public funders can audit over time [6–9,19–20]. Theremore a shift from growth by scale to growth by coordination, so that information moves faster than trucks and inland projects plan with confidence.

Empirically, logistics disproportions emerge when logistics capacity, performance, and reliability develop much faster in one group of regions than in others that are formally integrated into the same national market. Panel evidence for China's logistics industry confirms persistent east – west and coastal – inland gaps. Using a DEA-based provincial efficiency index for 2007–2018 ye et al. show that many eastern coastal provinces operate close to or even beyond the efficiency frontier, while several inland provinces remain in low-efficiency states despite growing demand [21]. For example, in 2018 the logistics efficiency scores of Shanghai, Jiangsu, Hebei and Guangdong were 1,179, 0,880, 1,006 and 0,947 respectively, whereas inland provinces such as Yunnan, Guizhou and Heilongjiang recorded much lower values of 0,260, 0,360 and 0,425. Across the four macro-regions, the least efficient region has an average logistics efficiency of only 0,476, and provinces with low scores are concentrated in central and western China [21]. This means that the same national market is served by two markedly different logistics systems: a high-efficiency coastal system and a structurally weaker inland system.

At the level of port operations, Li et al. measure the logistics efficiency of 20 Chinese coastal ports in 2014–2018 and find that the Bohai Rim port cluster operates with an adjusted comprehensive efficiency of 0,791, whereas the Southeast coastal cluster reaches only 0.366, with the overall mean for all coastal ports at 0,546 and an average comprehensive efficiency threshold of 0,604 used to distinguish high- and low-performance ports [22]. High-throughput hubs such as Qingdao, Rizhao and Shenzhen keep comprehensive efficiency values above 0,9 throughout the five-year period, while several other ports remain below 0,6, indicating that even within the coastal system there is a pronounced efficiency gradient between mature port clusters and lagging coastal nodes [22].

Digital diagnostics based on composite indices further reinforce this picture of coastal–inland disproportions. Liu and Zhao construct a Smart Logistics Development Index (SLDI) for China's provinces for 2013–2021 and show that the highest relative closeness degrees are concentrated in coastal and eastern provinces such as Guangdong, Beijing, Jiangsu, Zhejiang and Shanghai, while lagging regions include Jilin, Heilongjiang, Hainan and several western and northeastern provinces [23]. In 2021, for example, the SLDI of Tianjin and Hainan reaches only about 14 % of the ideal benchmark, even though both belong to the eastern macro-region [23]. The national Dagum Gini coefficient for SLDI differences exhibits a slow upward trend over 2013–2021, and regional imbalances are driven mainly by the gap between the eastern region and the rest of the country [23]. Thus, even as overall smart logistics capabilities improve, the digitalization gap between the coastal logistics system and the inland system remains large and, in some respects, is still widening.

Synthesized peer-reviewed studies on coastal logistics coordination and BIM/digital-twin adoption in China (2016–2025), triangulate with national policy documents on prefabrication, and reference international contractor rankings for external validity. The review emphasizes operational metrics over narrative claims and favors studies with disclosed datasets or case-traceable methods. Where aggregate numbers vary across sources, quoted the most conservative figures and mark them as "reported by" the original authors.

**Toward a Logistics-Centric Coordinating Architecture**

Evidence from coastal port logistics confirms that such a coordinating architecture works in practice. A four-stage DEA study of China's coastal ports shows that logistics efficiency is highest where port operations, hinterland road and rail connections, and customs processes are planned as one integrated system, and significantly lower where capacity expansion is not matched by process coordination [22]. For inland construction projects, this implies that a logistics-centric architecture should explicitly link site demand, regional freight nodes and digital planning tools. Without such integration, the project remains exposed to structural disproportions: materials may flow smoothly through coastal gateways while last-mile delivery to inland sites remains unreliable, lengthening construction cycles and eroding the economic rationale of investment [21–22].

China's construction performance exhibits a persistent inland-coastal asymmetry that is best understood through the lens of logistics. The concentration of ports and railheads along the coast, together with thicker supplier networks, compresses unit costs and stabilizes flows; but inland corridors are more exposed to weather and holiday shocks and more dependent on road haulage display higher average costs and greater variance. In a sequential industry where downstream tasks inherit upstream delays, such variance functions as a compounding "tax" on schedules and cash flow.

These outcomes reveals manifestations of logistics disproportions – systematic gaps in end-to-end lead-time predictability, in the modal split for heavy modules, and in the stability of payment cycles. Framed this way, digitalization is not an accessory but a coordinating mechanism. Empirical studies show that Building Information Modeling (BIM) produces meaningful gains when it extends beyond geometry to the calendars and hand-offs that govern supply; recent case evidence on digital twins further demonstrates that factories, yards, and sites can be synchronized so buffers become intentional, crane windows align with arrivals, and re-sequencing precedes disruption.

China's construction policy since 2016 has favored prefabrication and industrialized methods, supplying a conducive macro-frame. Yet prefabrication realizes its promise only when product data are standardized, procurement channels are reliable, and multimodal logistics reward rail and water where feasible. Otherwise, components arrive late, are re-handled, or crystallize as inventory that ties up working capital, especially inland.

What follows is a coordinating architecture rather than a collage of tools. For example supply-chain BIM provides a common language in which routings, staging areas, and inspection points live alongside drawings and quantities. Factory-yard-site digital twins render reservations and buffers visible to all parties, enabling proactive re-sequencing. Standardized product data templates embedded in e-procurement reduce technical ambiguity and make demand signals legible earlier. Telemetry and transport management systems keep movements observable and shift the longest leg toward rail or water when conditions allow. Milestone-based payments, grounded in verifiable event time-stamps, align cash with physical progress and lower dispute cycles.

Because coordination is ultimately a governance problem, the architecture presupposes interoperable data schemas, shared identifiers, and open APIs so that platforms can converse across provinces and portfolios. Procurement incentives should be tied to auditable operational indicators on-time delivery, rail/water share of ton-kilometres, re-handling



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reduction, the P90 – P50 spread of delivery windows, and days-sales-outstanding, so that variability is priced and performance is rewarded.

Taken together, these elements move the discussion from growth by scale to growth by coordination. They also set the stage for the SWOT analysis that follows, which distills the sector's assets and frictions, the policy and market openings, and the external threats that will shape the pace and breadth of transition (table 1).

The SWOT analysys compresses a broad evidence base into a single view. Strengths identify assets already in place contractor scale, coastal infrastructure, enabling policy that can be leveraged immediately. Weaknesses point to structural friction inland: a road-heavy mode mix, fragmented supplier bases, and data silos that inflate variance. Opportunities open once data formats are shared and platforms connected: inland hubs become economically attractive, twins shorten cycles in ways visible to financiers and owners, and AI is tethered to real operational choices. Threats remind us that the window is finite. If concentration continues and data regimes fragment, logistics disproportions harden into a long-term productivity gap.

**Table 1** – SWOT: Logistics and Digitalization in China's Construction

| Strengths | Weaknesses |
|---|---|
| Scale in major contractors; dense coastal port/rail networks; policy support for prefabrication and standardization; pockets of mature BIM and PMO practice | Inland dependence on road; fragmented suppliers and data silos; uneven digital skills beyond tier-one hubs; slow diffusion of supply-chain BIM |
| **Opportunities** | **Threats** |
| National e-procurement rails with shared data schemas; inland consolidation hubs; wider use of twins to shorten cycles; AI-assisted risk-aware re-sequencing | Continued coastal concentration; bottlenecks in specialized imports; cybersecurity and data-localization constraints; protectionist headwinds in export markets |

Based on SWOT provided the Transformation Roadmap for Narrowing Logistics Disproportions was developed (table 2).

**Table 2** – Transformation Roadmap for Narrowing Logistics Disproportions

| Measure | Owner(s) | Digital instrument | Target indicator | Horizon |
|---|---|---|---|---|
| National e-procurement rails with product data templates (PDT) and APIs | NDRC/MIIT + provinces + major GCs | E-proc platform + PDT registry | ≥80 % public works by value on-platform; bid variance – 8–12 % | 12–24 months |
| Supply-chain BIM across design – fabrication – logistics | Tier-1 GCs + design institutes + key subs | 4D/5D BIM + logistics calendars | Logistics – related delays – 20–30 % (inland) | 18–30 months |
| Inland consolidation hubs near railheads | Provincial PPPs + fabricators | Twin-enabled yard mgmt + IoT | Rail/water share of prefab ton/km ≥40 % | 24–36 months |
| Sector-wide IoT tracking and TMS | GC alliances + 3PLs | Telemetry + TMS optimizer | On-time delivery ≥95 %; – e-handling – 25 % | 12–18 months |
| Shipment/installation-based payment milestones | Owners + banks + GCs | Smart-contract or attested milestones | DSO – 15 days; disputes cycle – 40 % | 12–24 months |
| AI forecasting for demand spikes and route risks | GC PMOs + platform vendors | ML models + weather/port feeds | P90 schedule variance – 20 %; inventory buffers – 15 % | 9–15 months |
| Skills uplift in inland PMOs and supplier networks | MOE + firms + associations | National curricula + sandboxes | ≥10,000 staff certified in SC-BIM/TMS | 18–30 months |

Thus, the inland hospital scenario that underpins the Transformation Roadmap starts from a baseline in which precast panels are trucked by road from two fabricators, with frequent re-handling on the way to site and a wide gap between the P90 and P50 delivery times. After deploying SC-BIM with integrated logistics calendars, IoT tags on pallets and a rail-fed consolidation hub near the main railhead, the team reschedules deliveries into night windows, shifts the long leg of the journey to rail and links supplier payments to verified on-site installation events. In the roadmap, the percentage ranges assigned to reductions in re-handling, logistics-related delays and the P90 – P50 delivery band are calibrated from this type of scenario and from mid-range effect sizes reported in empirical studies of BIM-enabled and digitally coordinated prefabrication projects, so that the values in the Transformation Roadmap represent realistic, evidence-based targets rather than arbitrary assumptions. The same stepwise bundle of interventions and effects can then be transferred to schools and mid-rise housing projects, with numerical targets adjusted to their typical volumes and cycle times.

A well-documented example of narrowing logistics disproportions through digital tools comes from the emergency modular hospitals built during the COVID-19 outbreak in Wuhan. The Leishenshan Hospital, for instance, was designed, built and commissioned in about twelve days using a combination of modular construction, 24/7 supply operations and intensive reliance on building information modelling (BIM) for product – organization – process coordination [25]. In this project, BIM models and digital platforms were used not only to coordinate on-site assembly, but also to synchronise off-site manufacturing, transport slots and just-in-time delivery of prefabricated modules. This effectively transformed a potentially chaotic, multi-regional logistics chain into a tightly orchestrated system, reducing on-site congestion, rework and idle time. For inland construction projects facing chronic logistics disproportions, the lesson is that similar digital coordination of modular production, transport and site operations can dramatically compress construction time and stabilise supply flows, even when regional logistics infrastructure is uneven [24–25].

The transformation roadmap is a contract with time. Each row assigns responsibility, specifies the digital instrument, and proposes indicators that are operational and auditable. The sequencing is intentional: early wins in e-procurement data hygiene and IoT/TMS visibility arrive within 12–18 months, while heavier investments such as inland hubs require longer horizons. Read horizontally, each measure describes an organizational bet a change in how information moves, how risk is priced, and how work is sequenced. Read vertically, the table becomes a ladder for narrowing logistics disproportions in a way that is visible in monthly reports and credible to public funders.

For large construction programmes that depend on national or cross-regional supply chains, the roadmap can be calibrated not only in terms of milestones, but also in terms of target ranges for logistics disproportions. In analytical terms this means translating location-based and efficiency-based indicators – such as provincial logistics efficiency scores and smart logistics development indices – into simple thresholds that define acceptable and critical levels of disproportions for the project [21, 23]. Digitally, these targets can be embedded into dashboards that track, for example, the gap between coastal and inland delivery lead times, the dispersion of logistics efficiency scores across the project's key regions, or the spread between best- and worst-performing nodes in the construction supply network. When a threshold is breached, the roadmap treats it as a formal risk event, triggering predefined responses: re-routing flows, adjusting construction sequencing, or accelerating the deployment of digital tools in lagging regions [24].

**Limitations and further research**. This synthesis relies on secondary sources and sectoral case studies; inland heterogeneity within provinces and firm-level capability gaps require primary data. Future work should (i) publish open lead-time datasets for inland corridors, (ii) test PDT-based e-procurement in public works, and (iii) evaluate the causal impact of rail-hub deployment on re-handling and DSO at project scale.

**Conclusion**

The emergency hospital case and international evidence on BIM-enabled prefabrication show that double-digit reductions in logistics-related delays and re-handling are realistic when these instruments are combined, not used in isolation. In sum, Chinese evidence confirms that logistics disproportions are structurally embedded in the spatial organisation of the construction supply chain, but also shows that they can be deliberately narrowed when logistics is treated as a core design variable and supported by targeted digital tools – from smart logistics indices and DEA-based diagnostics to BIM-enabled coordination of off-site and on-site processes.

The contribution of this article, building on the original paper's diagnosis of coastal dominance and digital asymmetry, is to reframe China's regional construction gap as a logistics disproportions problem and then treat digitalization not as ornament but as the operating system for coordination. What is different here is the center of gravity. Instead of chasing scale effects project by project, the argument moves upstream to the flows that make projects predictable: access to modes and nodes, supplier depth, and shared data. It replaces project-centric BIM with supply-chain BIM that models routes, staging areas and fabrication slots; it expands "site optimization" into factory-yard-site twins; it swaps ad hoc purchasing for platform e-procurement with product data templates; it hard-wires movement with IoT/TMS visibility and replaces paper-based trust with verifiable milestones; it adds inland consolidation hubs so the longest leg defaults to rail or water. Equally important, it insists on incentives that pay for reduced variability and on interoperable schemas so platforms can talk across provinces. In short, the difference is a shift from growth-by-scale to growth-by-coordination, measured by logistics and cash-flow realities rather than slogans. The proposed roadmap translates this gap into six measurable targets (e-procurement share, delay reduction, rail/water share, re-handling, on-time delivery, DSO), each linked to digital instruments and owners

What this enables is a practical climbdown in uncertainty that inland projects feel first. Lead times become forecastable, buffers become intentional, and the default mode mix tilts toward rail and waterways; re-handling and damage claims fall; crews, cranes and trucks idle less; days-sales-outstanding shortens because payments travel with shipments and installations; suppliers inland gain repeatable demand and can invest in capability; owners see fewer change orders because product data is stable end-to-end. Prefabrication stops being a promise and starts penciling out, since information begins to outrun trucks. The same data spine that coordinates work also lifts transparency and ESG traceability in procurement, lowers dispute costs, and gives public funders auditable KPIs – on-time delivery, rail/water share of ton-kilometers, re-handling reduction, DSO – that travel cleanly into monthly reports. At sector scale, the payoff is resilience: when weather, holidays or external shocks arrive, re-sequencing is a rule, not a scramble. And because the playbook is about flows and standards rather than a single technology, it is replicable across provinces and export markets, turning international openness from a centripetal force that concentrates advantage at the coast into a coordinating force that spreads capability nationwide.

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# THE PARTICULARITIES OF INFORMATION EXCHANGE BETWEEN PARTICIPANTS DURING THE ORGANIZATION OF SUPPLY CHAINS IN RAILWAY TRANSPORT

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**Abstract**

The article formulates the principles of information exchange between participants of supply chains during the organization of railway freight transportation. In the research, the features of supply chains organization in railway transport were initially determined and their typology was substantiated. Consideration of supply chains in the sphere of railway transportation established the need to change the constituent and substantive elements of the extended and maximum chains, and at the same time determined the formation of a specific approach to determining the composition of the main links and areas of data exchange. In contrast to the classical understanding, in the proposed typology, an extended supply chain is formed from a simple one by including in its composition logistics, information and financial intermediaries, as well as other market entities, which is standardly provided for by the maximum supply chain.

Taking into account the established specifics, the participants in supply chains were further determined when organizing railway transportation in domestic and international traffic (reflecting options for both direct and extended supply chains), as well as with the participation of the carrier in intermodal transportation (as an example of building a maximum supply chain). The principles of information interaction of participants (shippers, consignees, cargo owners, freight forwarding organizations, financial organizations, government agencies, shipping line operators and road carriers) within the framework of the formed material, digital and financial flows with the organization of corresponding models were formulated. In conclusion, it was established that the scale of the established cooperation with each of the participants in the supply chain directly depends on the type of transportation and the adopted work technology.

**Keywords:** supply chains, railway transport, extended and maximal chains, information interaction, data exchange.

## ОСОБЕННОСТИ ИНФОРМАЦИОННОГО ВЗАИМОДЕЙСТВИЯ УЧАСТНИКОВ ПРИ ПОСТРОЕНИИ ЦЕПЕЙ ПОСТАВОК НА ЖЕЛЕЗНОДОРОЖНОМ ТРАНСПОРТЕ

**А. А. Хорошевич**

**Реферат**

В статье сформулированы основы информационного взаимодействия участников цепей поставок при организации железнодорожных грузовых перевозок. В рамках проведенного исследования первоначально определены особенности построения цепей поставок на железнодорожном транспорте и обоснована их типология. Рассмотрение цепей поставок в плоскости железнодорожных перевозок установило необходимость изменения составляющих и содержательных элементов расширенной и максимальной цепей поставок и одновременно обусловило формирование специфического подхода к определению состава их основных звеньев и областей обмена данными. В отличие от классического понимания в предложенной типологии расширенная цепь поставок формируется из простой включением в ее состав логистических, информационных и финансовых посредников, а также иных рыночных субъектов, что стандартно предусматривает максимальная цепочка поставок.

С учетом установленной специфики в дальнейшем определены участники цепей поставок при организации железнодорожных перевозок во внутриреспубликанском и международном сообщении (с отражением вариантов как для прямой цепи поставок, так и для расширенной), а также при участии перевозчика в интермодальных перевозках (в качестве примера построения максимальной цепи поставок). Сформулированы основы информационного взаимодействия участников (грузоотправителей, грузополучателей, грузовладельцев, экспедиторских организаций, финансовых организаций, органов государственного управления, операторов морских линий и автомобильных перевозчиков) в рамках формируемых материальных, цифровых и финансовых потоков с построением соотвествивующих моделей. В завершении установлено, что масштаб устанавливаемого сотрудничества с каждым из участников цепи поставок напрямую зависит от типа перевозки и принятой технологии работы.

**Ключевые слова:** цепи поставок, железнодорожный транспорт, расширенные и максимальные цепи, информационное взаимодействие, обмен данными.

### Introduction

Building supply chains in the modern conditions of development of the global market of transport and logistics services, characterized by high instability and a significant level of competition, requires a competent approach to determining the composition of participants and establishing their information interaction. High-quality data exchange between all participants in the supply chain, including in the volume of shipping and shipping documents, helps to speed up the transportation process and reduce the labor intensity of a number of operations by ensuring the completeness of the transmitted information.

The noted advantages determine the high relevance of the formation of the most complete information interaction within the organization of railway transportation, which is possible only with the initial establishment of conjugation points and key areas of data exchange. Taking into account the above, the main goal of the study was to determine the basics of information interaction of supply chain participants in the organization of railway freight transportation in various variations.

### Organization of supply chains in railway transport

Researchers (including R. B. Ivut [1, 2], I. A. Elovoy [3], V. I. Sergeev [4, 5], V. V. Dybskaya [6], E. R. Abramova [7], A. P. Tyapukhin [8], O. M. Kulikova [9], C. Harland [10], Zh. Chen, N. G. Hall [11], etc.) have addressed the issues of evolution and identification of determinants of development of the supply chain management concept. Have been paying attention to for over twenty years. Considering various areas of supply chain organization, these researchers came to the conclusion that a supply chain is: a) a network of interconnected and interdependent organizations that jointly control, manage and improve flows from suppliers to end consumers [12, p. 14; 13, p. 101;]; b) an ordered sequence of interacting links managed by participants that perform various functions during the passage of flows from the source of origin to the point of repayment [14, p. 25; 15, p. 23; 16, p. 39].

Within the framework of the functioning of railway transport, the supply chain should be interpreted as a set of interacting links that ensure the flow of goods, services and information from the consignor to the consignee [17, p. 104; 18, p. 126]. A supply chain link can be represented by both individual organizations and divisions, processes, technologies and activities involved in promoting the flow.

In the process of building supply chains, depending on the composition of the main links, they are formed within one of three types: direct, extended or maximum. In general terms, a direct supply chain consists of a focal company, a first-level supplier (cargo owner) and a first-level consumer (cargo owner) who participate in the external and internal flows of goods, information and finance. An extended supply chain additionally includes second-level suppliers and consumers. A maximal supply chain consists of a focal company and all participants in the chain from material suppliers to end consumers, as well as logistics and other intermediaries (agents) [19, p. 11–12; 20, p. 28–29].

In the context of the functioning of railway transport, the use of this classification and approach to distinguishing between participants in supply chains is significantly complicated. Taking into account the specifics of freight railway transportation, it would be more correct to use the typology presented in Figure 1.

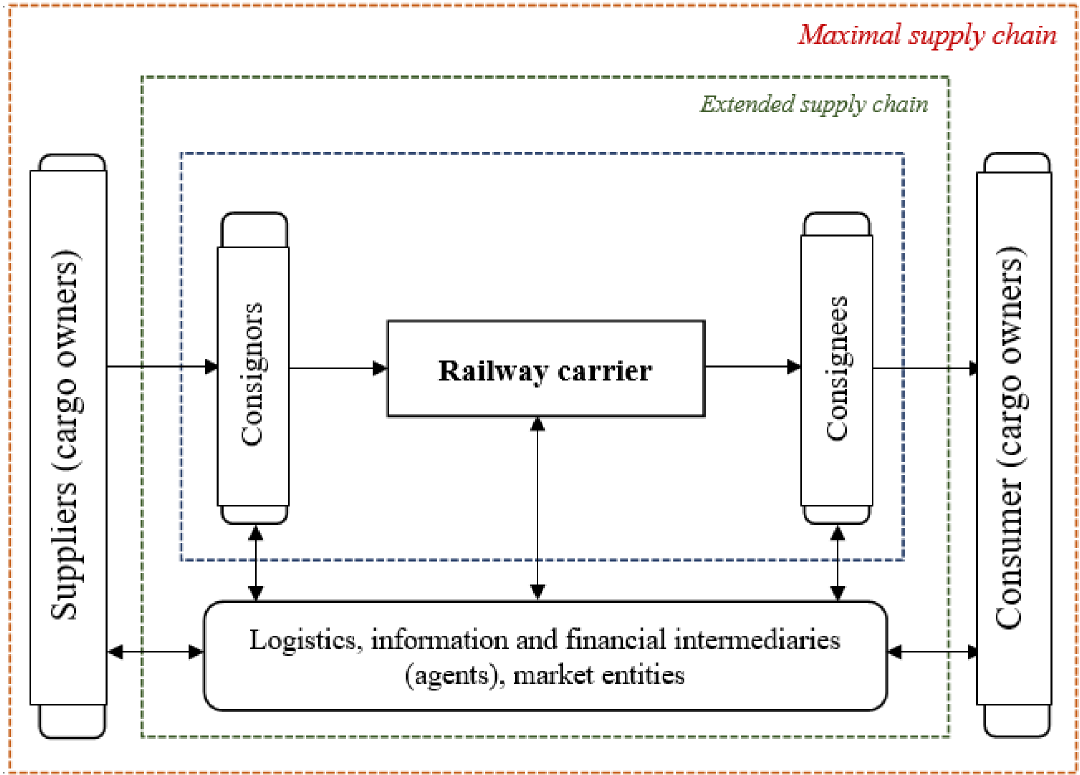


**Figure 1** – Typology of supply chains in railway transport

In contrast to the typology used in the scientific literature, within the framework of supply chains in railway transport, it is necessary to change the constituent and substantive elements of the extended and maximum chains. Thus, if in the classical sense modern researchers characterize the extended supply chain as a set of a focal company and suppliers and consumers of the first and second levels, then in the noted typology, the extended supply chain differs from the simple one by the inclusion of logistics, information and financial intermediaries, as well as other market entities – which is standardly provided for only by the maximum supply chain. This substitution of concepts is made due to the specifics of the industry under consideration and more frequent and necessary interaction of railway carriers with various types of logistics and financial intermediaries. Expansion of the supply chain to suppliers and consumers (for the classical theory of suppliers and consumers of the second and subsequent levels) simultaneously allows us to talk about the organization of a maximum supply chain, characterized by increased transparency and flexibility.

Effective supply chain management in this context involves the formation of a cooperation option within which, when building a maximum supply chain, all first-order relationships (relationships of the railway organization with shippers, consignees and intermediaries) for the railway carrier are manageable, and all second-order relationships (relationships of shippers with suppliers (cargo owners), consignees with consumers (cargo owners), as well as relationships of shippers, consignees and cargo owners with intermediaries) are tracked. Taking into account the above, it can be concluded that successful supply chain management is impossible without the formation and subsequent maintenance of high-quality information interaction between a wide range of participants, the key ones of which are:

- shippers;
- consignees;
- freight forwarding organizations at each of the sections of the route (if the route passes through the territory of several transit countries, freight forwarding companies will be involved in each of them);
- sea line operators and road carriers (when organization intermodal cargo transportation);
- customs declarants involved by consignors and consignees to perform customs operations;
- cargo owners (parties to the purchase and sale agreement when organizing transportation with the involvement of intermediary companies and container terminals);
- financial organizations;
- government bodies (including customs authorities).

When building a supply chain, flows of goods, information and finances are formed between its participants, as well as corresponding return flows. The completeness of data exchange within the formed flows is largely determined by the initially established level of information interaction and the quality of the established connections.


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**Information exchange between the participants during the organization of supply chains**

The level of information interaction between participants in supply chains when organizing freight railway transportation, as well as their composition, is largely determined by the nature of the transportation. Thus, when organizing intra-republican transportation in the classical version, there will be actual interaction between three direct participants in the transportation (consignor, consignee and railway carrier) and additional participation of financial organizations in the framework of ensuring payment for services (Figure 2).

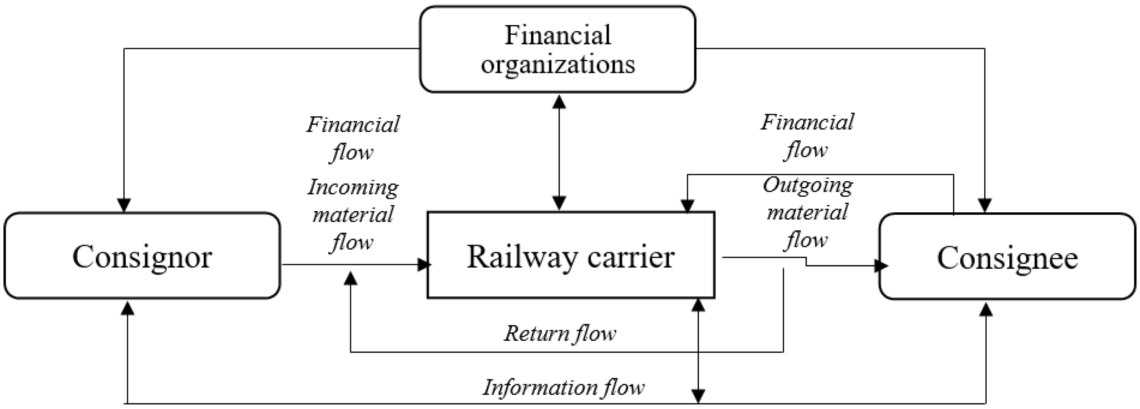


**Figure 2** – Data flows within the framework of the classic variant of intra-republican railway transportation (direct supply chain)

As can be clearly seen, data flows within the classical version of organizing intra-republican railway transportation are evenly distributed between all participants in the transportation and actually provide for the organization of a direct supply chain. In this case, the incoming material flow is formed from the consignor to the railway carrier, and the outgoing material flow comes from the carrier. Financial flows are simultaneously directed to the railway carrier, both from the consignor and from the consignee.

The information flow of data accompanies both the material and financial flows. Thus, within the material flow, information is transferred in the volume of the railway bill and shipping documents, as well as key data characterizing the transportation and movement of the train along the route. Information support of the financial flow consists of the formation and provision of the necessary documentation (invoices and certificates of completion) and tracking the timeliness and completeness of the transactions carried out.

In this case, the information interaction between the railway organization and consignors, consignees and financial intermediaries necessarily requires the inclusion of the following areas:

- exchange of primary data and documents with consignors and consignees;
- interaction with consignors and consignees within the framework of transportation and formation of material and financial flows;
- interaction of the carrier with financial organizations within the framework of execution and documentary registration of financial transactions.

Thus, the organization of freight railway transportation in intra-republican traffic provides for the establishment of the simplest relationships based on cooperation between the railway organization and consignors and consignees. In this case, standard information systems and typical work technology are used as part of the technological support for data exchange.

The organization of international freight transportation provides for the development of a system of interaction and information linking of the carrier in addition to the above option with freight forwarding companies and customs authorities. Data flows generated during the organization of international railway transportation are presented in Figure 3.

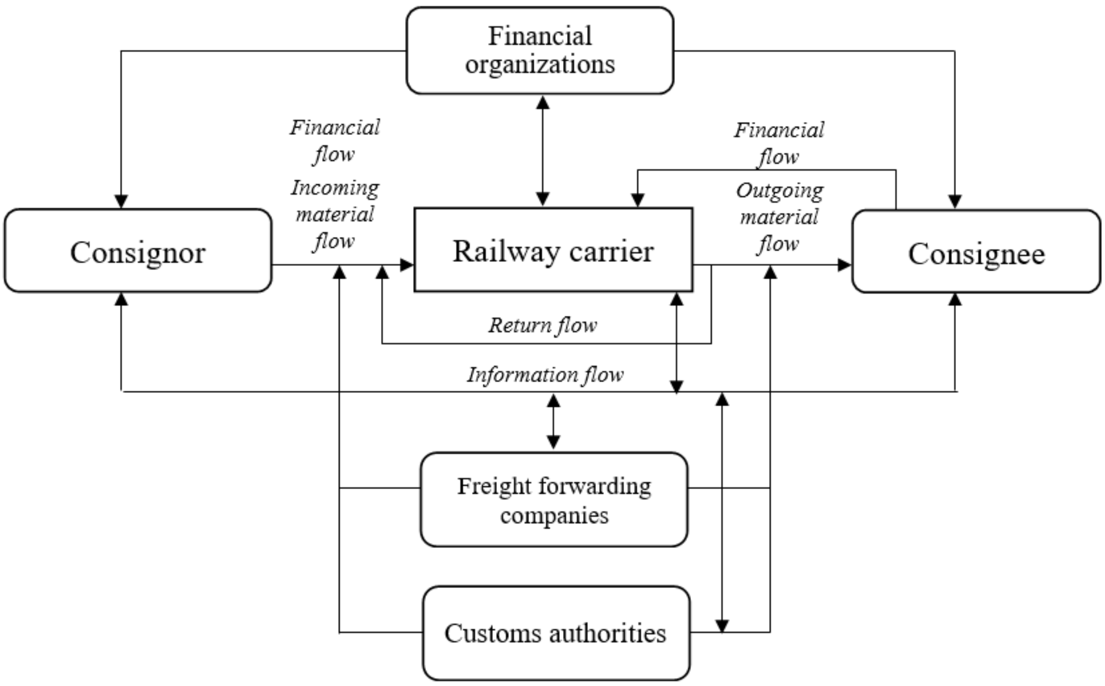


**Figure 3** – Data flows generated in international railway transportation with a small number of participants (extended supply chain)


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In this option, the railway organization, along with consignors and consignees, ensures interaction with freight forwarding companies and customs authorities included in the general information flow. In this case, the key areas of the established information interaction are:

• data and document exchange with other railway carriers, consignors, consignees and freight forwarding companies in the volume of shipping, accompanying and other documents;

• interaction with consignors, consignees at the stage of concluding transportation contracts, as well as with freight forwarders within the framework of transportation;

• interaction with customs authorities within the framework of customs operations and financial companies within the boundaries of financial transactions. Simultaneously with the organization of a common information flow, the organization of international transportation requires the carrier to build a financial flow in a new format, which provides for the inclusion of forwarders acting as the main payers under the transportation contract when traveling through the territory of transit countries, and also (if necessary) on the side of the consignee.

An important feature of this option is the need for the interconnection of information flows between all railway carriers participating in the transportation of goods. At the same time, the degree of coordination in the work between such participants should have the highest level within the framework of all types of flows (material, financial and information).

At the same time, the organization of international freight railway transportation often requires the involvement of additional participants and the corresponding organization of a maximum supply chain. Data flows in this case will take the following form (Figure 4).

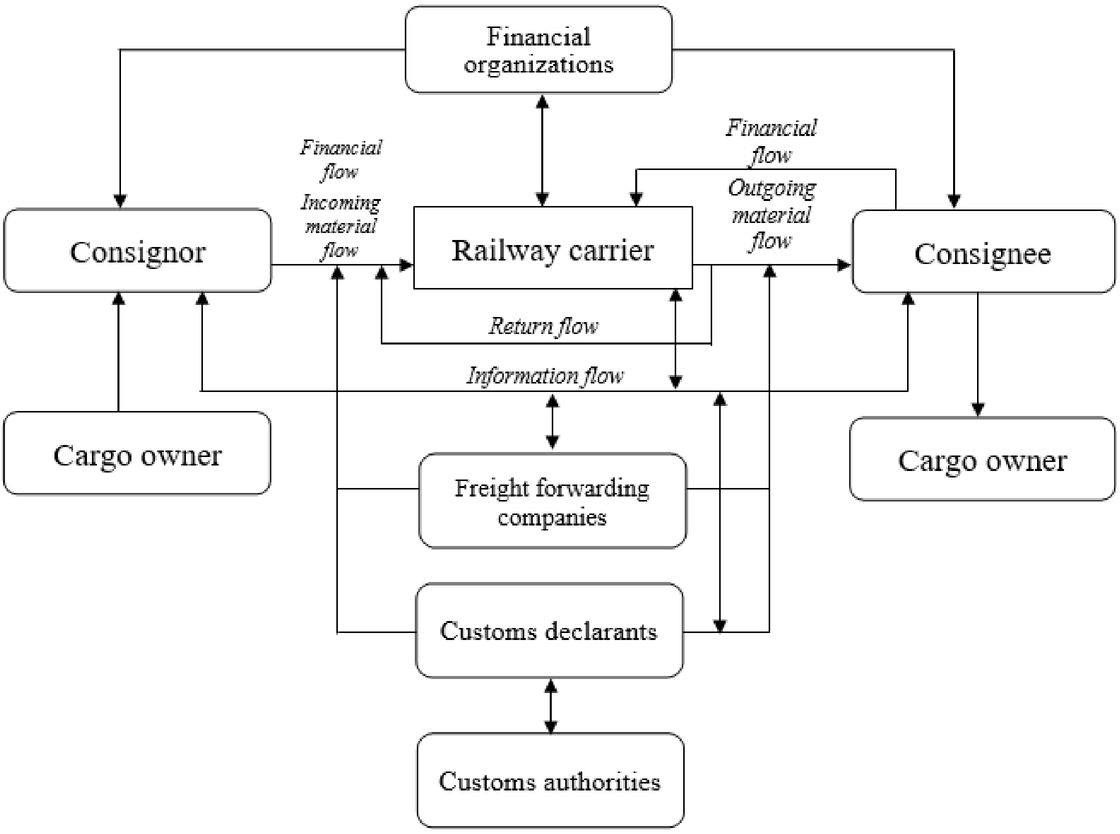


**Figure 4** – Data flows within the framework of the organization of international railway freight transportation when building a maximum supply chain

When organization a maximum supply chain, its participants are supplemented by suppliers and consumers who are the actual owners of the goods at the initial and final points, as well as customs declarants. The organization of high-quality information interaction in this version provides for:

• data and document exchange with other carriers, consignors, consignees and forwarders in the volume of shipping, accompanying and other documents, as well as interaction between consignors, consignees and cargo owners;

• interaction with consignors, consignees at the stage of concluding transportation contracts, as well as with forwarders within the framework of transportation;

• interaction with financial companies within the framework of registration of financial transactions and with customs declarants within the boundaries of receiving information and completing customs procedures.

Thus, when building a maximum supply chain, interaction should be ensured at two levels: at the first level - data exchange between the carrier and other administrations, consignors, consignees and forwarders, and at the second level – the formation of relationships between consignors and consignees with cargo owners. Communication with customs authorities is simultaneously provided through customs declarants who ensure the implementation of customs operations.

The last and most extensive interaction option is the option in which the organization of a maximum supply chain is carried out within the framework of organizing intermodal transportation. Data flows in this case will be as follows (Figure 5).

The main distinguishing feature of the presented option is the inclusion of sea line operators and/or road carriers in the composition of the supply chain participants. Information interaction when organizing international intermodal transportation involves the inclusion of the following key areas:

• data and document exchange with other carriers (sea line operators and/or road carriers, as well as railway organizations) in the volume of the SMGS consignment note, shipping and permitting documents;

• interaction with freight forwarders within the framework of transportation, as well as with consignors and consignees – at the beginning or end of transportation within the framework of railway transport;

• interaction with financial companies within the framework of financial transactions and with customs declarants within the boundaries of receiving information and completing customs procedures.

Organization of interaction within the framework of execution and transfer of transport and accompanying documents in this case is provided with carriers participating in the supply chain on an equal basis with the railway organization. Direct cooperation with consignors and/or consignees is practically not observed, while interaction with forwarding companies is maintained.



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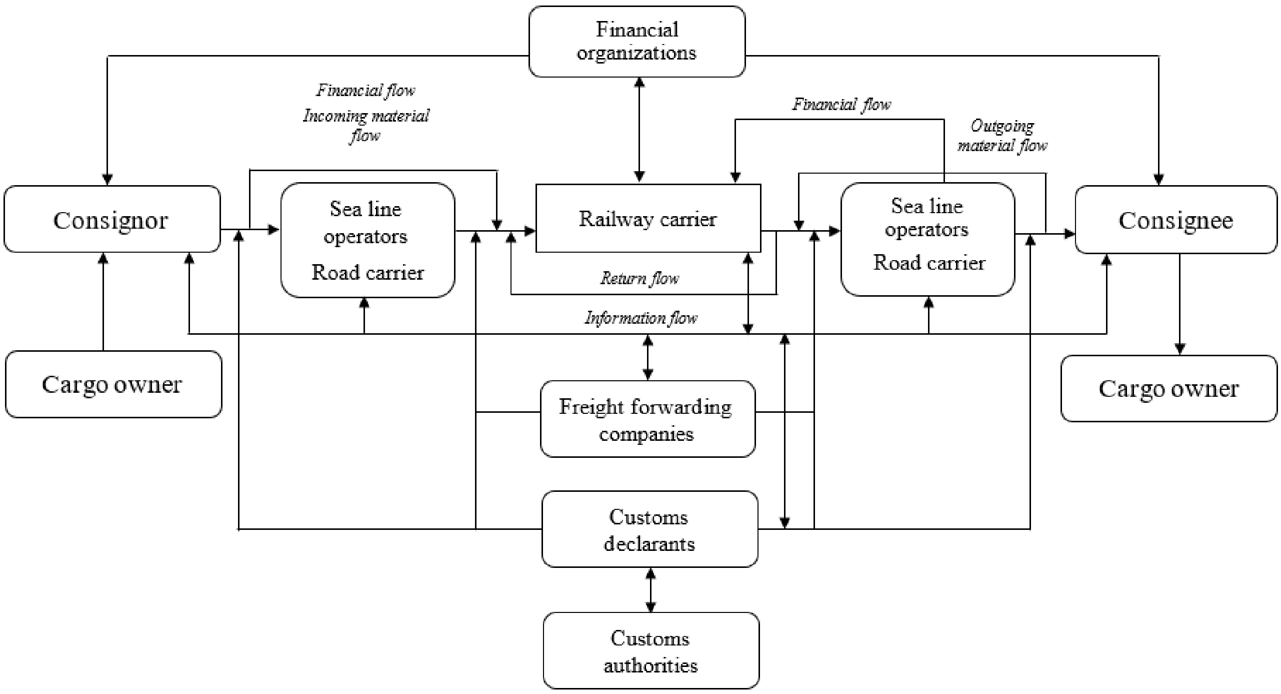


**Figure 5** – Data flows during the organization of maximum supply chain within the framework of intermodal international transportation involving railway transport

**Conclusion**

Thus, for effective supply chain management in modern conditions, it is necessary to form and maintain relationships with all participants in the transportation process, ensuring high-quality information interaction. Key participants in supply chains in railway transport are: consignors and consignees (cargo owners when organizing transportation using intermediary companies), freight forwarding organizations, financial organizations, government agencies (including customs authorities), operators of shipping lines and road carriers (when organizing intermodal transportation of goods), etc.

A distinctive feature of building supply chains in railway transport is the change in the constituent and substantive elements of the extended and maximum chains, which requires a specific approach to determining the areas of data exchange. The scale of the established information cooperation with each participant in the supply chain directly depends on the type of transportation and the adopted technology of work.

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# USING ARTIFICIAL INTELLIGENCE TECHNOLOGY IN PRODUCT PROMOTION

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**Abstract**

The article is dedicated to a comprehensive analysis of the application of artificial intelligence (AI) technologies in product promotion, with a focus on economic and ethical aspects. The relevance of the research is driven by the rapid digitalization of the economy and the need for a scientific understanding of the transformation of traditional marketing practices under the influence of AI.

The study employs a systematic approach, combining a comparative analysis of international and Russian cases, economic-statistical methods for evaluating effectiveness, and expert assessment of the ethical aspects of AI implementation. The research covers key AI technologies, including machine learning, natural language processing, and big data analytics, and their impact on marketing processes.

The main findings of the study indicate significant economic benefits from AI adoption, including a 25–40 % reduction in operational costs through the automation of routine processes, a 15–30 % improvement in targeting accuracy and conversion rates, and a 35–50 % increase in marketing campaign ROI. AI-powered solutions enable customer segmentation, churn prediction, the creation of recommendation systems, and real-time analysis of consumer feedback.

However, the implementation of AI is associated with substantial ethical and economic risks. The primary challenges include a loss of consumer trust due to non-transparent AI use, risks of discrimination stemming from algorithmic bias, and high barriers to entry for small businesses. Research shows that explicitly mentioning the use of AI in product descriptions can reduce consumer purchase intention by 10–15 %.

Based on the analysis of global and Russian cases, the article offers practical recommendations. These include implementing ethical standards for AI use in marketing, developing industry-wide regulations for algorithm transparency, and ensuring government support for small businesses in their digital transformation. Successful case studies from companies like Coca-Cola and Nike demonstrate that transparent AI practices can increase sales by 25 % and boost customer engagement by 30 %.

The scientific and practical significance of the work lies in the development of a comprehensive approach to balancing economic efficiency and ethical standards in AI-driven marketing practices. The research findings are valuable for developers of marketing strategies in the digital age, digital economy regulators, and researchers in the fields of business ethics and digitalization.

Prospects for further research are linked to studying the long-term effects of AI on consumer behavior, regional specifics of AI technology adaptation in marketing, and the relationship between algorithm transparency and customer loyalty.

**Keywords:** artificial Intelligence, marketing, product promotion, economic impact, machine learning, natural language processing, big data analytics, consumer trust, data privacy, ethical challenges, competitiveness, market growth.

## ИСПОЛЬЗОВАНИЕ ТЕХНОЛОГИИ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА В ПРОДВИЖЕНИИ ПРОДУКЦИИ

**А. Н. Лабкович**

**Реферат**

Статья посвящена комплексному анализу применения технологий искусственного интеллекта в сфере продвижения продукции с акцентом на экономические и этические аспекты. Актуальность исследования обусловлена стремительной цифровизацией экономики и необходимостью научного осмысления трансформации традиционных маркетинговых практик под влиянием ИИ.

В работе использован системный подход, сочетающий сравнительный анализ международных, российских и белорусских кейсов, экономико-статистические методы оценки эффективности и экспертную оценку этических аспектов внедрения ИИ. Исследование охватывает ключевые технологии ИИ, включая машинное обучение, обработку естественного языка и анализ больших данных, и их влияние на маркетинговые процессы.

Основные результаты исследования свидетельствуют о значительных экономических преимуществах внедрения ИИ, включая снижение операционных затрат на 25–40 % за счет автоматизации рутинных процессов, повышение точности таргетирования и рост конверсии на 15–30 %, а также увеличение ROI маркетинговых кампаний на 35–50 %. Технологические решения на основе ИИ позволяют осуществлять сегментацию клиентов, прогнозирование оттока, создание систем рекомендаций и анализ потребительских отзывов в реальном времени.

Однако внедрение ИИ сопряжено с существенными этическими и экономическими рисками. К основным вызовам относятся снижение потребительского доверия при непрозрачном использовании ИИ, риски дискриминации из-за предвзятости алгоритмов, а также высокие барьеры входа для малого бизнеса. Исследования показывают, что явное упоминание использования ИИ в описании продуктов может снижать намерения потребителей к покупке на 10–15 %.

На основе анализа глобальных и российских кейсов предлагаются практические рекомендации, включающие внедрение этических стандартов использования ИИ в маркетинге, разработку отраслевых нормативов прозрачности алгоритмов и обеспечение государственной поддержки малых предприятий в цифровой трансформации. Успешные примеры компаний Coca-Cola и Nike демонстрируют, что прозрачные ИИ-практики могут увеличивать продажи на 25 % и повышать вовлеченность клиентов на 30 %.

Научная и практическая значимость работы заключается в разработке комплексного подхода к балансированию экономической эффективности и этических стандартов в маркетинговых практиках, основанных на ИИ. Результаты исследования представляют ценность для разработчиков маркетинговых стратегий цифровой эпохи, регуляторов цифровой экономики и исследователей в области бизнес-этики и цифровизации.

Перспективы дальнейших исследований связаны с изучением долгосрочных эффектов влияния ИИ на потребительское поведение, региональных особенностей адаптации ИИ-технологий в маркетинге и взаимосвязи между прозрачностью алгоритмов и лояльностью потребителей.

**Ключевые слова:** искусственный интеллект, маркетинг, продвижение продукции, экономическое воздействие, машинное обучение, обработка естественного языка, анализ больших данных, доверие потребителей, конфиденциальность данных, этические вызовы, конкурентоспособность, рост рынка.

**Report**

The article is dedicated to a comprehensive analysis of the application of artificial intelligence technologies in product promotion, with a focus on economic and ethical aspects. The relevance of the study is underscored by the rapid digitalization of the economy and the necessity for a scholarly understanding of the transformation of traditional marketing practices under the influence of AI.

A systematic approach has been employed in this research, combining comparative analysis of international and Russian cases, economic and statistical methods for assessing effectiveness, and expert evaluation of the ethical implications of AI implementation. The study encompasses key AI technologies, including machine learning, natural language processing, and big data analytics, and their impact on marketing processes.

The main findings of the research indicate significant economic advantages associated with the adoption of AI, including a reduction in operational costs by 25–40 % due to the automation of routine processes, an increase in targeting accuracy, and a growth in conversion rates by 15–30 %, as well as a 35–50 % increase in the ROI of marketing campaigns. AI-based technological solutions enable customer segmentation, churn prediction, the creation of recommendation systems, and real-time analysis of consumer feedback.

However, the implementation of AI is accompanied by substantial ethical and economic risks. Key challenges include a decline in consumer trust due to opaque AI usage, discrimination risks stemming from algorithmic biases, and high entry barriers for small businesses. Research indicates that explicit mention of AI usage in product descriptions can reduce consumer purchase intentions by 10–15 %.

Based on the analysis of global and Russian cases, practical recommendations are proposed, including the establishment of ethical standards for AI use in marketing, the development of industry regulations for algorithmic transparency, and the provision of government support for small enterprises in their digital transformation. Successful examples from companies like Coca-Cola and Nike demonstrate that transparent AI practices can increase sales by 25 % and enhance customer engagement by 30 %.

The scientific and practical significance of this work lies in the development of a comprehensive approach to balancing economic efficiency with ethical standards in AI-based marketing practices. The results of this study hold value for developers of marketing strategies in the digital age, regulators of the digital economy, and researchers in the fields of business ethics and digitalization.

Future research prospects are associated with examining the long-term effects of AI on consumer behavior, regional characteristics of AI technology adaptation in marketing, and the relationship between algorithmic transparency and consumer loyalty.

***Introduction***

Artificial intelligence (AI) has emerged as a key factor in the transformation of marketing processes, particularly in product promotion. In marketing, AI encompasses a set of technologies, including machine learning algorithms, natural language processing, and big data analytics, which facilitate the analysis of consumer data, prediction of customer behavior, and automation of marketing tasks. These technologies enable the development of effective and personalized promotional strategies, contributing to the growth of the AI market in marketing. By 2025, the utilization of AI has become essential for the successful operation of companies in the digital environment.

From an economic perspective, AI offers significant advantages, including reduced operational costs, increased return on investment, and enhanced competitiveness. The automation of tasks and precise targeting optimize marketing budgets, allowing companies to achieve higher results at lower costs. However, the implementation of AI is accompanied by challenges, such as high initial investments, the need for workforce retraining, and ethical concerns, including data privacy and consumer trust. These aspects necessitate a balanced approach to maximize benefits while minimizing risks.

From a macroeconomic standpoint, AI contributes to global economic growth by stimulating productivity and innovation. In marketing, microeconomic effects are manifested in improved process efficiency and enhanced customer experience, which strengthen the market positions of companies. At the same time, the uneven distribution of access to technologies highlights the need for regulatory measures to ensure fairness.

The objective of this article is to analyze the use of AI in product promotion. The first chapter examines the theoretical foundations of AI application, including key technologies and their evolution. The second chapter analyzes practical examples of AI implementation in global and Russian markets and their economic effects, addressing issues of trust, privacy, and technology accessibility, along with recommendations for overcoming these challenges. The article aims to identify the optimal balance between economic efficiency and ethical standards in the use of AI.

**Economic and Ethical Aspects of Artificial Intelligence Application in Product Promotion**

Artificial intelligence (AI) has become a key factor in the transformation of marketing processes, especially in product promotion. In the context of marketing, AI represents a set of technologies, including machine learning algorithms, natural language processing, and big data analytics, which are used for analyzing consumer data, predicting customer behavior, and automating marketing tasks [2]. These technologies enable companies to develop more effective and personalized promotional strategies, significantly contributing to the growth of the AI market in marketing [15]. Research indicates that by 2025, the use of AI has evolved from being merely a competitive advantage to a necessity for successful operation in the digital environment [2].

Contemporary marketing strategies rely on several key AI technologies that ensure their effectiveness:

**Machine Learning (ML):** ML algorithms analyze large volumes of data to identify patterns and predict consumer behavior. In marketing, ML is applied for customer segmentation, churn prediction, and creating recommendation systems, allowing for precise campaign adjustments.

**Natural Language Processing (NLP):** NLP is utilized for analyzing textual data, such as customer reviews, and for creating chatbots that facilitate real-time consumer interaction. This enhances customer experience and increases engagement [5].

**Big Data Analytics:** The ability to process and interpret vast amounts of data enables marketers to identify market trends, analyze consumer behavior, and make informed decisions to optimize product promotion [15].

These technologies form the foundation for AI application in marketing processes, providing high accuracy and adaptability of strategies.

The evolution of AI application in marketing has gone through three main stages: the initial adoption phase (2000–2010), mass implementation (2010–2020), and integration with knowledge management systems (2020 – present) [2]. At each stage, AI has increasingly integrated into marketing processes, facilitating the transition from traditional mass marketing to hyper-personalization, where each interaction with the customer is tailored to their individual needs [10]. According to Marvi et al. (2025), the integration of AI with knowledge management systems allows companies not only to analyze data but also to create intelligent systems that anticipate customer needs [2]. Modern marketing strategies utilizing AI encompass four key areas: customer relationship management, advertising, pricing, and product development. In particular, customer relationship management is significantly enhanced through AI, leading to increased engagement and customer retention [7]. This evolution underscores AI's ability to respond promptly to changes in consumer behavior and market conditions [3].

From an economic perspective, the use of AI in product promotion provides companies with significant advantages. Ding and Goldfarb (2023) note that AI enhances the efficiency of advertising expenditures, improves customer segmentation, and increases conversion rates by optimizing targeting and reducing wastage in campaigns. For example, the automation of routine tasks, such as content creation and data analysis, lowers operational costs and allows marketers to focus on strategic planning [15]. Additionally, AI provides a competitive advantage by enabling companies to adapt more quickly to market changes and gain deeper insights [15]. However, the implementation of AI is accompanied by several limitations. High costs associated with the development, integration, and maintenance of AI systems can pose barriers for small and medium-sized enterprises. Data privacy concerns and the risks of algorithmic bias also present significant challenges, necessitating compliance with regulatory requirements such as GDPR [11]. Research shows that explicit mention of AI use in product descriptions can reduce consumer purchase intentions, highlighting the need for a cautious approach to communication [8]. Furthermore, the effectiveness of AI models depends on data quality, and poor data quality can lead to inaccurate predictions and decreased campaign efficiency [5].


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From a macroeconomic perspective, AI has a significant impact on the global economy by fostering productivity and innovation. Acemoglu (2025) estimates that AI could contribute approximately 1 % to global GDP growth each decade, with substantial variations across sectors [12]. In the context of marketing, microeconomic benefits manifest in enhanced productivity and optimized customer interaction processes [15]. However, the implementation of AI may lead to an uneven distribution of economic benefits, necessitating new regulatory approaches to ensure equitable access to technologies [12]. These aspects underscore the importance of integrating AI into marketing while considering both economic and social consequences [16].

The theoretical foundations of AI application in marketing demonstrate its potential to transform product promotion through personalization, targeting, and campaign optimization. Economic benefits, such as increased efficiency and return on investment, make AI an essential tool for companies seeking to strengthen their market positions. However, high costs, privacy concerns, and risks of bias require a careful approach to AI implementation. Additionally, research points to future trends, such as further integration of AI with other technologies and growing attention to the ethical aspects of its use [14]. Thus, AI not only changes marketing strategies but also demands that companies adapt to new challenges and opportunities.

**Table 1** – Key AI technologies and their application in marketing

| AI Technology | Application in Marketing | Economic Effect |
|---|---|---|
| Machine Learning | Customer segmentation, churn prediction, recommendations | Increased ROI through precise targeting |
| Natural Language Processing | Chatbots, review analysis, content generation | Reduced customer service costs |
| Big Data Analytics | Trend identification, consumer behavior analysis | Improved strategic planning |

AI technologies, including machine learning, natural language processing, and big data analytics, provide personalization, automation, and strategic planning in marketing, enhancing return on investment and reducing costs. However, high implementation costs, risks of diminished trust, ethical issues regarding data privacy, and dependence on data quality present limitations. To maximize economic efficiency, it is essential to balance the advantages of AI with the mitigation of its limitations through transparent and ethical approaches [17].

**Table 2** – Advantages and Limitations of AI in Product Promotion

| Aspect | Advantages | Limitations |
|---|---|---|
| Economic Efficiency | Cost reduction, increased ROI | High implementation costs |
| Personalization | Customized campaigns | Risk of decreased trust when mentioning AI |
| Data Privacy | In-depth consumer analysis | Ethical and legal issues |
| Data Quality | Accurate predictions with high-quality data | Errors with low-quality data |

AI technologies, including machine learning, natural language processing, and big data analytics, provide personalization, automation, and strategic planning in marketing, enhancing return on investment and reducing costs. However, high implementation costs, risks of diminished trust, ethical issues regarding data privacy, and dependence on data quality present limitations. To maximize economic efficiency, it is essential to balance the advantages of AI with the mitigation of its limitations through transparent and ethical approaches [17].

AI enhances marketing profitability, lowers campaign costs, and increases consumer loyalty, thereby strengthening companies' competitiveness in the digital economy.

AI transforms advertising by tailoring content to consumer preferences through user behavior analysis. For example, Spotify utilizes AI to personalize playlists, thereby increasing retention and revenue. The Sill personalizes subscriptions, reinforcing loyalty. The effect is that personalization reduces costs associated with ineffective campaigns while boosting conversion rates. More than 40 % of marketers reported an increase in campaign success in 2021–2022 [4].

AI improves the customer experience through chatbots and recommendations. For instance, Amazon offers personalized discounts, enhancing customer satisfaction. Woebot provides cost-effective mental health support. The Pounce chatbot reduced student attrition by 22 %. The effect is that automation lowers call center costs and increases repeat purchases.

AI optimizes marketing budgets by identifying effective channels. For instance, Accenture increased sales by $ 300 million through budget optimization. The Economist attracted 650,000 customers with a budget of £ 1.2 million. The effect is that programmatic advertising reached $ 558 million in 2023, enhancing profitability [18].

AI increases productivity by forecasting demand and optimizing processes. For example, P&G promotes eco-friendly campaigns, boosting sales. Google and Amazon optimize inventory, reducing costs. The effect is that early adopters of AI gain a competitive advantage.

In the Russian market, AI is actively being implemented. For example, online retailers use recommendations to increase average order value. Virtual fitting technologies reduce returns by 30 %. The effect is revenue growth and a potential XR market worth $ 53.7 billion by 2027.

AI transforms product promotion by lowering costs and improving the customer experience. Global cases (Spotify, Accenture, P&G) and the Russian market demonstrate economic benefits. Companies must invest in technologies and training to adapt their practices [7].

The online hypermarket 21vek.by, the largest e-commerce platform in Belarus, has implemented AI to personalize product recommendations. Using machine learning algorithms, the platform analyzes user behavior data, purchase history, and preferences to suggest relevant products. For example, when customers browse electronics, they are offered accessories or related items that match their interests.

Economic Impact:

A 10 % increase in the average order value due to precise targeting.

Improved customer loyalty thanks to an enhanced user experience.

Reduced marketing costs through the automation of recommendations.

Technologies:

Machine learning for data analysis and customer segmentation.

Recommendation systems integrated into the e-commerce platform.

TOPBRAND.MEDIA: "BE №1" Quiz for Lead Generation

Belarusian media company TOPBRAND.MEDIA used generative AI (based on GPT) to create an interactive "BE № 1" quiz aimed at lead generation. The quiz included AI-generated questions, logic, and personalized recommendations, which helped to increase audience engagement. The campaign was implemented as part of the company's promotion of its media services.

Economic Impact:

Generation of 55 leads and 55 new Telegram subscribers.

Doubling the number of leads compared to manual methods.

Reduced content creation costs through automation.

Technologies:

Generative AI (GPT) for content and quiz logic creation.

Data analysis to assess campaign effectiveness.

Based on the analysis of these cases, the following recommendations are proposed for Belarusian companies:

1. Investment in AI technologies: Implement personalization and automation systems, as in the case of 21vek.by, to enhance marketing efficiency.
2. Development of expertise: Invest in staff training for working with AI to overcome the barrier of knowledge shortage, noted in 70 % of cases of AI rejection (belretail.by).
3. Ethical standards: Ensure transparency in AI use and data protection to maintain consumer trust, as emphasized in the article.
4. Government support: Utilize the resources of the High-Tech Park for access to AI technologies and subsidies.
5. Study of successful practices: Adapt the experience of Russian companies, such as online retailers using virtual fitting rooms, for the local market.

**Table 3** – Examples of AI Applications in Product Promotion and Their Economic Effects

| AI Application | Case | Economic Effect |
|---|---|---|
| Personalized Advertising | Spotify (hyper-personalization of playlists), The Sill (lifestyle subscriptions) | Reduction in advertising costs, increase in conversion rates and revenues |
| Customer Experience Management | Amazon (recommendations), Woebot (support), Pounce (Georgia State University) | Decrease in service costs, increase in loyalty and repeat purchases |
| Marketing Budget Optimization | Accenture ($ 300 million in sales), The Economist (650,000 customers) | Increase in ROI, reduction in costs associated with ineffective channels |
| Demand Forecasting | P&G ("Do It Every Night"), Google, Amazon (inventory optimization) | Decrease in operational costs, increase in profitability and competitiveness |
| Russian Market | Online retailers (recommendations), virtual fitting technologies | Increase in average order value, enhancement of loyalty, potential growth of the XR market to $ 53.7 billion |

Based on the conducted analysis, it can be asserted that the application of AI in sales can be classified into three levels of integration: basic, adaptive, and transformational. Each level is characterized by varying degrees of technological complexity and economic impact. The basic level ensures operational efficiency, the adaptive level focuses on campaign optimization, while the transformational level provides strategic advantage through innovative business models. For Russian companies, such as online retailers, the priority is to transition from the basic to the adaptive level, which will enable an increase in average order value and customer loyalty with moderate investments. However, achieving the transformational level requires overcoming barriers, including high costs and the necessity of adhering to ethical standards, such as data transparency and compliance with regulatory requirements, for instance, GDPR. The proposed classification emphasizes the need for a strategic approach to the implementation of AI that considers both economic benefits and limitations to ensure the sustainable development of marketing practices.

**Ethical and Economic Aspects of Artificial Intelligence Application in Marketing**

The application of artificial intelligence (AI) in product promotion transforms marketing processes, enhancing their effectiveness while simultaneously presenting a range of challenges related to ethics and economics. Based on the analysis of research from 2024 to 2025 and practical examples, key issues can be identified and recommendations proposed to address them, ensuring a balance between efficiency and social responsibility. To structure the analysis, this section is divided into three stages: identification of challenges, analysis of their impact, and development of recommendations.

Stage 1: Identification of Key Challenges

The use of AI in marketing faces several obstacles that pertain to both economic and ethical aspects. The main challenges include:

Decreased Consumer Trust: Research indicates that mentioning AI in marketing materials can reduce customers' purchase intentions due to the perception of technologies as opaque. This creates a necessity for transparent communications.

Data Privacy: The analysis of consumer data raises questions about consent and information security. Breaches of privacy threaten companies' reputations and require adherence to strict standards, such as GDPR [19].

Risk of Manipulative Practices: Algorithms that utilize emotional data can influence consumer behavior, leading to ethical dilemmas. The lack of transparency in such practices exacerbates distrust.

High Implementation Costs: The development and integration of AI require significant investments, limiting small and medium-sized enterprises' access to these technologies.

Changes in the Labor Market: Automation, which may encompass up to 30 % of working hours by 2030, necessitates retraining employees to adapt to new conditions.

Unequal Access to Technologies: Large corporations have an advantage in utilizing AI, which exacerbates economic inequality, especially in resource-limited regions.

Stage 2: Analysis of the Impact of Challenges

Each of the aforementioned challenges impacts marketing effectiveness and companies' reputations. For instance, decreased consumer trust, as seen with explicit mentions of AI, can reduce conversion rates by 10–15 % [8]. Data privacy issues lead to legal risks and fines, as stipulated by GDPR, which increases operational costs. Manipulative practices, while capable of temporarily boosting sales, undermine long-term customer loyalty. High implementation costs of AI restrict the competitiveness of small enterprises, while automation requires investments in employee training to avoid social consequences, such as rising unemployment. Unequal access to technologies amplifies disparities, allowing major players like Coca-Cola or Nike to dominate the market while small businesses remain sidelined [20].

Practical examples corroborate these findings. For instance, Coca-Cola, which implemented transparent AI practices, increased sales by 25 %, while Nike enhanced customer engagement by 30 % through ethical technology use. These cases demonstrate that overcoming challenges is possible with a strategic approach.

Stage 3: Recommendations for Overcoming Challenges

To ensure the sustainable application of AI in marketing, the following measures are proposed, based on an interdisciplinary approach and aimed at balancing economic benefits with ethical standards:

Openness in Communication: Companies should inform customers about the use of AI, clarifying how algorithms process data. Tools like the Ethical Marketing Suite from SuperAGI enhance transparency and build trust.

Data Protection Technologies: Utilizing federated learning and differential privacy minimizes leak risks, ensuring compliance with international standards.

Ethical Standards: Developing regulations governing the use of AI prevents manipulative practices. This requires the involvement of ethics and legal experts.

Investment in Training: Employee retraining programs tailored to automation preserve employment and enhance productivity.

Support for Small Businesses: Government subsidies and grants for small enterprises will ensure equal access to AI, reducing economic inequality.

Environmentally Sustainable Solutions: The application of energy-efficient algorithms reduces costs and supports environmental responsibility.

**Table 4** – Challenges of AI Implementation in Marketing

| Challenge | Characterization |
|---|---|
| **Consumer Trust** | Algorithmic opacity reduces purchasing activity [1, p. 15] |
| **Data Privacy** | The risk of privacy breaches necessitates strict compliance with regulatory standards (e. g., GDPR) [2] |
| **Manipulative Practices** | The analysis of emotional data can undermine trust in the absence of ethical guidelines [3] |
| **Implementation Costs** | High initial investments limit accessibility for small and medium-sized enterprises (SMEs) [4] |

**Conclusions**

The analysis demonstrates that the use of AI in marketing, while enhancing efficiency, necessitates addressing complex ethical and economic issues. Transparency in communication, data protection, and personnel training are key measures for building trust and minimizing risks. Supporting small businesses through government programs and implementing environmentally sustainable solutions will help reduce inequality and ensure long-term benefits. These steps, corroborated by the successes of Coca-Cola and Nike, form the foundation for the responsible application of AI, thereby promoting the sustainable development of marketing strategies.

The application of artificial intelligence in product promotion is fundamentally transforming marketing approaches, ensuring cost-effectiveness and creating new opportunities for customer engagement. Technologies such as machine learning, natural language processing, and big data analytics enable the development of personalized strategies, cost reduction, and the strengthening of market positions. Global examples, including Spotify, Amazon, and Accenture, demonstrate increased revenue, improved conversion rates, and process optimization. Meanwhile, Belarus cases, encompassing online retailers and virtual fitting technologies, highlight the potential for the local market.

However, these economic benefits are accompanied by challenges that require a comprehensive approach. Algorithmic opacity undermines consumer trust, data privacy concerns generate legal risks, and manipulative practices threaten brand reputation. High implementation costs limit access for small and medium-sized enterprises (SMEs), exacerbating market inequality, while automation necessitates workforce retraining. To systematize AI application, a classification by integration level is proposed: basic (task automation), adaptive (campaign optimization), and transformational (innovative business models). For Belarus businesses, the adaptive level is a priority, as it ensures growth in customer loyalty with moderate investment.

To address these challenges, several measures are proposed: transparent communication, data protection technologies, ethical guidelines, personnel training, support for small businesses, and environmentally sustainable solutions. These steps form the basis for the responsible use of AI, ensuring a balance between economic benefit and social responsibility, thereby contributing to the sustainable development of marketing strategies.

**Table 5** – Measures for Addressing the Challenges

| Measure | Description |
|---|---|
| **Transparent Communication** | Informing customers about the principles of AI operation to build and reinforce trust [7] |
| **Data Protection** | Implementing privacy-enhancing technologies (PETs) to ensure compliance with standards like GDPR [8] |
| **Ethical Guidelines** | Establishing AI governance frameworks with multi-stakeholder expert involvement to prevent manipulation [9, p. 8] |
| **Workforce Training** | Implementing upskilling and reskilling programs to facilitate employee adaptation to automation [10] |
| **SME Support** | Providing subsidies and grants to ensure equitable access to AI technologies for small businesses [11] |
| **Environmental Sustainability** | Adopting energy-efficient algorithms to mitigate the environmental footprint and operational costs [12] |

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# METHODOLOGICAL SUPPORT FOR THE ASSESSMENT AND DEVELOPMENT OF THE DIGITAL TRANSFORMATION OF TRANSPORT AND LOGISTICS ACTIVITIES

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**Abstract**

With the rapid development of technology and the globalization of the economy, the transport and logistics sector is facing new challenges and opportunities. Digitalization, covering all aspects of business, is becoming a key factor determining the effectiveness and competitiveness of an organization in this area. The introduction of digital solutions will optimize supply chain management processes, improve interaction between market participants, and enhance customer service.

The article presents an analysis of the processes of digitalization as a whole, as well as the existing methodological support in this field for assessing digital transformation. Thus, the methods of digital development developed by JSC Giprosvyaz (Republic of Belarus), the Department of Management of Perm State National Research University (Russian Federation), and the Analytical Agency Arthur D. Little (USA) are described. All three techniques have both advantages and disadvantages. In this regard, there is a need to develop our own methodology that would take into account all the nuances of existing assessment systems.

In addition, the article describes the methodology developed by the authors for assessing the level of digital transformation, which will allow taking into account the opinions of various participants in transport and logistics activities, thanks to the developed expert indicators and the weight indicators assigned to them.

Thus, the article examines the key aspects of digitalization of transport and logistics activities, analyzes existing methods for assessing digital transformation, and develops an author's methodology for assessing the level of digitalization of transport and logistics activities.

**Keywords:** transport and logistics activities, development, digital transformation, methodological support.

## МЕТОДИЧЕСКОЕ ОБЕСПЕЧЕНИЕ ОЦЕНКИ И РАЗВИТИЯ ЦИФРОВОЙ ТРАНСФОРМАЦИИ ТРАНСПОРТНО-ЛОГИСТИЧЕСКОЙ ДЕЯТЕЛЬНОСТИ

**П. И. Лапковская, Е. А. Семашко**

**Реферат**

В условиях стремительного развития технологий и глобализации экономики транспортно-логистическая сфера сталкивается с новыми вызовами и возможностями. Цифровизация, охватывающая все аспекты бизнеса, становится ключевым фактором, определяющим эффективность и конкурентоспособность организации в данной области. Внедрение цифровых решений оптимизировать процессы управления цепями поставок, улучшать взаимодействие между участниками рынка и повышать уровень обслуживания клиентов.

В статье представлен анализ процессов цифровизации как в целом, так и существующего в данной области методического обеспечения для оценки цифровой трансформации. Так, описаны методики уровня цифрового развития, разработанные ОАО «Гипросвязь» (Республика Беларусь), кафедрой менеджмента Пермского государственного национального исследовательского университета (Российская Федерация), аналитическим агентством – Arthur D. Little (США). Все три методики имеют как преимущества, так и недостатки. В связи с этим возникает необходимость в разработке собственной методики, которая учла бы все нюансы существующих систем оценки.

Кроме того, в статье описана разработанная авторами методика оценки уровня цифровой трансформации, которая позволит учесть мнения различных участников транспортно-логистической деятельности, благодаря разработанным экспертным показателям и присвоенным им весовым показателям.

Таким образом, в статье исследованы ключевые аспекты цифровизации транспортно-логистической деятельности, проанализированы существующие методики оценки цифровой трансформации, а также разработана авторская методика для оценки уровня цифровизации транспортно-логистической деятельности.

**Ключевые слова:** транспортно-логистическая деятельность, развитие, цифровая трансформация, методическое обеспечение.

### Introduction

At the current stage of economic development, digitalization plays an important role. The processes of digital transformation are developing very rapidly, as evidenced by its penetration into all types of economic activity without exception. If we turn to the transport and logistics field of activity, the use of the latest inventions and the latest digital achievements in it helps to increase the effectiveness of relationships between participants, as well as guarantees competitive advantages, which makes the presented topic relevant. The development of informatization and digitalization sets a peculiar rhythm for the development of the economy, logistics and the public as a whole. The instantaneous penetration of digitalization into everyday life is an unambiguous and distinctive feature of the process under consideration.

### Analysis of the existing methodological support for digital transformation assessment

It is worth noting that the concept and essence of the digitalization process, as well as a detailed description of the tools of digital transformation of transport and logistics activities, have been studied in detail in previous articles [1, 2]. Thus, digitalization of transport and logistics flows makes it possible to optimize the transport and logistics process. Digital technologies guarantee an increase in the economic efficiency of business processes in logistics, increase the safety and quality of transport and logistics services, and provide a significant competitive advantage [3, 4].

Today, there are already some examples of models that systematize the process of digital transformation of an organization.

The first model to start researching any techniques in the field of digitalization is presented by the Center for Digital Business at the Massachusetts Institute of Technology. This center was established in 1999 and is currently the most advanced in the industry. As a result of the analysis and synthesis of the digital development of more than 400 organizations over the course of more than one year, experts have identified the main blocks in the development of their own model. The essence of this model is that all its blocks, namely customer service, the production process and the provision itself, are interdependent. By working with these elements of the system, it is possible to achieve the desired level of digital development. However, it is impossible to achieve total digitalization in each individual block, since each organization only works on a specific block that it wants to bring to a new level for itself.

The first block is a block consisting of elements specific to working with clients, i.e. the relationship with the external environment. This block has three components inside itself:

– understanding of the clientele (working with the client through social networks, etc.);
– increase in income (revenue);
– finding points of intersection with clients.

The second block characterizes the production process itself. Namely:

– the very process of digitalization of a certain business process;
– the discovery of new employee opportunities during the production process, since with the increase in digitalization of a particular process, the employee has a new production reserve that can be directed in the right direction;
– the ability to manage and control the output and labor intensity of production.

The third block is the model itself, which must be achieved using the best practices of the first and second blocks. The third block is the goal to be achieved [5]:

– the introduction of digitalization in the organization;
– creating a new digital product or company as a whole;
– creating a global digital community.

However, it should be borne in mind that the necessary result can be achieved only if there is a leader who can organize the well-coordinated work of the entire team and who clearly understands what needs to be achieved in the final result.

The second model is Deloitte's Digital Maturity Model (DMF). This model evaluates the level of digital transformation using the following indicators:

– customer;
– the production process;
– the organization 's strategy;
– production technology;
– structure;
– the culture of the organization.

At the initial stage, the organization's strategy is being investigated. According to the results of her research, further directions of the organization's development in the field of digital transformation are visible [6].

Such a task as the digital transformation of a process or business as a whole, and in this case, flow management, is in service with the vast majority of organizations among various types of economic activity. Being a fairly new direction that has replaced partial computerization and informatization of business processes, digitalization creates conditions for the growth of the number of companies that need to develop and implement their own digital software products. Thus, there is an increase in the innovative component of the business, which in turn contributes to the effective development of the economy and logistics.

It is important to note the opinion of T.G. Shulzhenko, which states that digitalization of transport and logistics flow management contributes to the emergence and further development of innovative production, increasing competitiveness in conditions where the role of individualization of consumer requirements for goods and services increases [7]. However, based on the above, logistics at the current stage of development is somewhat lagging behind such types of economic activities as banking, trade, telecommunications and communications, etc. In the vast majority of transport and logistics organizations, there are many manual operations involved in organizing the workflow, and the organization's assets are not fully used effectively, which slows down the process of digital business transformation. It is important to note that many scientific papers on digitalization have been written today that define its conceptual framework, scope, technological component of digital transformation, etc., but it is difficult to find any recommendations that should be followed by transport and logistics organizations implementing digitalization tools, which is associated with some complexity of the process of perceiving such an abstract at the moment phenomena.

Today, there are various methods for assessing the level of digital development of organizations among various types of economic activity. In this article, we will compare some of them.

The methodology for assessing the level of digital development of organizations, industries and functional areas developed by JSC Giprosvyaz (Republic of Belarus) in its approach is based on a set of data from individual business processes and their contribution to the overall result, as well as summarizing information about the level of computerization, automation and informatization. The relationship between computerization, automation, informatization and digitalization is shown in Figure 1.

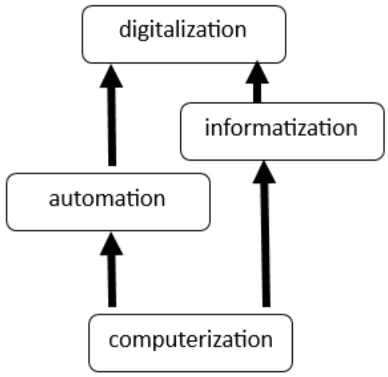


**Figure 1** – The relationship of the methodology elements

The approach to assessing the level of digitalization of an organization is presented in formula (1):

$$C = \frac{\sum_{1}^{n} \alpha_i \cdot C_i}{\sum_{1}^{n} \alpha_i} \left| \begin{array}{lll} K_i & \geq & K_{tr} \\ A_i & \geq & A_{tr} \\ E_i & \geq & E_{tr} \end{array} \right. , \quad (1)$$

where $C$ – an indicator of the level of digitalization of an organization;

$C_i$ – an indicator of the level of digitalization of the first business process;

$\alpha_i$ – the weight of the I-th business process in the organization's activities;

$K_i$, $A_i$, $E_i$ – levels of computerization, automation and informatization of the I-th business process;

$K_{tr}$, $A_{tr}$, $E_{tr}$ – required levels of computerization, automation and informatization.

In cases where it is difficult to obtain information about the impact of individual factors on the digitalization process, you can use a simplified version of formula (2):

$$C = \sqrt[2]{\frac{C_O^2 + C_B^2 + C_Y^2}{3}} , \quad (2)$$

where $C_Y$ – an indicator of the level of digitalization of business management processes;

$C_O$ – an indicator of the level of digitalization of the main business processes;

$C_B$ – an indicator of the level of digitalization of auxiliary business processes;

$n$ – the number of private indicators of automation and informatization related to a specific type of business processes.

The value of the indicator of the level of digitalization is determined based on expert estimates in accordance with the developed assessment scale:

0 – there is no digitalization;

1 – computerization of the enterprise (organization) and automatic digital data collection is carried out in real time, without human involvement (your business, suppliers, consumers, competitors, market conditions, logistics, preferences of a higher-level system, market trends);


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2 – the informatization of the enterprise (organization) is carried out, automatic digital data collection in real time, without human intervention, and subsequent dynamic analysis of this data in real time (a digital asset has been created);

3 – an intelligent decision support system has been implemented, including automatic digital data collection and subsequent dynamic analytics, the results (digital asset) are used by the company's management to make operational and optimal decisions;

4 – an enterprise ecosystem has been created in which all business processes are digitized, management decisions are formed and implemented automatically (if necessary, some of them are approved or adjusted by the company's management, who is responsible for the consequences of the management decision made and implemented). The role of managers is to determine the goals (sub-goals) of the functioning of the enterprise management system, the system of constraints and performance criteria, development directions and areas of activity [8–12].

This method of assessing the level of digitalization based on data on the levels of computerization, automation and informatization allows you to obtain general information about the company, monitor changes in the field of digitalization and identify growth points.

The Department of Management of Perm State National Research University (Russian Federation) has developed a methodology that allows assessing the degree of use of modern information and communication technologies for the implementation of various business processes of the organization.

The essence of this methodology is to identify six large business processes (personnel management, service provision (production), marketing, logistics, finance and accounting, general business activities) and divide them into subprocesses. The assessment process itself consists of three stages: mailing, filling out and processing questionnaires. As a result, you can get an accurate level of digital development. A distinctive feature of the method under study is the simplicity of working with the questionnaire, minimal time, but accurate and reliable results [13]. A fragment of the questionnaire is shown in Figure 2.

| IV. Logistics | | | |
|---|---|---|---|
| 4.1 Procurement management | yes | no | - |
| 4.2 Sales management | no | no | no |
| 4.3 Managing the movement of inventory within the company | yes | no | no |
| 4.4 Transportation of inventory (to/from the company) | yes | yes | Beltransputnik, Resurscontrol |
| 4.5 Warehousing | no | no | - |
| Is at least one of the software you specified in paragraphs 4.1 - 4.5 an integrated module of a unified company management system (for example, ERP systems)? | no | | |
| Does at least one of the software/cloud services you specified in paragraphs 4.1 - 4.5 provide interaction with at least one external counterparty? | no | | |

**Figure 2** – Fragment of a questionnaire for assessing the level of digitalization according to the methodology of Perm State National Research University

The Arthur D. Little analytical agency has developed the Digital Transformation Index (USA), which evaluates the level of digitalization in the following sectors: strategy and leadership, products and services, customer management, operations and supply chains, corporate services and control, information technology, workplace and culture. This is a cumulative indicator based on comparative expert estimates [14]. The essence of the methodology is to compile a radar with industry averages and indicators of companies that have achieved significant success in digitalization. Such a system makes it possible for an organization to understand its level in comparison with other enterprises. However, the negative side of this technique is that it is difficult to find the necessary statistical information, and you also need to have certain skills to build a radar, and then process the results from the radar.

Thus, after conducting a comparative analysis of three methods for assessing the level of digital development of transport and logistics enterprises, it can be concluded that a distinctive feature of all methods is the interpretation of the final evaluation results, while the indicators themselves for assessing the level of digitalization are generally similar. In addition, a consistent process of processing results is not indicated either in the methodology of the Perm Institute or in the index of the Arthur D. Little agency, therefore, further improvement of the methods under consideration is necessary.

**Methodology for assessing the digital transformation of transport and logistics activities**

Based on the analysis of various methods for assessing the level of digital transformation of a transport and logistics organization, it is concluded that all approaches are based on similar aspects. However, the author suggests another method that takes into account the opinion about the level of digital development of a transport and logistics organization from various sides.

The essence of the proposed methodology is that it is necessary to develop a specific list of indicators characterizing the digital transformation of the transport and logistics business and assign weight to each of the presented indicators (criteria). This weight will reflect the importance of a criterion for the digitalization process. It is worth noting that the technique is quite flexible and both the indicators and their weight can be adjusted depending on the case and need. The only distinguishing feature is that the sum of the weights of all criteria should give 1 or 100 % if the weight is presented in relative terms. In addition, the developed methodology is applied twice, namely, at the first level, the weights are set by a trained group of experts, and at the second by the organization's staff. The average is derived from the two values obtained. This allows for a more comprehensive assessment of the degree of digitalization, as the assessment takes into account the opinions of different parties. It is important to note that the number of such assessments can be increased, which will allow for an even more accurate assessment of the level of digital transformation of transport and logistics activities.

The result of assessing the level of digital transformation of a transport and logistics organization can be presented graphically.

Table 1 shows the indicators for assessing the digital transformation of transport and logistics activities.

After summing up the weights of those indicators that can be attributed to the organization under study, it is possible to assess the degree of digital development of the transport and logistics organization.

If the sum of all indicators is up to 30 %, then we can talk about the digitalization of several business processes.

If the sum of all indicators is up to 85 %, then the main business processes of the organization are being digitized.

If the sum of all indicators is over 85 %, then all business processes of the organization are fully digitized.

Thus, this methodology is simple enough to evaluate any organization and shows accurate end results.

It is important to note that the assessment of the digital transformation of an organization using this methodology should be carried out over a certain period of time in order to monitor the "digital" situation. This will make it possible to quickly make attempts to improve the company's development in the field of business digitalization, if there is an emphasis on this. For greater clarity, it is possible to depict the results of the assessments in the form of a graph, where there will be a clear trend of development or, conversely, decline. An example graph is shown in Figure 3.


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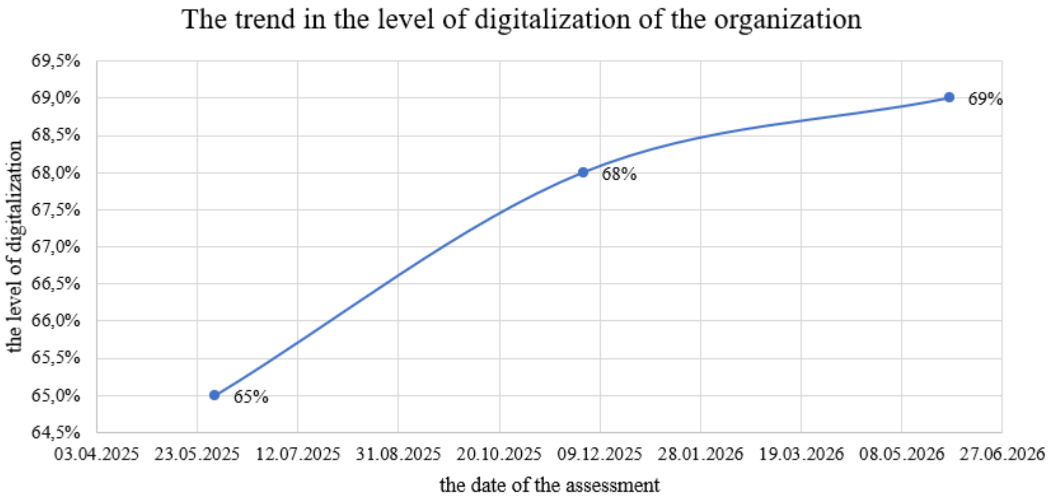


**Figure 3** – The trend in the level of digitalization of a transport and logistics organization

**Table 1** – Indicators for the methodology of assessing the digital transformation of a transport and logistics organization

| **Experts** | | |
|---|---|---|
| *Indicator number* | *Indicator* | *Weight (fraction)* |
| *1* | *2* | *3* |
| 1 | Costs of innovation in digitalization | 0,07 |
| 2 | Own digital developments (patents) | 0,25 |
| 3 | Using electronic document management | 0,1 |
| 4 | Availability of digital systems (e. g. ERP) | 0,15 |
| 5 | Working with Artificial Intelligence (AI) | 0,08 |
| 6 | Updating data online | 0,09 |
| 7 | Working on an electronic platform | 0,06 |
| 8 | The ratio of workers to machinery (computer) | 0,05 |
| 9 | The organization's prominence through the use of digital transformation achievements | 0,05 |
| 10 | Working with clients online | 0,1 |
| **Employees of the organization** | | |
| *Indicator number* | *Indicator* | *Weight (fraction)* |
| 1 | Costs of innovation in digitalization | 0,07 |
| 2 | Own digital developments (patents) | 0,25 |
| 3 | Using electronic document management | 0,1 |
| 4 | Availability of digital systems (e. g. ERP) | 0,15 |
| 5 | Working with Artificial Intelligence (AI) | 0,08 |
| 6 | Updating data online | 0,09 |
| 7 | Working on an electronic platform | 0,06 |
| 8 | The ratio of workers to machinery (computer) | 0,05 |
| 9 | The organization's prominence through the use of digital transformation achievements | 0,05 |
| 10 | Working with clients online | 0,1 |

**Conclusion**

Thus, the developed methodology for assessing the level of digital transformation of a transport and logistics organization differs from other existing methods due to the simplicity of obtaining results and the low time required for its implementation. However, the accuracy of the obtained results remains at a high level and with minimal error. This methodology will allow, using real data, to analyze your position in the field of business digitalization, compare yourself with other organizations engaged in the same type of economic activity, and, consequently, identify possible growth points. Obviously, the digitalization of an organization is a rather lengthy and complex process that requires a certain level of attention. In addition, the digital transformation of a business at its various stages should have a positive impact on the company's performance indicators. In this regard, a model of digital transformation of transport and logistics activities has been developed in previously published articles [15–20].

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# UTILITY APPROACH TO THE ANALYSIS AND EVALUATION OF SCIENTIFIC AND TECHNICAL ACTIVITIES

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**Abstract**

The scientific research is devoted to the application of the utility approach to the study of socio-economic processes occurring in the scientific and technical sphere. It is shown that one of the reasons for the inconsistency of scientific and technical progress is the cost (cost) method of assessing its effectiveness, which consists in identifying costs with results and ignoring the usefulness of its achievements. The target (useful) result of the functioning of the scientific and technical sphere should be considered not the maximization of R & D costs and not even the scientific and technical information obtained as a result of them, but a change (improvement) in the structure (quality) of GDP. At the same time, for the quantitative assessment of the GDP structure, the indicator of the level of technological effectiveness of the economic system is proposed for use, and as another useful criterion for the efficiency of the above-mentioned sphere – an increase in the utility coefficient of R & D costs and the procedure for its calculation is determined. The dynamics of the utility coefficient of R & D costs is also shown both in the Republic of Belarus and in the Russian Federation. Based on the analysis of statistical information available in the public domain on the development of the scientific and technical sphere in a number of technologically advanced European countries, it was proven that the useful characteristics of its functioning are as significant as traditional cost indicators, such as the science intensity of GDP and others. Based on this, appropriate recommendations were given on the development and implementation of a strategy for technological catch-up as a tool not only for strengthening the technological security of the state, but also for overcoming global contradictions generated by scientific and technical progress.

**Keywords:** scientific and technique progress, scientific and technical sphere, scientific and technical activity, scientific and technical information, level of processability, R & D costs, utility, R & D costs utility ratio, technological safety.

## ПОЛЕЗНОСТНЫЙ ПОДХОД К АНАЛИЗУ И ОЦЕНКЕ НАУЧНО-ТЕХНИЧЕСКОЙ ДЕЯТЕЛЬНОСТИ

**С. В. Макаревич**

**Реферат**

Научное исследование посвящено применению полезностного подхода к исследованию социально-экономических процессов, происходящих в научно-технической сфере. Показано, что одной из причин противоречивости научно-технического прогресса является затратный (стоимостной) метод оценки его эффективности, заключающийся в отождествлении затрат с результатами и игнорировании полезности его достижений. Целевым (полезным) результатом функционирования научно-технической сферы должна считаться не максимизация затрат на НИОКР и даже не полученная в их результате научно-техническая информация, а изменение (улучшение) структуры (качества) ВВП. При этом для количественной оценки структуры ВВП предложен к использованию показатель уровня технологичности экономической системы, а в качестве еще одного полезностного критерия эффективности функционирования вышеуказанной сферы – увеличение коэффициента полезности затрат на НИОКР и определен порядок его расчета. А также показана динамика коэффициента полезности затрат на НИОКР как в Республике Беларусь, так и в Российской Федерации. На основе анализа статистической информации, размещенной в открытом доступе, о развитии научно-технической сферы ряда технологически развитых европейских стран было доказано, что полезностные характеристики ее функционирования столь же значимы, что и традиционные затратные показатели, такие как наукоемкость ВВП и другие. Исходя из этого, даны соответствующие рекомендации по разработке и реализации стратегии технологического наверстывания в качестве инструмента не только укрепления технологической безопасности государства, но и преодоления порожденных научно-техническим прогрессом глобальных противоречий.

**Ключевые слова:** научно-технический прогресс, научно-техническая сфера, научно-техническая деятельность, научно-техническая информация, уровень технологичности, затраты на НИОКР, полезность, коэффициент полезности затрат на НИОКР, технологическая безопасность.

## Introduction

Modern global economic processes have a specific impact on scientific and technological progress in different countries of the world, including Belarus and friendly countries, which is significantly different from what it was 2–3 years ago. Among the main features of the current stage of development of the earth's civilization, the following should be mentioned first of all:

1) digital transformation of the economy and society as a modern phase of industrialization – a permanent process of equipping them with modern technical devices (in this case, with digital software control) [1, 2, 3];

2) an unprecedented aggravation of global contradictions in the development of the earth's civilization caused by scientific and technological progress, including raw materials, energy, environmental, food, demographic, migration, military and other similar problems in their scale [4, 5, 6];

3) a sharp complication of the geopolitical situation on the planet, including the introduction of political and economic sanctions by some countries against others, including the unleashing of a technological war by Western countries against Belarus, Russia and other powers defending their sovereignty as a process of excommunicating them from access to Western high-tech products and technologies for their production [7, 8, 9];

4) an objective need to modernize the domestic economy and implement an active industrial policy in Belarus and other friendly states [10, 11, 12].

The above and some other circumstances dictate the need to accelerate the technological development of the Belarusian and Union (meaning the Union State of Belarus and Russia) economy. Unfortunately, there are a number of serious obstacles along this path, the main one of which is, perhaps, the cost-based, inherently expensive approach to assessing socio-economic processes, including the analysis of the functioning of the scientific and technical sphere [13].

In the most general sense, the term "cost approach" implies the fact, which generally lies on the surface, that due to the insufficient theoretical development of the category of "utility" and, most importantly, the objective difficulties of its quantitative measurement, economists prefer to focus their attention on the cost characteristics of economic goods associated with cost analysis. At the same time, their utility parameters are not considered in detail, since it is believed that this function is carried out in practice by free markets instead of economists, "trained" to deprive those who produce less useful goods of profit and to reward those whose products better satisfy consumer demands [13]. At the same time, however, it should be understood that even profit, which the absolute majority of modern economists perceive as a result exceeding costs, from the standpoint of classical political economy represents only a part of the costs of surplus labor of hired workers. Thus, it turns out that the competitive-market capitalist doctrine of development, which places the maximization of profit and its derivatives at the forefront, in reality orients the economy and society as a whole toward an endless increase in costs, which in fact leads humanity to a global conflict with nature and a general environmental catastrophe.

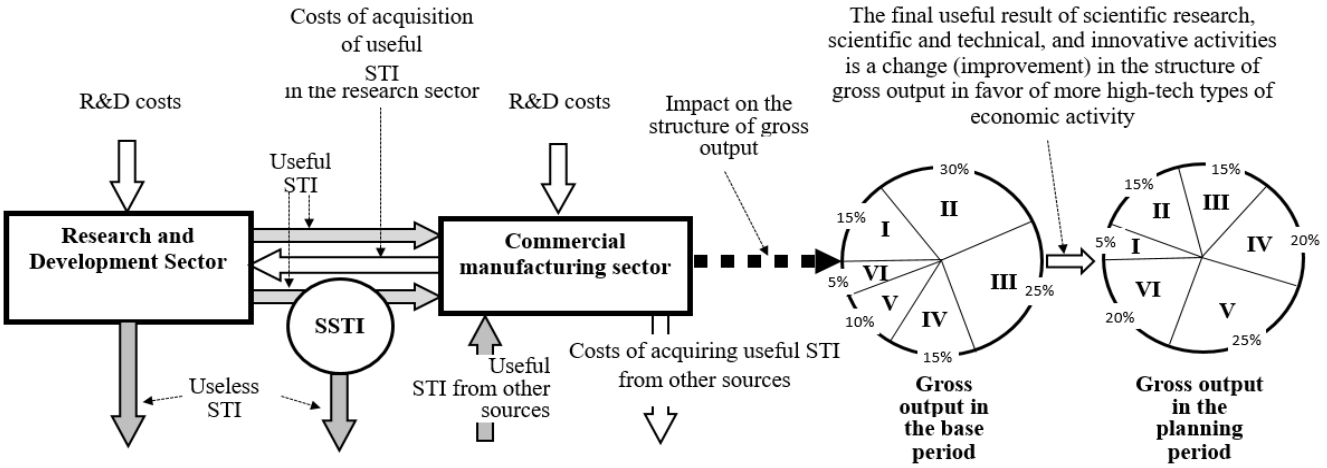
The above circumstances at the planetary level make it urgent to search for (develop) a new anti-crisis (anti-cost, useful in its meaning) economic scientific and educational paradigm capable of leveling and even overcoming the complex of the above-mentioned global contradictions of human development caused by the conflict of its insatiable needs and the possibility of their satisfaction by nature. Since many researchers, not without reason, believe that the complex of the above problems is caused by scientific and technological progress, it seems that the use of a useful approach to assessing the functioning of the scientific and technical sphere is the path that can finally lead humanity to a trajectory of truly sustainable development. In this regard, we are deeply convinced that a useful, anti-cost in its essence approach to the analysis of socio-economic processes and, above all, the scientific and technical sphere should become the main direction of further development of economic theory in the 21st century and the third millennium.

**Results and their discussion**

One of the areas of implementation of the research work at BSU "Development of the high-tech sector of the economy as a factor in ensuring scientific and technological security of the Republic of Belarus" (task of the State Program of Scientific Research "Economy and Humanitarian Security of the Belarusian State" for 2021–2025) is the development of a utility method for studying scientific and technological progress. Unfortunately, it must be admitted that the analysis and assessment of its achievements is still dominated by the cost approach characteristic of economists, which boils down to identifying the costs and results of economic (in this case, scientific and technical) activities. A typical example of the manifestation of the cost approach to the study of the scientific and technical sphere is, for example, the tradition that has developed among economists and officials to consider (define, assign) the science intensity of gross output (GDP, GRP, etc.) as the main integral criterion for its development [14]. For example, in the Program of Socioeconomic Development of the Republic of Belarus for 2021–2025, one of the most pressing tasks is identified as "achieving the level of innovative development of the leading countries of Eastern Europe based on the implementation of the intellectual potential of the Belarusian nation by improving the conditions for the implementation and stimulation of scientific, technical and innovative activities, and the accelerated development of innovative infrastructure. This task involves increasing the science intensity of GDP to a level of at least 1 percent" [15].

The results of our studies show that the GDP science intensity indicator, being a typical cost parameter of the scientific and technical sphere, does not always adequately reflect the actual level of its development. The fact is that in practice, costs are never fully transformed into the final useful result, for example, due to their excessively large useless losses. It is no coincidence that in engineering sciences, the criteria for the efficiency of technical systems are the efficiency coefficients (EC) and useful use coefficients (UUC), since with low values of these clearly useful characteristics, any increase in the consumption of energy consumed by equipment will be equivalent to its banal waste. In order to exclude similar "waste" in the scientific and technical sphere, we propose to replace (or even better in addition to) the traditional cost criteria for its assessment using utility parameters that focus attention not on costs, but on the final useful result. Of course, the most difficult scientific problem is the definition and quantitative measurement of this very useful result, which was already discussed above.

In the process of solving the set tasks, we managed to develop a methodology and technique for quantitative determination of the final result of scientific and technical activity. In our opinion, its final useful result is not the costs of R & D or even the scientific and technical (including useful) information obtained in the process of their implementation, but a change (improvement) in the structure of gross output in favor of the products of more high-tech types of economic activity (Figure 1).




Designations:
STI – scientific and technical information; SSTI – (national, state) system of scientific and technical information; R & D – research and development work; I, II, III, IV, V, VI – contributions to gross output of types of economic activity related to the first through sixth technological waves, respectively

**Figure 1** – Illustration for determining the final useful result of scientific and technical activity

Source: own development of S. V. Makarevich under the scientific supervision of Professor V. F. Bainev

For an objective quantitative measurement of this improvement, we proposed a special indicator of the level of technological readiness of an economic system (enterprise, industry, region, country) TL ("technological level"), which characterizes the average weighted contribution of specific types of economic activity to its gross output, taking into account their typification by the level of applied technologies based on the European Classification of Types of Economic Activity. This indicator is a real number from the range from 1 to 6 (distinguished technological structures), reflecting the average weighted technological structure of the economic system. The methodology and techniques for determining this indicator are described in detail in [16, p. 213–226], and the results of his calculations for Belarus, Russia, China and the assessment for the G7 countries are presented in Figure 2.



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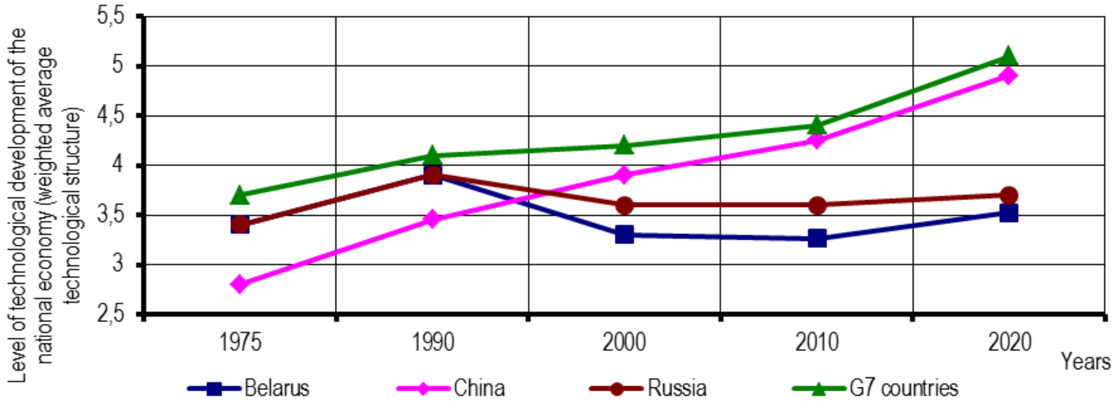


**Figure 2** – Dynamics of the level of technological development of the national economy of some countries of the world [16, p. 221, 225–226]

Using and developing the utility method of assessing scientific and technical activity and, in particular, relying on its central position that its final useful result is manifested in the form of an improvement in the structure of gross output, we came to some important conclusions. First of all, we had to admit that only that part of scientific and technical information that has been tested (verified) by commercial interest should be considered useful (see Figure 1). The fact is that, firstly, it is the commercial (private and public) sector that produces material goods, provides services, performs work and thereby directly influences the structure of gross output of the national (industry, regional) economy, directly setting the level of its technology. And secondly, only commercial interest can, in our opinion, be considered a more or less reliable filter that cuts off useless expenses from useful expenditures on R & D [17, p. 30].

Analyzing the information presented in Figure 1, it is necessary to specifically characterize the role assigned to the national (state) system of scientific and technical information (SSTI). This role, in our opinion, consists of reducing transaction costs (expenses) in the transfer of scientific and technical information from generators to its consumers and, accordingly, facilitating access to it by commercial production organizations, which contributes to improving the parameters of the functioning of the scientific and technical sphere and increasing the quality of GDP as a whole.

Taking into account the above, we proposed to use several useful indicators characterizing scientific and technical activity, among which the most significant are:

– useful R & D costs, which are the sum of commercially verified (implemented in the commercial private and public sector) R & D costs and similar costs that led to a change in the structure of fixed assets in the non-profit sectors of the national economy – in the non-profit public sector, the higher education sector and the non-profit organizations sector. In our opinion, the composition of useful R & D costs should include costs for special equipment and capital costs arising in the specified non-profit sectors, since these costs also directly affect the structure of fixed assets of the national economy and its gross output [18, p. 45];

– the R & D cost utility coefficient, calculated as the ratio of useful R & D costs to the total volume of R & D costs. This coefficient, being close in its essence to the technical efficiency indicators Efficiency (KPI), reflects the share of expenditure on research and development, which contributed to the change in the structure of gross output, in their total volume [18, p. 46].

Based on the relevant statistical information for Belarus and Russia, it was possible to analyze the dynamics of the R & D cost efficiency coefficient in comparison with the science intensity of GDP for the period from 2017 to 2023 (Table 1).

**Table 1** – Dynamics of some utility and cost indicators reflecting the efficiency of the scientific and technical sphere in Belarus and Russia

| Indicator | Years | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
| **Republic of Belarus** | | | | | | | |
| R & D Cost Utility Ratio | 0,730 | 0,728 | 0,713 | 0,696 | 0,681 | 0,668 | 0,713 |
| Science intensity of GDP, % | 0,58 | 0,61 | 0,58 | 0,54 | 0,46 | 0,47 | 0,58 |
| **Russian Federation** | | | | | | | |
| R & D Cost Utility Ratio | 0,913 | 0,884 | 0,899 | 0,888 | 0,866 | 0,803 | 0,627 |
| Science intensity of GDP, % | 1,10 | 0,99 | 1,04 | 1,10 | 0,99 | 0,94 | 1,00 |

Source: authors' own development based on data from [19, 20].

The data in the table show that in the last years under study, a systematic increase in R & D costs in monetary terms has been noted for both analyzed countries, but the share of useful costs in their scientific and technical sphere was shown only by the Republic of Belarus. And in the Russian Federation, a strong decrease in useful costs in the scientific and technical sphere is observed, which indicates a decreasing efficiency of using the expended resources.

Proposing the R & D expenditure utility coefficient for use as an alternative (supplement) to the traditional indicator of GDP science intensity, we carried out a correlation and regression analysis of the impact of these two significant parameters on GDP and investment activity based on statistical data from seventeen Western technologically advanced countries whose share in the global economy is relatively comparable to Belarus. Thus, the sample included Hungary, Germany, Denmark, Latvia, Lithuania, the Netherlands, Poland, Romania, Serbia, Slovakia, Slovenia, Finland, France, Croatia, the Czech Republic, Sweden and Estonia. The time range of the analysis extended from 2010 to 2021. The GDP indicator, which quantitatively characterizes gross output, and the volume of investment in fixed capital, a parameter that has a direct impact on changes in the structure (quality) of GDP, were selected as dependent parameters (regressors). Let us recall that within the framework of the utility method of research into scientific and technical activity that we are developing, it is the change in the structure of gross output that is its final useful result.

As a result of this part of the study, a system of regression equations was obtained [21, p. 23]:

$$\begin{cases} ВВП = 6\,097\,324{,}1 \cdot КПЗ_{НИОКР} + 847\,081{,}2 \cdot Н_{ВВП} - 4\,036\,471{,}6; \quad R^2=0{,}98; & (1) \\ (p) \quad (0{,}0004398) \quad (0{,}0057439) \quad (0{,}0000021) & \\ ИнвОК = 15\,789{,}0 \cdot КПЗ_{НИОКР} + 1676{,}1 \cdot Н_{ВВП} - 11\,168{,}7; \quad R^2=0{,}97, & (2) \\ (p) \quad (0{,}00059) \quad (0{,}02581) \quad (0{,}0000018) & \end{cases}$$

where *ВВП* – gross domestic product, million euros; $КПЗ_{НИОКР}$ – R & D cost efficiency ratio; $Н_{ВВП}$ – science intensity of GDP, %; *ИнвОК* – volume of investments in fixed assets, million euros.

It is obvious that the regression equations (1) and (2) obtained by us characterize the impact of the regressors – cost (science intensity of GDP) and utility (utility coefficient of R & D expenditures) characteristics of scientific and technical activities on the quantitative and qualitative parameters of GDP of the countries we analyzed. Comparison of the values of the coefficients for the regressors allows us to conclude that both science intensity of GDP and the utility coefficient of R & D expenditures affect the qualitative and quantitative parameters of gross output. At the same time, the specified impact from the utility coefficient of R & D expenditures is quite comparable with a similar impact exerted on dependent variables by science intensity of GDP. Consequently, when analyzing and planning scientific and technical activities, it is important to take into account (increase) not only the indicator of science intensity of GDP traditionally used for these purposes, but also the utility coefficient of R & D expenditures. We are convinced that the use of the new useful criteria and indicators for assessing the scientific and technical sphere that we have proposed will increase the efficiency of the resources it uses and will serve as a stimulating factor for the scientific, technical and technological development of Belarus and other friendly countries.

**Conclusion**

The unprecedented aggravation of global problems of civilization, the associated sharp complication of the geopolitical situation on the planet and, finally, the need to form a technetronic economy, urgently dictate the search for (development) of a fundamentally new socio-economic scientific and educational paradigm. It seems that the solution to this problem is possible through a wider use of useful criteria for assessing the achievements of scientific, technical and socio-economic progress instead of traditional cost indicators, which, alas, are oriented towards increasing costs. For Belarus and Russia, for a number of reasons, this is of vital importance. The fact is that the technological lag between our countries and their strategic competitors, against the background of tough technological and other sanctions applied to them, has designated a clear threat to their economic and national security.

To overcome this threat, we consider it necessary:

– to officially designate the strategy of accelerated technological development (strategy of technological catch-up) as the main state strategic priority of Belarus and Russia, subordinating its implementation to the monetary, budgetary, tax, scientific and educational, etc. policies of both countries;

– within the framework of the implementation of this strategy, the indicator of the level of technological development of the national economy of both our countries should be made not just statistically taken into account, but a strategically priority target parameter of their development, and we should also move to planning and strict control over the growth of this indicator in order to systematically reduce and eliminate the technological lag we have allowed. In particular, we consider it necessary to set the governments of Belarus, Russia and their Union State the task of ensuring a systematic increase in the indicator of the level of technological development of the union economy from its current value of 3.5–3.7 (see Figure 2) to, say, 4.5 by 2030 and 5.0 by 2035;

– the increase in the indicator of science intensity of GDP must be necessarily linked to the increase in the coefficient of utility of R & D expenditures, giving the utility parameter of development of the scientific and technical sphere significant importance.

It seems that a wider use of the utility approach to the study of socio-economic processes opens up great prospects not only for increasing the efficiency of the scientific and technical sphere, but also for solving global problems of earthly civilization generated by scientific and technical progress.

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# SOCIO-ECONOMIC SPACE OF SMALL AND MEDIUM ENTREPRENEURSHIP: MAIN ASPECTS OF POTENTIAL DEVELOPMENT

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**Abstract**

The article considers aspects of potential development of the socio-economic space of small and medium entrepreneurship. Particular attention is paid to the consideration of issues of roadmap formation, digital transformation and standardization. The roadmap for various entrepreneurial initiatives is a modern way to activate the development of small and medium entrepreneurship based on long-term planning for the development of this sector of the economy. The use of such practices in our country will solve a range of socio-economic problems in the development of small and medium entrepreneurship. The use of the Roadmap will synchronize the processes of development and support of small and medium entrepreneurship at three levels: republican, regional and local. In connection with the processes of digitalization and digital transformation of small and medium entrepreneurship, the issue of using digital platforms to support small and medium entrepreneurship arises to ensure targeting, measurability, validity, unambiguity, sustainability, achievability and attachment to a specific reporting period at various levels of government. This type of platform refers to digital government services. Options for digital transformation of state support for small and medium entrepreneurship should include the introduction of digital platforms to support small and medium-sized businesses, taking into account usability and a customer-oriented model. The model of the regional standard for state support for small and medium entrepreneurship is associated with the concept of «reputation economy» and is based on the principles and standards of customer centricity, customization based on the concepts of «quality» and «quality of public service». Customization should play a decisive role in the standard, based on the degree of budgetary provision of the regions and the development of the entrepreneurial community.

**Keywords:** small and medium entrepreneurship, space, digital transformation, roadmap, standardization.

## СОЦИАЛЬНО-ЭКОНОМИЧЕСКОЕ ПРОСТРАНСТВО МАЛОГО И СРЕДНЕГО ПРЕДПРИНИМАТЕЛЬСТВА: ОСНОВНЫЕ АСПЕКТЫ ПОТЕНЦИАЛЬНОГО РАЗВИТИЯ

**И. В. Мальгина**

**Реферат**

В статье рассматриваются аспекты потенциального развития социально-экономического пространства малого и среднего предпринимательства. Особое внимание уделяется рассмотрению вопросов формирования дорожной карты, цифровой трансформации и стандартизации. Дорожная карта для различных предпринимательских инициатив является современным способом активизировать развитие малого и среднего предпринимательства на основе долгосрочного планирования развития данного сектора экономики. Применение подобной практики в нашей стране позволит решить комплекс социально-экономических проблем в развитии малого и среднего предпринимательства. Применение Дорожной карты позволит синхронизировать процессы развития и поддержки малого и среднего предпринимательства на трех уровнях: республиканском, региональном и местном. В связи с процессами цифровизации и цифровой трансформации малого и среднего предпринимательства встает вопрос использования цифровых платформ для поддержки малого и среднего предпринимательства для обеспечения адресности, измеримости, обоснованности, однозначности, устойчивости, достижимости и привязанности к определенному отчетному периоду на различных уровнях государственного управления. Данный вид платформ относится к цифровым государственным услугам. Варианты цифровой трансформации государственной поддержки малого и среднего предпринимательства должны включать внедрение цифровых платформ для поддержки малого и среднего предпринимательства с учетом юзабилити и модели клиентоориентированности. Модель регионального стандарта государственной поддержки малого и среднего предпринимательства связана с понятием «репутационная экономика» и основывается с учетом принципов и стандартов клиентоцентричности, кастомизации на основе понятий «качество» и «качество государственной услуги». Кастомизация должна играть решающую роль в стандарте, основываясь на степени бюджетной обеспеченности регионов и развития предпринимательского сообщества.

**Ключевые слова:** малое и среднее предпринимательство, пространство, цифровая трансформация, дорожная карта, стандартизация.

### Introduction

The President of the Republic of Belarus A. G. Lukashenko in his Address to the Belarusian People and the National Assembly on April 21, 2017 noted: «The priority is to create a strong, competitive economy. The economy of tomorrow. It is the basis of our sovereignty...».

Small and medium entrepreneurship (SME) play a significant role in the development of the economy of any country in the world. The feasibility of its development is enshrined in state economic policy and programs for the socio-economic development of many countries. When developing country and regional strategies for socio-economic development, an important element inherent in these two processes is the combination of the entrepreneurial spirit and culture with the need to ensure the competitiveness of the national economy.

Entrepreneurs and their new enterprises should be the key to the effective growth and competitiveness of the economy of the Republic of Belarus. As the President of the Republic of Belarus A. G. Lukashenko said in his Address to the Belarusian People and the National Assembly on April 19, 2019: «The conditions for the development of business initiative and labor activity have been created. But, as the people say, the Lord gives food to the birds, but does not throw this food into the nest. Those who make their own efforts are successful, first in their studies, then in finding a job, professional realization anywhere in our country».

### Main aspects of potential development

The processes of transformation of the SME organizational boundaries due to the change in the landscape of state economic policy in the sphere of small and medium-sized businesses have led to the expansion of the concepts of external and internal environment of entrepreneurship. Based on the understanding of the economic space, which is also closest to the socio-economic space of small and medium entrepreneurship (SESSME), as a set of production factors, economic agents and their community, economic and social institutions, in a broad sense SESSME can be understood as a set of market, economic and social institutions, entrepreneurial processes, external and internal environment of entrepreneurship.

SME support plays an important role in economic growth and development. In connection with the processes of SME digitalization and digital transformation, the issue of using digital platforms to support SME arises. In our opinion, in order to ensure the targeting, measurability, validity, unambiguity, sustainability, achievability and attachment to a specific reporting period of the processes of formation of the SESSME, it is necessary *to develop digital platforms for SME state support* (DPSMESS) at various levels of government. In essence, the proposed DPSMESS can be a round-the-clock state service for supporting SME and be considered as a new element of the SME support infrastructure. In our opinion, this type of platform refers to digital government services. At the same time, a potential risk of the platform in question may be the inadequacy of the content and the lack of cybersecurity of both the platform and the personal accounts of SMEs.

In our opinion, public services play an important role in the formation of the SESSME, since it is such an element of the SESSME as the SME support infrastructure that provides various services to SMEs (consulting, information, marketing, etc.). At the same time, the state, as an element of the SESSME, also provides various services to SMEs (registration, liquidation, registration of intellectual property rights, etc.). In this regard, it is advisable to consider the definitions of «public service» and «business service». Various authors identify the concepts of «public» and «state» services. In our opinion, in the context under consideration, it is necessary to distinguish between state and business services. At the same time, the issue of providing business services by the SME support infrastructure is quite controversial, since it also performs the function of the state – it promotes the development of SME. In addition, the subjects of the SME support infrastructure receive status in the Ministry of Economy of the Republic of Belarus, which essentially brings their business services closer to state services. An analysis of individual types of definitions of «state service» and «business service» that are closest to the SESSME showed their similarity (Table 1, Table 2).

**Table 1** – Certain types of definitions of «public service» that are closest to the socio-economic space of small and medium entrepreneurship

| Author | Year | Definition |
|---|---|---|
| Falina A. S. [1, p. 138] | 2012 | an action by an executive authority carried out in contact with a specific citizen, legal entity, or organization, who most often themselves contact the relevant authority regarding the implementation of their legal rights and obligations |
| Rudenko I. A. [2] | 2014 | activities of executive authorities, state extra-budgetary funds, carried out at the request of applicants and aimed at obtaining benefits within the limits established by regulatory legal acts of the state |
| Kandrina N. A. [3] | 2018 | public goods intended for the entire population and provided to an individually defined person (natural or legal) at his request in the manner prescribed by law |
| Alizade oglu M. G. [4, p. 178] | 2019 | a function of an executive authority established by a legal act of management, performed by it free of charge or for a fee, at the request of an individual or organization that has voluntarily declared a desire to provide it |

Note: The author's own development based on [1–4].

**Table 2** – Individual types of definitions of «business service» that are closest to the socio-economic space of small and medium entrepreneurship

| Author | Year | Definition |
|---|---|---|
| Oganisyan N. A. [5, p. 2] | 2012 | services provided by one party to another with the aim of enhancing the latter's competitiveness or effectively promoting professional activities |
| Tyukavkin N. M. Nadein N. V. [6, p. 117] | 2015 | a set of economic relations between the producer of a given service and its consumer regarding a specific production of some economic good in an intangible form, necessary to satisfy the material and intangible needs of the customer to ensure the functioning of the organization or business as a whole, as well as to develop the efficiency of activities |
| Nadein N. V. [7] | 2015 | are intended as services for business and not as services for personal consumption |

Note: The author's own development based on [5–7].

Noting the difference and identity of public and state services, R. V. Doronkin points out that «public services are state services within the concept of a service state» [8]. From our point of view, it is the service state based on new state management that relates to the activities of state administration bodies (SAB) within the framework of building the SESSME.

In our opinion, the DPSMESS is part of the platform economy. An analysis of public service platforms showed that only the State Services Internet portal of Russia and Uzbekistan have a separate SME section. Only the Russian Internet portal has links to the SME Digital Platform and the «My Export» Digital Platform. The rest function without additional Internet links [9]. In Russia, the creation of the DPSMESS is part of the National Project «Small And Medium Entrepreneurship and Support for Individual Entrepreneurial Initiatives». An analysis of the websites of governments of individual foreign countries showed that information on state economic policy and the activities arising from it is present in almost all countries. Joint-stock company «The Federal Corporation for the Development of Small And Medium Entrepreneurship» of Russia oversees the development of the SME business navigator, which is an information resource (system) developed to ensure the organization of marketing and information support to SME. A detailed analysis showed that the information resource under consideration has all the features of a digital platform for supporting SME. In our opinion, it seems appropriate to create a single digital gateway of the Union State of Russia and Belarus for SME. A detailed analysis showed that today in Belarus there are several types of Internet resources related to the formation of the SESSME. Of the total number of analyzed Internet resources, only 53.84 % have a special SME section. Only 40.38 % of analyzed Internet resources have Internet links to SME support organizations. In our opinion, the creation of the DPSMESS is a continuation of the formation of a single gateway and is based on the concept of «the state as a platform» and at the national level should become an online connection of entrepreneurs to the SAB. The DPSMESS should also provide entrepreneurs with reliable information from the SAB of Belarus, approved by law, covering the entire range of issues related to doing business. The implementation of the DPSSSME and the digital twin of the regional entrepreneurial potential will reduce the «digital divide» and its consequence – the gap in the level of well-being of people living in one country.

*The second main area of potential development* of the SESSME is the Roadmap (RM). The role of SME in forecasting the long-term development of the country is given a fairly large place. According to the characteristics of the RM developed by M. P. Loginov, the Roadmap for the SME Development and Support (RMSMEDS) refers to the territorial, sectoral, and social types of roadmaps [10, p. 6–7]. A comparative analysis of management decision-making tools conducted by M. A. Cherepanov shows that «building a roadmap … provides a graphic plan-scenario for dynamic development...» [11, p. 56].

As noted by D. R. Belousov, I. O. Sukhareva and A. S. Frolov, «… road maps perform two interrelated functions: forecasting and planning» [12, p. 7]. For a more complete understanding of the role of the RM in the development of the SESSME, it is advisable to consider various definitions of «roadmap». A detailed analysis of various definitions of «road map», the closest to the SEPMSP, showed the closeness of these concepts (table 3).

**Table 3** – Various definitions of the «road map» that are closest to the socio-economic space of small and medium entrepreneurship

| Author | Year | Definition |
|---|---|---|
| Krylova Yu. [13, p. 15] | 2007 | a comprehensive plan for the development of an organization or industry in the medium or long term, based on the integration of product, technological and strategic planning |
| Belousov D. R. Sukhareva I. O. Frolov A. S. [12, p. 6] | 2012 | a tool for developing long-term strategies that determines optimal ways to achieve a goal, used in exploratory research that does not have set benchmarks and evaluates potential directions for the development of the area under study |
| Kotov A. V. [14] | 2013 | institutional mechanism, … a means of supporting decision-making in a complex and uncertain environment |
| Mukhametova L. R. Akhmetova I. G. Zatsarinnaya Yu. N. [15] | 2014 | a strategic plan that describes the steps an organization must take to achieve its stated results and goals |
| Karasev O. I. Doroshenko M. E. [16, p. 76–77] | 2015 | a document developed on the basis of the generalized opinion of the expert community and containing a description and visual representation of global and national challenges, as well as the most important events that can have a significant impact on the development of the subject area under consideration |
| Yakimets V. N. Kurochkin I. I. [17, p. 2] | 2020 | the selected option for the development (or improvement) of the project activities …, corresponding to the group opinion of the representatives of the distributed team of project participants, containing a description and visual representation of the desired state of the project … taking into account the capabilities and resource availability of the team |

Note: The author's own development based on [12, p. 6; 13, p. 15; 14; 15; 16, p. 76–77; 17, p. 2].

From our point of view, based on the data in Table 3, the purpose of the RMSMEDS is a development option that meets the group opinion of representatives of the state and SMEs in the medium or long term, determining the optimal ways to achieve the state's goal in the area of SME development. At the same time, a potential risk of the considered RMSMEDS may be the lack of competent experts both on the part of the state and on the part of SME.

From our point of view, the development of the RMSMEDS for various entrepreneurial initiatives is a modern way to activate the development of SME based on long-term planning for the development of this sector of the economy. The use of such practices in our country will help solve a range of socio-economic problems in the development of SME. The tasks of its formation and development necessitate the development of approaches to solving the issues of optimizing the system of SME state support as a key direction to a market economy based on the development of the DC in all SME areas development and support.

In our opinion, the RMSMEDS will synchronize the processes of SME development and support at three levels: national, regional and local. The creation of effective RM requires an understanding of the appropriate time horizon. If the planning horizon is too short, the RMSMEDS may jeopardize the consistency and ability to communicate new future functions and opportunities. The algorithm for developing the RMSMEDS should have several stages, including regional champions; a culture of entrepreneurship and innovation, etc.

When developing the RMSMEDS, it is advisable to use various types of state economic policy related to the SESSME and the SESSME canvas. At the same time, planning for the development of the SESSME should be comprehensive, functional, and long-term.

*The third main direction of the formation of the SESSME* should be the regional standard of SME state support (RSSMESS) based on the principles and standards of client-centricity, taking into account the customization of the state program of SME support. At the same time, it is customization that ensures the individualization of services of the SME support infrastructure and other organizations that support SMEs and are elements of the SESSME. At the same time, a potential risk of the RSSMESS under consideration may be excessive enthusiasm on the part of the state for satisfying the desires of the business community. Customization should play a decisive role in the standard, based on the degree of budgetary provision of the regions and the development of the entrepreneurial community (Table 4).

**Table 4** – Individual types of definitions of «customization» that are closest to the socio-economic space of small and medium entrepreneurship

| Author | Year | Definition |
|---|---|---|
| Vedernikova A. A. [18] | 2007 | individualization of relations between producer and consumer |
| Dyachkova M. S. [19] | 2020 | the process of delivering to a broad marketplace goods and services that are modified to meet the needs of a specific customer |
| Lopanova E. V. Savina N. V. [20] | 2021 | individualization of services and goods in order to achieve maximum satisfaction of the end customer |

Note: The author's own development based on [18–20].

It also plays an important role in the development of the priority of the Social and Economic Development Program of the Republic of Belarus for 2021–2025 and subsequent programs in the «partner state» section, since the psychological property of customization «implies not only an individual approach to satisfying the needs of customers, but also a psychological technique, since while the client selects the configuration of the product «for himself», he begins to feel like the owner of this thing» [21].

When considering the standards of public services, it is necessary to turn to the concepts of «quality», «quality of service», «quality of public service», which are very important in the context of the RSSMESS. We agree with the opinion of A. S. Fraiman that «the category «quality» characterizes not so much the internal properties of an object as its external properties, the features of its interaction with other objects» [22, p. 47]. From our point of view, the development of the RSSMESS is part of the formation of the reputation of the region and the government. It is necessary to develop a matrix of competencies required by client-centric entities of the entrepreneurship support infrastructure based on their human resources and the needs of SME. In our opinion, the client-centricity of the RSSMESS should be based on the classical new public administration, but not the new public and social administration, including civil-centric and human-centric approaches. In order to form a client-centric approach to the RSSMESS, it is necessary to use such tools as feedback, research, training, entrepreneurial thinking, etc. Mandatory digitalization of the results of client-centric actions within the RSSMESS is necessary.

**Conclusion**

Taking into account the above, the following conclusions can be drawn:

– options for SME digital transformation state support should include the introduction of the DPSMESS taking into account usability and a customer-oriented model. The implementation of the DPSMESS will essentially allow the organization of a round-the-clock state service for supporting SMEs to ensure the targeting, measurability, validity, unambiguity, sustainability, achievability and attachment to a specific reporting period of the processes of forming the SESSME;

– RMSMEDS will allow synchronizing the processes of SME development and support at three levels: republican, regional and local. In essence, the RMSMEDS for various entrepreneurial initiatives is a modern way to activate the development of SME based on long-term planning for the development of this sector of the economy;

– the RSSMESS model is associated with the concept of «reputation economy» and is based on the principles and standards of customer centricity, customization based on the concepts of «quality» and «quality of public service». At the same time, customization should ensure individualization of services for SMEs from the state and the SME support infrastructure.



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# IMPROVEMENT OF METHODS AND TOOLS FOR MANAGING INVESTMENT ACTIVITIES AT THE REGIONAL LEVEL IN THE REPUBLIC OF BELARUS

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**Abstract**

The need to increase investment activity in the regions, which is a factor in their socio-economic development, is one of the strategic guidelines for medium-term planning of the regions of the Republic of Belarus and requires a revision of approaches to its management at the regional level from the perspective of the dynamics of modern economic conditions. The deficit in investments increases the relevance of revising the methods of investment activity management and finding tools for stimulating investment processes adapted to modern economic conditions, contributing to the accumulation of investment resources in the region. The purpose of the research article is to formulate practical recommendations for refining the management methods of investment activity at the regional level in the Republic of Belarus by advancing their regulatory and stimulating tools. The theoretical basis for the research is the works of domestic and foreign authors, the legislative framework, as well as scientific and practical literature devoted to the issues of investment activity management, methods and tools for its regulation, stimulation of investment processes and investment activities at the regional level. The study applied a systems approach, general logical (analysis, synthesis, comparison, generalization, analogy), and special (monographic) methods of cognition. The article examines the specifics of regional management practices in the Republic of Belarus and makes proposals for improving the tools for managing regional investment activity across four groups of methods: administrative (methodological apparatus for forming a list of priority activities (economic sectors) for implementing investments at the regional level), economic (measures stimulating the practical implementation of the public-private partnership mechanism, with the formalization of the organizational and economic mechanism for influencing public-private partnership on the investment activity of the region), institutional (creation of a specialized organization at the regional level to work with investors in the "single-window" mode), and organizational and managerial (creation of a regional web platform for working with investors). The article reveals the content and practical aspects of implementing the tools. The results obtained can be used by meso-level government bodies in developing and implementing regional investment policy.

**Keywords:** region, investment activity, management methods, tools, regulation, stimulation areas, regional investment policy.

# СОВЕРШЕНСТВОВАНИЕ МЕТОДОВ И ИНСТРУМЕНТОВ УПРАВЛЕНИЯ ИНВЕСТИЦИОННОЙ АКТИВНОСТЬЮ НА РЕГИОНАЛЬНОМ УРОВНЕ В РЕСПУБЛИКЕ БЕЛАРУСЬ

**Н. А. Мацукевич**

**Реферат**

Необходимость повышения инвестиционной активности регионов, являющейся фактором их социально-экономического развития, выступает одним из стратегических ориентиров среднесрочного планирования регионов Республики Беларусь и, требует ревизии подходов к управлению ею на региональном уровне с позиции динамики современных условий хозяйствования. Дефицит в инвестициях повышает актуальность пересмотра методов управления инвестиционной активностью и изыскания адаптированных к современным условиям хозяйствования инструментов стимулирования инвестиционных процессов, способствующих аккумулированию инвестиционных ресурсов в регионе. Целью исследования статьи является выработка практических рекомендаций по совершенствованию методов управления инвестиционной активностью на региональном уровне в Республике Беларусь посредством развития их регулирующих и стимулирующих инструментов. Теоретической основой исследований послужили труды отечественных и зарубежных авторов, законодательная база, а также научно-практическая литература, посвященные вопросам управления инвестиционной активностью, методам и инструментам ее регулирования, стимулирования инвестиционных процессов и инвестиционной деятельности на региональном уровне. В ходе исследования применены системный подход, общелогические (анализ, синтез, сравнение, обобщение, аналогия), специальный (монографический) методы познания. В статье изучены особенности управленческой практики на региональном уровне в Республике Беларусь и внесены предложения по совершенствованию инструментов управления инвестиционной активностью региона в разрезе четырех групп методов: административных (методический аппарат по формированию перечня приоритетных видов деятельности (секторов экономики) для осуществления инвестиций на региональном уровне), экономических (меры, стимулирующие практическое внедрение механизма государственно-частного партнерства, с формализацией организационно-экономического механизма влияния государственно-частного партнерства на инвестиционную активность региона), институциональных (создание на региональном уровне специализированной организации по работе с инвестором в режиме «одно окно»), организационно-управленческих (создание региональной web-платформы для работы с инвестором). Раскрыты содержание и практические аспекты реализации инструментов. Полученные результаты могут быть использованы органами государственного управления мезоуровня при разработке и реализации региональной инвестиционной политики.

**Ключевые слова:** регион, инвестиционная активность, методы управления, инструменты, регулирование, направления стимулирования, региональная инвестиционная политика.

**Introduction**

Regional investment activity is a property of the regional economic system that dynamically reflects the intensity of investment activity in the region, taking into account the scale, focus, and effectiveness of investment within it [1]. Its level is determined by the participation of the region (its constituent entities) in the investment process through available internal investment resources (funds of business entities, borrowed funds, local budgets, and others), attracted funds (foreign, national budgets, and others), and the achievement of investment goals through existing opportunities and potential with maximum economic, budgetary, environmental, and social impact [2].

High investment activity in a region predetermines the potential for its investment-based socioeconomic development and is a key factor in the region's long-term economic growth [3], which is especially significant in the context of modern challenges associated with limited resource flows and the need to improve the efficiency of investment activities.

Despite the measures taken in recent years to improve legislation regarding investment implementation, the provision of benefits and preferences, and the expansion of the range of investment management tools, the problem of increasing investment activity remains highly relevant for regional government bodies and requires further refinement of management methods and tools, taking into account current economic conditions and environmental dynamics.


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As part of a comprehensive analysis of foreign [4, 5] and domestic experience in stimulating investment processes at the regional level [4, 6–11], a gap in the practice of regulating regional investment activity was identified and areas for improving investment regulation tools in the regions of the republic were identified, requiring further development and detailing in terms of practical implementation.

The purpose of this article is to develop practical recommendations for improving investment management methods at the regional level in the Republic of Belarus through the development of regulatory tools aimed at creating conditions conducive to increasing investment potential and accumulating investment resources in the region.

**Proposals for Improving Investment Activity Management Methods at the Regional Level**

An analysis of domestic practice in managing investment activity at the regional level has shown that the investment activity management mechanism presented in [1] is functioning in the regions of the Republic of Belarus.

In terms of the composition of the entities, regional investment activity management is characterized as multi-level: government bodies, economic entities and public organizations of the region, and local governments.

In general, at the regional level, the powers to formulate and implement regional investment policy and the main functions for regulating investment activity and investment activities are accumulated in the economics committees of the regional executive committees (meso-level) and in the economics departments and divisions of the city and district executive committees (micro-level).

Regional investment activity management in the republic is carried out within the framework of: a) state regulation and internal management across 5 modules (institutional, economic, personnel, marketing, and information support) [2]; b) 4 groups of management methods: administrative, institutional, organizational and managerial influence, economic [1]; c) strategic, tactical, and operational planning of socio-economic development;
d) implementation of regional investment policy.

The main elements of regional investment policy are:

– adoption, within the limits of legal authority, of its own legislation (decisions of the regional and Minsk city executive committee, regional and Minsk city Council of Deputies), regulating the investment process [12];

– development of medium- and short-term strategic planning documents for the development of investment activities and socio-economic development, including investment components (strategies, programs, plans);

– regional investment budgeting;

– provision (within the limits of authority) of various financial and non-financial benefits and stimuli to investors [7–11];

– creation of organizational structures in the field of entrepreneurship to promote investment at the regional level (entrepreneurship support centers, incubators, science and technology parks, etc.) and in the field of innovation;

– development and evaluation of investment projects financed by public sources [13];

– assisting investors in obtaining (providing) tax and customs benefits [13];

– providing guarantees and sureties to banks for funds allocated by them for the implementation of investment projects selected on a competitive basis;

– ensuring the functioning of stock market and securities market institutions in the region;

– increasing investment attractiveness and attracting investors to create new production facilities and develop the service sector in the administrative-territorial units of the region (microregions), etc.

In the course of a comprehensive analysis, the feasibility of improving the tools used to regulate and stimulate regional investment activity in domestic practice was revealed in the direction of creating conditions conducive to inducing investment activity in the regions of the republic. Given the specifics of regulating investment activity and implementing investment processes at the regional level, it is proposed to develop organizational and economic tools for managing investment activity at the regional level by improving management tools across four groups of management methods.

**Administrative Methods**

A distinctive feature of foreign investment activity stimulation practices within this group of methods is the support of enterprises and industries, key (priority) economic sectors and areas of activity [4], and the differentiation of key (priority) areas and industries to stimulate and attract investment, including foreign investment. A study of foreign and domestic experience in managing regional investment activity revealed the feasibility of forming key investment sectors taking into account the specifics of a region's production and investment specializations, the level of development of investment potential, and the institutional structure of the region's economy.

In domestic practice, the list of priority activities (economic sectors) for investment and the minimum investment volume for the implementation of investment agreements are defined by legislation at the national level [14], granting regional authorities (regional executive committees) the right and authority to regulate the regional list at the regional level [13] for the implementation of preferential investment projects. It would be appropriate to regulate priority activities (economic sectors) for investment at the regional level with a broad scope of application, including for the implementation of preferential projects. The methodological approach and results of assessing the current and prospective investment specialization of a region, as outlined in [15], are proposed as a methodological tool for developing such a list. Priority activities should be considered in sectors (types of economic activity) with current and prospective investment specialization and sectors with potential for investment specialization [15].

Developing this list at the regional level using methodologically sound methods for assessing the priority of financing sectors (sections of the economy) will allow for focusing investments on the types of economic activity that yield the greatest return in the form of a multiplier effect from investments and growth in regional investment activity.

**Institutional Methods**

International experience shows that the effectiveness of government stimuli for investment activity depends on both the set of tools and the economic situation, as well as the investment attractiveness of the region. Therefore, to ensure a stable influx of investment into economic entities, it is necessary to consolidate the efforts of regional authorities in this area and create a developed, functional investment infrastructure. The analysis of regional investment infrastructure in the Republic of Belarus has established the feasibility of its development.

As a tool for developing the investment infrastructure of the republic's regions, it is proposed to establish a specialized organization at the mesoregional level – a regional state institution, the Investment Development Agency (hereinafter referred to as the Agency) – to attract investment and work with investors, ensure interaction between state/local authorities and investors, and support investment projects using the "one-stop-shop" principle. At the initial stage of its operation, partial funding of the organization from the local budget and extra-budgetary activities is advisable.

The Agency's main activities include: supporting the development and implementation of regional investment policy; providing information and consulting support to investors; Interacting with investors to support investment projects; promoting the region's investment attractiveness.

The agency's overall objectives will be:

– analyzing and regulating investment activity and investment potential in the region;

– attracting investment to the region's economy, creating a favorable investment climate, and enhancing its investment attractiveness;

– providing customized support for investment projects at all stages of implementation;

– providing information and consulting support to investors and investment project initiators;

– creating, maintaining, and updating a regional web-platform and reference and information databases on the website of the Regional Executive Committee (Minsk City Executive Committee) regarding the region's investment opportunities;

– organizing and holding events;

– developing and promoting public-private partnerships (hereinafter referred to as PPP);

– conducting training courses (seminars) in investment implementation;

– ensuring the development of professional competencies in investment;

– outsourcing the functions of the Economics Committee of the Regional Executive Committee (Minsk City Executive Committee), etc.

The target audience is consumers of the agency's services (start-up and existing entrepreneurs, organizations/enterprises, domestic investors, foreign investors, and local governments).

The creation of an investment institute will shorten the investor's customer journey, improve the quality of forecasting and development of investment projects, and the formation of a regional investment portfolio. It will also ensure growth in investment activity and the investment attractiveness of the region, as well as provide methodological support to executive authorities in implementing the region's investment policy and investment strategy.

As demonstrated by the practice of the Russian Federation in establishing regional development agencies [16], the Federal Republic of Germany in establishing state economic development agencies and district economic development agencies [17], and Japan in establishing Single Contact Points for Foreign Investors in ministries and departments, including major embassies and consulates general [18], this institution is successfully functioning, creating the conditions for increased investment activity in the regions.

**Methods of organizational and managerial influence**

The analysis conducted in [4] revealed the need to streamline information support for investment activities at the regional level in the Republic of Belarus and predetermined the development of investment activity management tools using this method through the creation of a regional web-platform for working with investors. This platform represents a digital complex of systematized information for investors, including the ability to interactively consult with potential investors in real time. The feasibility of its implementation is determined by the interregional fragmentation of information regarding investment activities [19, 20], presented on a variety of information resources, which creates difficulties for investors in analyzing, systematizing, and formulating investment decisions applicable to the region. Furthermore, this tool is aimed at increasing investment activity, taking into account the regional specifics of investment processes and the socio-economic development of the region in contrast to the Investment Portal of the Republic of Belarus, which operates at the national level [21].

The following services are proposed for creation on the regional web platform:

– "Benefits and Preferences", which displays in tabs current benefits and preferences provided at the regional level by preferential regimes: FEZ (tabs: preferential regime; available space and land plots; available production sites within the FEZ; FEZ website), science and technology parks (benefits provided taking into account decisions of local authorities), the State Innovation Program, in the sector of small and medium-sized businesses (hereinafter referred to as SMEs), investment agreement, preferential project, PPP, territories of medium-sized and small urban settlements, rural areas, and others, taking into account regional specifics;

– "Priority sectors (foreign economic activity) for investment financing";

– "Regional investment specialization";

– "Regulatory Framework" – a list of regulatory acts in the field of investment activity at the state and regional level, state support, business implementation in the SME sector, implementation of innovative projects, and others with a link to the current web resource of the regulatory framework (ilex.by or pravo.by);

– "Offers" – constantly updated information with a breakdown by proposal and tabs: investment proposals; investment ideas; vacant production sites; vacant land plots; regional initiative; list of unused equipment offered for sale; property (list of property offered for sale), list of concession objects, etc.;

– "Investment infrastructure" – up-to-date information on services and contacts broken down by tabs of institutions: participants in the investment process with information or a link to a website or resource (structural divisions of the regional executive committee; the Belarusian Fund for Financial Support of Entrepreneurs; commercial banks located in the region; JSC "Development Bank of the Republic of Belarus", etc.);

– "Investment resources" tabs broken down by sources – "Credit resources": information on credit resources provided by commercial banks and JSC "Development Bank of the Republic of Belarus" and the terms of their provision (link to credit projects and programs) or tabs broken down by banks; "Innovation Fund": up-to-date information on the competition for resources from the regional or national innovation fund, and the terms and conditions; "Budget Subsidies": updated information on the terms, competitions, competition results, and subsidy provision; "Subsidies for SMEs," and more.

– "Microregions/ATE" – up-to-date information by microregion – current investment passports reflecting the investment potential and attractiveness of the microregion; investment proposals (ideas); regional initiatives, available land plots; production sites; benefits and preferences taking into account microregional characteristics; property, equipment, list of concession objects;

– "Implemented Projects"– up-to-date information on investment projects implemented in the region this year and in previous periods (landmark projects);

– "Investment Development Agency" – About Us tab; services; cost of services; contacts; news (information on projects implemented with the Agency's assistance; past events, etc.);

– "Training/Courses" – a list of educational programs and terms;

– "Ask a Question" – interactive online consultation via a chatbot;

– "News" – key developments in investment implementation in the region, including legislative updates, etc.

Implementing the platform at the regional level will shorten the investor's journey to implementing an investment project and making an investment decision by providing systematized, up-to-date information, and will create a comprehensive investment image for the region.

**Economic Methods**

Given the persistent shortage of investment resources (budgetary resources and businesses' own funds for investment financing) for the development of certain sectors of industrial and social infrastructure (energy, transport, road management, education, healthcare, culture, and others) in the regions [2, 22], it is advisable to optimize the project management system by implementing PPP [23] mechanisms and concentrating private investment resources on a long-term basis [4].

It should be noted that at the regional level, project implementation is most often supported by enterprises playing a significant role in the regional economy. However, this is not always comprehensively effective. For the socioeconomic development of a region, investment is often necessary in socially significant projects that do not yield immediate economic results but have a high social impact. For this purpose, PPP-based investment mechanisms are widely used in the global market [2, 22, 24].

Analysis of international experience has led to the conclusion that the implementation of PPP projects creates a multiplier effect in regional economies [22]. Thus, the implementation of PPP projects facilitates additional utilization of production capacities in the regions, provides orders to design and construction organizations servicing organizations during the operational phase, creates conditions for the accumulation of investment resources, and increases investment activity for both individual economic entities and the region as a whole, as reflected in the formalized model of the organizational and economic mechanism of PPP influence on regional investment activity (figure). The presented organizational and economic mechanism takes into account the specifics of investment activity at the regional level in the Republic of Belarus.

To enhance the practical implementation of the PPP mechanism as a means of implementing investment projects and simultaneously developing regional investment activity, it is advisable to increase the visibility of PPPs through the following measures:

– support and promotion of the PPP-based investment project implementation method by the Investment Development Agency (media, interactive advertising, conferences, etc.);

– training seminars/courses conducted by the Investment Development Agency for local government employees, potential investors, and the business community;

– posting proposals (with information on the cost and financial model of the proposed project) and up-to-date information on project implementation on the regional web-platform.

The development of PPPs for the purpose of attracting investment and increasing investment activity is defined as one of the areas of investment policy implementation for the Republic of Belarus and its regions within the framework of the Socioeconomic.

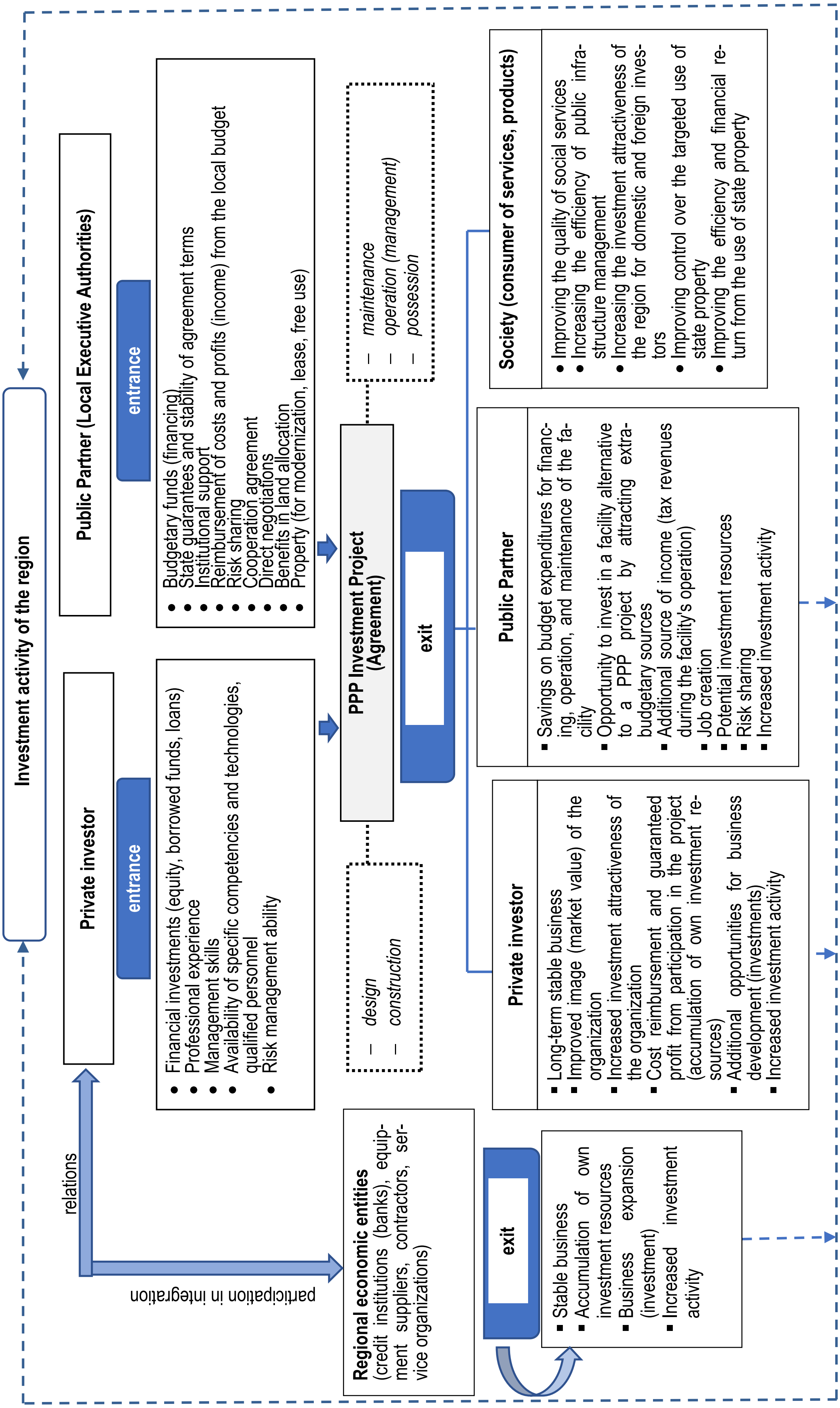


**Figure** – Mechanism of PPP influence on regional investment activity

Note – own development based on [2, 22–24]

Development Programs for 2021–2025 [25], as well as strategic policy documents for the long and medium term.

The use of PPPs has an economic and social impact due to the reduction of administrative costs and operational risks. Exclusively state financing of investment processes increases the burden on the budget, therefore, the effectiveness of financing investment projects based on the PPP mechanism is based on the use of a diversified set of state support tools.

**Conclusion**

Implementation of the author's recommendations for state regulation of investment activity at the regional level through administrative, institutional, economic, and organizational management methods, which include improving investment management tools, will improve the quality and validity of investment decisions at the regional level, both in terms of implementing investment projects and regulating investment activity, including:

a) improving investment institutions and the mechanism for interaction between investors and local authorities;

b) implementing the principle of supporting investment projects and working with investors in a "single-window" mode;

c) improving investor information support and providing them with access to a systematized database of investment information resources applicable to the region;

d) stimulating the implementation of the PPP mechanism as a tool for developing regional investment activity and the launch of investment projects based on it;

d) focusing investments and corresponding benefits and preferences on priority sectors (types of economic activity) for the region, including at the legislative level.

The obtained results can be used by meso-level government bodies in the development and implementation of regional investment policy.

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# INDICATORS FOR ASSESSING THE STATE OF SCIENTIFIC AND TECHNOLOGICAL SECURITY

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**Abstract**

This research article examines various approaches to defining scientific and technological security indicators. It contains an analysis of the scientific literature to identify scientific and technological security indicators and their applicability. The authors' approaches to identifying relevant indicators are presented. These approaches depend on the scope of their application and conditions of use for assessing the state of scientific and technological security. Criteria for applying these indicators to assess scientific and technological security are established. International rankings and official statistical information available for assessment are also used as information sources. Special attention is paid to educational potential indicators. Indicators related to scientific research and the technological development of the national economy are examined. Considerable attention is given to indicators used to evaluate various government programs related to scientific and technological potential.

Relevance: The importance of the research subject for the development of the national economy of the Republic of Belarus is highlighted. Today, ensuring scientific and technological security is becoming increasingly important given the importance of technological development for the national economy and society as a whole.

The aim of the research: To identify indicators that can be used to analyze scientific and technological security through its components: scientific, technological and educational potentials.

Materials and methods: While preparing this article, we used scientific literature, international rankings, official statistical information, and regulatory legal acts defining the content of state programs in the field of innovation and science.

Results and conclusions: The principles for defining scientific and technological security indicators have been determined, and key indicators reflecting the state of scientific, technological, and educational potential have been identified. The indicators of state programs are examined as a means of reflecting these potentials.

The purpose of this study is to identify and classify indicators that can be used to assess scientific and technological security.

**Keywords:** scientific and technological security, scientific and technological potential, educational potential, R&D, innovative development, state programs, rating.

## ПОКАЗАТЕЛИ ОЦЕНКИ СОСТОЯНИЯ НАУЧНО-ТЕХНОЛОГИЧЕСКОЙ БЕЗОПАСНОСТИ

**А. С. Новиков**

**Реферат**

В данной научной статье исследованию подверглись различные подходы, направленные на определение показателей научно-технологической безопасности. Проводится анализ научной литературы на предмет определения показателей научно-технологической безопасности и возможности их использования. Установлены критерии применения показателей для оценки научно-технологической безопасности. В качестве предмета исследования используются также международные рейтинги и официальная статистическая информация, доступная для проведения оценки. Отдельно внимание уделено показателям образовательного потенциала. По общему направлению изучаются показатели, связанные с научными исследованиями и технологическим развитием национальной экономики. Значительное внимание уделено показателям, используемым для оценки различных государственных программ, связанных с научно-технологическим потенциалом.

Актуальность: представлена важностью предмета исследования для развития национальной экономики Республики Беларусь. Сегодня обеспечение научно-технологической безопасности выходит на первый план в контексте важности технологического развития для экономической системы государства и общества в целом.

Цель исследования: определить показатели, которые могут быть использованы для анализа научно-технологической безопасности посредством ее составляющих: научно-технологического и образовательного потенциалов.

Материалы и методы: в процессе подготовки статьи использовалась научная литература, данные международных рейтингов, официальная статистическая информация, нормативные правовые акты, определяющие содержание государственных программ в области инноваций и науки.

Результаты и выводы: выделены принципы определения показателей научно-технологической безопасности, установлены основные показатели, отражающие состояние научно-технологического и образовательного потенциалов. Исследованы показатели государственных программ как способа отражения указанных потенциалов.

Назначение исследования состоит в определении и классификации показателей, которые могут быть использованы для оценки научно-технологической безопасности.

**Ключевые слова:** научно-технологическая безопасность, научно-технологический потенциал, образовательный потенциал, НИОК(Т)Р, инновационное развитие, государственные программы, рейтинг.

## Introduction

The legislatively established formulation of scientific and technological security (abbreviated as STS) as the state of protection of scientific, technological, and educational potentials from threats that hinder the development of scientific activities, the creation and implementation of innovations, and advanced technologies in the real economy sector and other areas [1] is the starting point that is used by officials and state authorities, responsible for its provision. Generally, the above mentioned policymakers are involved in the formation of scientific, technological, and educational potentials.

The official definition of the STS allows to differentiate the state of the designated potentials in order to identify their presence and possible subsequent assessment.

The assessment of the state of STS is important in the context of scientific research and significantly more for achieving the goals of the state's economic policy, industrial production, the development of the scientific sphere, and others. Establishing the evaluation indicators of scientific and technological security, that is of prior importance for its assessment, is necessary to reveal its subject thoroughly, establish connections between its components, and thus gain the ability to influence the scientific and technological sphere of the country by affecting the actors involved in creating scientific, technological, and educational potentials.

**Principles and indicators for assessing the state of scientific and technological security**

It should be noted that significant attention is paid by researchers to the issues of ensuring scientific and technological security and scientific and technological development. The most significant contribution is made by Russian scientists, who have historically been the first to explore various aspects of STS, considering local specifics. Among the most well-known theorists of scientific and technological security A. E. Varshavsky can be mentioned. His works pay significant attention to the issues of STS and technological development in Russia as a whole. The works of A. I. Ladynin, who highlighted the basic indicators of STS, are of great importance for identifying such indicators. The researcher proposed a model of the system of indicators and drew attention to the possibilities of using neural networks, as well as stock indices for the purpose of monitoring STS. Considering the close connection between STS and technological security, L. D. Kapranova studied the impact of the sanctions regime on the ability to ensure technological security in the Russian Federation.

It is worth to note the approach of some researchers who define STS as part of economic security, using relevant indicators. Belarusian researchers, in particular, V. F. Bainev and T. Yu. Goraeva, in their works allocate an important role to STS in ensuring economic security, considering the problem of technological development as one of the most significant in the development of the national economy. E. V. Presnyakova separately highlights high-tech industries as the basis for forming the added value of the manufacturing industry abroad, which is also promising for the Republic of Belarus.

In general, as a result of analyzing the works presented in the scientific literature, it can be noted that the subject area of STS is reflected in them fragmentarily, and the indicators and mechanisms for its assessment do not cover a significant number of processes and/or participants in creating scientific, technological, and educational potentials, which necessitates further research.

Since STS affects processes occurring not only in recognized sectors of the national economy but also in the education sector, scientific activities, innovative development, and others, the assessment of the state of STS can be described as a complex, multifaceted process that involves multiple objects of assessment. As one of the ways to assess scientific, technological, and educational potentials, the most well-known international rankings related to them can be considered. The advantage of using such rankings and assessments is their wide recognition worldwide, the general acceptance of the methodology used, and the lack of necessity to spend resources on conducting assessments independently. Disadvantages include subjectivity concerning some countries, which significantly distorts the results; the narrow focus of applying such rankings, neglecting local specifics that significantly affects national economies. Nevertheless, an external look on Belarusian science allows to present its state from a different perspective, reflecting its specifics and thereby determining areas for effort application to enhance the effectiveness of activities taken to support it.

Table 1 presents some of the most well-known international ratings and their indicators reflecting certain components of scientific, technological and educational potentials of the Republic of Belarus.

**Table 1** – International ratings and their indicators reflecting certain components of scientific, technological and educational potentials

| Index | Index Position of the Republic of Belarus, 2024 (total number of countries) |
|---|---|
| Sustainable Development Goals Index (SDG INDEX) | 30 (166) |
| Graduates in Natural Sciences and Engineering | 13 (133) |
| Patent applications for utility models of the Global Innovation Index | 12 (133) |
| Indicator «Science and technology» of the Good country index | 34 (185) |
| Indicator «Global Contribution to Science and Technology» of the Good country index | 55 (174) |
| Indicator «Human capital and research» of the Global Innovation Index | 43 (133) |
| Indicator «Knowledge and Technology Outcomes» of the Global Innovation Index | 46 (133) |

Note – Source: [15–17].

The content of Table 1 indicates that the state of Belarusian science is assessed abroad at a fairly high level.

Indicators that can be used to assess STS are indicative. They belong to the components of STS, forming its subject area, and can be used, among other things, to assess the scientific and technological development as well as the state of the scientific and technological sphere of the country as a whole.

It is appropriate to start identifying indicators of scientific and technological security with the basic area by which they are defined – the Concept of National Security of the Republic of Belarus, approved by the decision No. 5 of the All-Belarusian People's Assembly on April 25, 2024. The main indicators of national security are determined by paragraph 70 of the Concept. By examining these indicators, the following related to scientific, technological and educational potentials can be chosen:

– the share of innovatively active organizations in the total number of manufacturing organizations;

– internal research and development costs.

Scientific, technological and educational potentials in the context of their connection with STS should be considered in a comprehensive manner, together with the elements that form them. Assessment of the indicated potentials is possible by conducting a single-level assessment – through the analysis of quantitative indicators and a two-level assessment – by analyzing the results obtained at the first level in order to identify trends.

Scientific, technological and educational potentials cannot be considered as an independent subject of assessment without separation from the participants involved in the process of their creation, since they do not exist separately from them. Accordingly, assessment indicators should reflect the state and (or) activities of such participants. Among them business entities, scientific organizations, government agencies, etc. can be distinguished [18, p. 7].

Educational potential created with the participation of educational institutions is necessary in the process of providing STS due to the need for a competent personnel capable of conducting scientific research, creating new technologies, and introducing them into the production process.

One of the components of the educational potential is the training of highly qualified scientific personnel. On the basis of practice it is appropriate to state that experienced researchers who have devoted considerable time to scientific research and have achieved significant results in the particular scientific area by defending a candidate and (or) doctoral dissertation are more successful in research activities.

Assessment of the country's educational potential can be carried out according to the indicators in Table 2.

The analysis of the actual (quantitative) values of the indicators for assessing educational potential specified in Table 2 for a certain period, including using such additional criteria as gender and age structure, territorial distribution, etc., makes it possible to establish a change in potential and identify trends.

Indicators used to assess scientific, technological and educational potentials should meet such criteria (conditions) as:

1) Belonging to scientific, technological and educational potentials. It is mandatory to have a direct, – in some cases indirect – connection of the indicator with a certain potential.

2) Accessibility. The actual value of the indicator, other information about it, should be available to the participant in the assessment process.

3) Applicability. Quantitative, qualitative and/or other characteristics of the indicators should provide an opportunity for assessment.

4) Objectivity. The indicator should objectively reflect the state of scientific, technological and (or) educational potentials, without any distortions.

5) Sufficiency. The assessment methodology used, including the set of indicators, should fully reflect the status of the indicated potentials.

6) "Local" character. The indicator used for the assessment should be presented by local actual data, which is associated with the peculiarities of the national economy and the possibilities of assessment. Such indicators can be represented, for example, by official statistics of a government agency.

One of the directions for assessing scientific, technological and educational potentials is the publicly available indicators and their actual values provided by the National Statistical Committee of the Republic of Belarus (abbreviated as Statistics Committee). These indicators have open access - you only need to have access to the Internet - and a fairly wide coverage of the subject area of STS.

Above mentioned indicators, presented in such areas as: "science," "innovation," "technological development of sectors of the economy of the Republic of Belarus," correspond to the suggested criteria. They cover the national economy as a whole depending on a certain direction of assessment.

The indicators presented by the Statistical Committee in the direction of "science" can be divided into two areas: the personnel, engaged in scientific activities and the indicators of organizations performing research and development.

**Table 2** – Educational potential indicators

| Indicator | Value | Dynamics for 1 year, five years |
|---|---|---|
| Number of institutions that implement programs of* | x | x |
| secondary special education | x | x |
| higher education, advanced higher education, specialty | x | x |
| Number of students of secondary specialized education institutions * | x | x |
| Number of graduates from secondary specialized education institutions * | x | x |
| Number of students of higher education institutions, specialty *, ** | x | x |
| Number of graduates from higher education institutions, specialty *, ** | x | x |
| Number of students enrolled in advanced higher education programs * | x | x |
| Number of graduates enrolled in advanced higher education programs * | x | x |
| Number of institutions that provide postgraduate studies | | |
| Number of institutions that provide doctoral studies | x | x |
| Number of postgraduate students | x | x |
| Number of doctoral students | x | x |
| Number of graduates qualified as «Researcher» in the reporting year | x | x |
| Number of certified PhD candidates | x | x |
| Number of certified doctors | x | x |

Note: * specialties that are used for the assessment relate to scientific and technological potential (technical, engineering, biological, medical, physical and mathematical, etc.).

The specialties used for the assessment are chosen in accordance with the national classifier of the Republic of Belarus OKRB 011-2022 «Specialties and Qualifications», approved by the Decree of the Ministry of Education of the Republic of Belarus dated March 24, 2022 No. 54.

For example, specialties with codes: 6-05-0113-04 (05), 0311, 0411, 0511, 0531, 0533, 06, 07, 081, 09 can be used for specialties, qualifications and the degree of general higher education, providing the degree "Bachelor."

* * retraining specialties may also be included in the group.

Source: author's own result of studies based on [19], [20].

The scientific workforce can also be identified and, accordingly, analyzed separately as part of the overall research capacity and as one of the characteristics of the research and development (abbreviated as R&D) process in conjunction with the assessment of the performance of organizations involved in the R&D process. The pointed indicators classified in accordance with the "cost-result" principle are given in Table 3.

According to the current methodology, "employees" refers to only full-time employees of the organization. External part-timers and persons working under civil contracts are not taken into account [20].

Statistical accounting also does not reflect external costs for R&Ds performed under contracts by external contractors.

Analysis of the content of Table 3 allows to identify quantitative indicators of investments (costs) ("input"), result ("output"), personnel potential ("researchers"). Accordingly, the effectiveness of activities in the field of research and development can be conventionally defined as the ratio of invested resources and the result obtained.

One of the directions for assessing the state of scientific and technological potential is the assessment of the technological development of sectors of the economy, which is a significant factor affecting the provision of scientific and technological safety. This direction of assessment is determined by the importance of technological development for the national economy and the material welfare of society as a whole, since high-tech goods have the greatest added value. The assessment methodology used in the Republic of Belarus is based on the statistical classification of economic activity NACE Rev. 2.0, that is widely known and used around the world. Indicators for assessing the technological development of the national economy, involving their classification on determining and status indicators, are given in Table 4.

**Table 3** – Indicator of the Research and development organizations

| Indicator Value by year | Value by year (previous period) | Value by year (current value) |
|---|---|---|
| Status indicator | | |
| Number of: | | |
| R&D organizations (total),<br>of which (those, that represent): | x | x |
| public sector | x | x |
| commercial sector (business sector) | x | x |
| higher education sector | x | x |
| non-commercial sector | x | x |
| employees *: | x | x |
| of them researchers,<br>of them: | x | x |
| candidates of science | x | x |
| doctors of science | x | x |
| Cost indicator | | |
| Internal R&D costs | x | x |
| of which current costs | x | x |
| Performance indicator | | |
| Amount of R&D performed, R&D services rendered | x | x |

Note – Source: compiled by the author on the basis of [20].

**Table 4** – Indicators of assessment of technological development of the national economy

| Indicator | Value by year (previous period) | Value by year (current value) |
|---|---|---|
| Defining indicator | | |
| Labor productivity index by the type of economic activity | x | x |
| Index of change of stock-making capacity by the types of economic activity | x | x |
| Index of change in fund output by the type of economic activity | x | x |
| Commissioning of fixed assets for 1 thousand rubles of investments by the types of economic activity | x | x |
| The share of investments in machinery and equipment in the total volume of investments in fixed assets aimed at reconstruction and modernization, by the type of economic activity | x | x |
| Share of employees in high-tech and knowledge-intensive economic activities * | x | x |
| Production index for high-tech and medium-tech (high level) manufacturing facilities | x | x |
| Structure of industrial production volume by manufacturability level * | x | x |
| Manufacturing value added structure by manufacturability Level * | x | x |
| Status indicator | | |
| Coefficient of renewal of fixed assets by the types of economic activity | x | x |
| Depreciation of fixed assets by the type of economic activity | x | x |
| Share of investments aimed at reconstruction and modernization, by the type of economic activity | x | x |
| The share of investments in machinery and equipment in the total volume of investments in fixed assets aimed at reconstruction and modernization, by the type of economic activity | x | x |
| Index of physical volume of investments in fixed assets aimed at reconstruction and modernization, by the types of economic activity | x | x |
| Index of the physical volume of investments in machinery and equipment carried out during reconstruction and modernization, by the types of economic activity | x | x |

Note: * indicators that refer both to defining and status groups. Source: compiled by the author on the basis of [21].

The division of the indicators of Table 4 into defining and status indicators is associated with their applicability for assessing scientific and technological potential. In case it is necessary to carry out an assessment at any time in order to simplify it, it is advisable to use the actual values of the defining indicators, since status indicators have a delayed impact on scientific and technological potential.

One of the directions for assessing the scientific and technological potential is the assessment of public policy instruments aimed at increasing it. Unlike the group of indicators presented in Tables 1–4, which largely cover the national economy, the assessment of public policy instruments in the field of scientific, technological and innovative development and the corresponding indicators are more specific in nature due to the targeting of such instruments, certain restrictions related to their specifics. An important role in the implementation of these tools is played by the State Committee on Science and Technology of the Republic of Belarus (abbreviated as SCST). The competence of the SCST as a republican government body is related to the regulation of scientific, technical and innovative activities of the country [22].

Since the instruments of public policy aim to increase scientific and technological potentials, it is advisable to assess the impact of such instruments by analyzing their content, implementation progress and results.

One of the main instruments of state policy aimed at the innovative development of the national economy within the framework of the program-target method is the State Program for Innovative Development of the Republic of Belarus (abbreviated as SPID) [23]. The program is aimed at stimulating innovation by providing irrevocable and refundable financing, various benefits in the process of implementing innovative projects. SPID is primarily designed for enterprises in the real sector of the economy. The importance of the program for the development of the national economy can be determined regarding the amount of funding for its activities and projects, which amounts to 6750876,8 thousand rubles during the period of 2021–2025 years [23].

To participate in the SPID, it is necessary to comply with a number of conditions, in particular, those indicated in paragraph 4 of the Regulation on the procedure for the formation and use of innovative funds, approved by the Decree of the President of the Republic of Belarus No. 357, dated August 7, 2012.

Assessment of SPID as one of the tools for the implementation of innovation policy, a way to increase scientific and technological potential and, accordingly, ensure STS, can be carried out in two directions:

1) using indicators and evaluation mechanisms laid down in the program;
2) based on the actual content of the program through various third-party indicators.

Evaluation indicators defined in the program include target and forecast indicators. These are shown in Tables 5 and 6.

**Table 5** – Target indicators of SPID

| Indicator (target) | Value by year | |
|---|---|---|
| Share of innovatively active organizations in the total number of manufacturing organizations, % | x | x |
| Share of organizations implementing process innovations in the total number of innovatively active organizations in the manufacturing industry, % | x | x |
| Share of shipped innovative products in the total volume of shipped products of manufacturing organizations, % | x | x |
| Share of shipped innovative products new or significantly improved for the domestic or global market in the total volume of shipped innovative products of manufacturing organizations, % | x | x |
| Share of science-intensive and high-tech products in the total volume of Belarusian exports, % | x | x |
| Number of jobs created (modernized), units | x | x |

Note – Source: [23].

**Table 6** – Forecast indicators of SPID

| Indicator (forecast) | Indicator value by years | |
|---|---|---|
| Number of innovation infrastructure entities, units | x | x |
| Number of jobs created (modernized) by subjects of innovation infrastructure and residents of scientific and technological parks, units | x | x |
| Production output by residents of scientific and technological parks, mln. rubles | x | x |

Note – Source: [23].

It is important to note that target and forecast indicators of the SPID are used not only to assess innovative projects and program activities. They are also deployed to evaluate innovation progress of industries.

Evaluation of the actual content of the programs, namely innovative projects and activities, can be carried out by the means of indicators that trace certain quantitative parameters of the process and the status of participants, mainly performers. Such indicators grouped on the basis of the "cost-result" principle are specified in Tables 7, 8.

**Table 7** – Indicators for assessing the implementation of SPID and its individual innovative projects

| Indicator | Quantity (number) | Growth/decrease compared to the previous year |
|---|---|---|
| Status indicator | | |
| Number of innovative projects | x | x |
| Distribution of innovative projects by sectors of the economy (contractors): | x | x |
| Regional distribution of innovative projects | x | x |
| including transient | x | x |
| of which are based on technologies of higher technological structures (V and VI) | x | x |
| Cost indicator | | |
| Amount of financing, including: | x | x |
| republican budget funds | x | x |
| local budget funds | x | x |
| Funds of the Belarusian Innovation Fund | x | x |
| Own funds of executing organizations | x | x |
| Credit resources | x | x |
| Foreign investment | x | x |
| Other sources | x | x |
| Performance indicator | | |
| New production facilities put into service | x | x |
| That have reached the design capacity | x | x |
| Production volume of products (works, services), mln. rubles | x | x |
| Shipped for export of products (works, services), mln. rubles | x | x |
| Jobs created (upgraded) | x | x |

Note – Source: compiled by the author on the basis of [23].

Apart from innovative projects, the State Program for Innovative Development also provides for activities in the field of innovative infrastructure. Innovative infrastructure plays an important role in the country's innovative development by assisting innovative entrepreneurship in various forms. At the same time, the indicators of Table 8 can be used both to assess the process of implementation of the SPID, and in general to assess the state and effectiveness of the innovation infrastructure in the country.

The mechanism for assessing SPID, indicated in the program, involves a comparison of planned (target) and actual indicators for a certain period.

In order to do this we should use the formula [23]:

$$E = \frac{1}{n} \times \sum_{i=1}^{n} \frac{P_{фi}}{P_{пi}} \times \frac{F_{п}}{F_{ф}},$$

where *E* – the performance indicator of the program;

n – number of targets;

$P_{фi}$ – the value of the n-d target indicator actually achieved during the implementation of the program;

$F_{ф}$ – the planned value of the i-th target indicator of the program;

$F_{п}$ – the planned value of budget expenditures on scientific, scientific and technical and innovative activities as a percentage of the gross domestic product (taken equal to 1 percent);

$F_{ф}$ – the actual value of budget expenditures on scientific, scientific and technical and innovative activities as a percentage of gross domestic product.

The effectiveness of the program is evaluated based on the result of applying the above formula, which is compared with the indicator:

0.9 and higher – effective;

0.8–0.9 – moderately effective;

0.7–0.8 – ineffective;

less than 0.7 – ineffective [23].

**Table 8** – Indicators of innovation infrastructure development

| Indicator | Quantity (number) | Impact of indicator change (Growth/decrease compared to previous year |
|---|---|---|
| Status indicator | | |
| The number of activities to develop innovative infrastructure, of which referring to: | x | x |
| Scientific and technological parks | x | x |
| Technology Transfer Centers | x | x |
| Belarusian Innovation Fund | x | x |
| National Technology Transfer Center | x | x |
| Cost indicator | | |
| Amount of financing, including: | x | x |
| republican budget funds | x | x |
| own funds of executing organizations | x | x |
| credit resources | x | x |
| foreign investment | x | x |
| other sources | x | x |
| Performance indicator | | |
| Number of residents | x | x |
| Production volume, planned / actual: | x | x |
| in comparison to 1 ruble of invested budget funds | x | x |
| Specific gravity of shipped innovative products, planned/actual | x | x |
| Share of exports of knowledge-intensive and high-tech products planned / actual | x | x |
| Number of jobs created (upgraded), planned / actual | x | x |

Note – Source: compiled by the author on the basis of [23].

Another important instrument of state policy implemented within the framework of the program-target method, which can be considered as a means of ensuring STS by increasing scientific and technological potential, are various programs in the field of scientific activities. Such programs approved by resolutions of the Council of Ministers of the Republic of Belarus include state programs (abbreviated as SP), state programs of scientific research (abbreviated as SPSR), state scientific and technical programs (abbreviated as SSTP) [24], [25], [26].

A significant difference between these programs and the SPID is their focus mainly on the development of science and the development of new knowledge, including that for the creation of new and improvement of existing production technologies. The executors of these programs are mainly scientific organizations.



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As a rule, SPs include a set of subprogrammes devoted to a wide range of humanitarian and other research. They are characterized by a wider profile with a significant number of contractors and performers, for example, SPs «High-tech technologies and technology» for 2021–2025, «Scientific and innovative activities of the National Academy of Sciences of Belarus» for 2021–2025.

SPSRs and SSTPs have a narrower focus, their main goal is the development of the main areas of scientific, scientific, technical and innovative activities through the acquisition of new knowledge, the study of methods for the practical application of previously discovered phenomena, and the solution of certain practical problems [27]. At the same time, unlike SPSRs, a mandatory stage in the implementation of SSTPs is the creation of final products based on the results of R&Ds and its subsequent production.

SPSRs are focused mainly on basic research, as well as partially applied, related to solving specific fundamental and applied problems promoting country's socio-economic development.

Currently, 12 SPSRs are implemented. Within their framework a significant amount of research is carried out in a wide range of areas, including: new materials, experimental medicine, biotechnology, photonics, energy security, soil fertility, etc. [28].

SSTPs can be assessed according to the indicators presented in the official documents of state bodies, in particular, the order of the SCST No. 212, dated July 19, 2019. These indicators, applicable to SPs and SPSRs depending on their specifics, are presented in Table 9, taking into account the classification used by the author.

The second area of assessing research programs involves an assessment of the implementation of the program and its participants. Thus, you can evaluate the effectiveness of the program. The corresponding indicators in relation to SPs and SPSRs, classified into three groups, are presented in Table 10.

Indicators applicable for assessing the efficiency of SSTPs, and in some cases – SPs and SPSRs are presented in Table 11.

It should be noted that production-related indicators are partially applicable to SPSRs since some of these state programs, for example «Society and Humanitarian Security of the Belarusian State» do not involve the production of goods.

**Table 9** – SPSRs assessment directions

| Indicator | Actual value of the indicator | Planned value of the indicator | Indicator dynamics (in comparison with the actual value in the previous year) |
|---|---|---|---|
| Status indicator | | | |
| Number of programs | x | x | x |
| Number of program tasks, of which: | x | x | x |
| aimed at performing R&D activities, including (those) | x | x | x |
| based on technologies of higher technological structures (V and VI) | x | x | x |
| Newly mastered (new) products, including (those): | x | x | x |
| based on technologies of higher technological structures (V and VI) | x | x | x |
| Number of organizations participating in the program | x | x | x |
| Number of tasks of the program for performance of R&D activities, including: | x | x | x |
| performed in the reporting year | x | x | x |
| not performed in the reporting year | x | x | x |
| transient | x | x | x |
| new | x | x | x |
| excluded | x | x | x |
| Cost indicator | | | |
| Actual amount of expenses for performing R&D, including: | x | x | x |
| budget funds | x | x | x |
| local budgets | x | x | x |
| extrabudgetary funds, including: | x | x | x |
| own funds of performers | x | x | x |
| credit resources | x | x | x |
| Other sources | x | x | x |
| Performance indicator | | | |
| Number of innovations created as a result of the program, put in production | x | x | x |
| Number of protection documents that protect the result of scientific and technical activities | x | x | x |
| Number of submitted applications for protection documents for scientific and technical activities results | x | x | x |
| Number of new production facilities created using technologies developed under the program | x | x | x |
| Number of modernized production facilities as a result of technologies developed under the program | x | x | x |
| Number of completed production (implementation) tasks in the reporting year | x | x | x |
| Volume of new goods produced, bel. rubles | x | x | x |
| Volume of new goods sold, bel rubles, including: | x | x | x |
| sold in the Republic of Belarus | x | x | x |
| exported | x | x | x |
| Program effectiveness for the reporting year * | x | x | x |

Note: * is assessed as a degree of achieving program's planned (target) indicators for the reporting year. Source: based on [29].

**Table 10** – SPs and SPSRs assessment indicators

| Indicator | Indicator actual value | Indicator dynamics (in comparison with the actual value in the previous year |
|---|---|---|
| Status indicator | | |
| Number of programs, of which: | x | x |
| divided by areas (industries, contractors): | x | x |
| number of subprograms, of which: | x | x |
| divided by areas (industries, contractors): | x | x |
| number of subprograms' tasks, including (those): | x | x |
| divided by areas (industries, contractors) | x | x |
| Number of R&D activities, including (those): | x | x |
| divided by areas (industries, contractors) | x | x |
| performed under separate subprograms | x | x |
| Cost indicator | | |
| Program funding, including (that): | x | x |
| divided by areas (industries, contractors): | x | x |
| involving budget funds | x | x |
| involving extrabudgetary funds | x | x |
| Performance indicator | | |
| The volume of goods produced under the programs, including (those): | x | x |
| divided by areas (industries, contractors) | x | x |
| produced under separate subprograms | x | x |
| Total sales, including (those): | x | x |
| divided by areas (industries, contractors) | x | x |
| sold under separate subprograms | x | x |
| sold in the Republic of Belarus, including (those): | x | x |
| divided by areas (industries, contractors) | x | x |
| sold under separate subprograms | x | x |
| exported, including (those): | x | x |
| divided by areas (industries, contractors) | x | x |
| exported under separate subprograms | x | x |

Note – Source: compiled by the author on the basis of [30].

**Table 11** – Indicators for assessing the efficiency of SSTPs, as well as SPs and SPSRs, depending on their content

| Indicator | Actual value of the indicator | Planned value of the Indicator | Indicator dynamics (in comparison with the actual value in the previous year) |
|---|---|---|---|
| Number of innovations | x | x | x |
| Number of new production facilities | x | x | x |
| Number of modernized production facilities | x | x | x |
| Volume of manufactured products, bel. rubles | x | x | x |
| Volume of products sold, bel. rubles | x | x | x |
| Volume of exported products, bel. rubles | x | x | x |
| Number of R&D activities | x | x | x |
| Amount of R&D funding | x | x | x |
| Number of protection documents that protect the result of scientific and technical activities | x | x | x |

Note – Source: compiled by the author on the basis of [30].

**Conclusion**

Based on the study's results, it should be noted that the scientific and technological security can be assessed by assessing the state of its components – scientific, technological, and educational potentials. Various indicators are used for this purpose.

Such indicators can be established by regulation or chosen by the researches on the basis of the specifics of the subject that is to be assessed. Regardless of the exact choice all indicators must meet specific criteria involving belonging to scientific, technological and educational potentials, accessibility, applicability, objectivity, sufficiency.

The above mentioned indicators may relate to the technological development of the national economy, innovation, scientific research, and various government programs in the field of science and innovation development. Some of them cover all branches of the national economy, the others are specific, indicating specific areas of research that also contribute to the creation of the scientific and technological potential, such as various state programs in the field of innovation and scientific activities.

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# EMERGING TRENDS IN DIGITAL TRADE: A GLOBAL PERSPECTIVE

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**Abstract**

The article analyzes digital trade of goods and services as an economic category. The author studies definitions of the term "digital trade" presented by international researchers, as well as those established in documents of international organizations.

One should note that there are multiple interpretations of the concept of digital trade, and researchers lack common understanding of digital trade. One of the approaches to define the content of the concept of digital trade implies the identification of its distinctive features or attributes, as well as its advantages over traditional trade.

Thus, according to the scientific works, the main advantages of the digital trade of goods and services include the elimination of the geographic distance between counterparties, a reduction in implementation costs, adding to the price of products, increased delivery speed; the use of demonstration opportunities for product presentations that are not limited by physical boundaries; the organization of simultaneous access to the offerings of all sellers taking part in digital trade; and an unlimited consumer audience.

The author thoroughly examined digital trade trends, including the use of artificial intelligence technologies and business process automation to perform routine tasks, the implementation of blockchain to ensure data security, increase consumer confidence, and combat fraud, the development of interactive online sales methods, voice assistants to facilitate product searches, and predictive user data analytics to anticipate customer preferences and offer them products that meet their expectations; the integration of various communication channels into a single system for continuous communication with customers and target audiences; the introduction of virtual and augmented reality technologies in retail, allowing for product evaluation without the need to physically visit a store; and payment instruments and services that provide a wide range of payment options available to customers.

**Keywords:** digital trade, emerging trends, global value chains, consumer behavior, demand for innovation, regulatory environment, virtual and augmented reality.

## СОВРЕМЕННЫЕ ТЕНДЕНЦИИ ЦИФРОВОЙ ТОРГОВЛИ: ВЗГЛЯД НА ГЛОБАЛЬНОМ УРОВНЕ

**С. С. Новиков**

**Реферат**

В статье проведен анализ цифровой торговли товарами и услугами как экономической категории. Автором изучены определения термина цифровая торговля, представленные зарубежными исследователями, а также установленные в документах международных организаций. Отмечается наличие множества трактовок понятия цифровой торговли, отсутствие единого понимания среди исследователей. Одним их подходов к определению содержания понятия цифровой торговли является выявление ее отличительных черт или признаков, а также преимуществ по отношению к традиционной торговле. Так, согласно работам исследователей, главными преимуществами цифровой торговли товарами и услугами являются нивелирование территориальной удаленности контрагентов, снижение затрат на реализацию товаров, закладываемых в цену продукции; повышение оперативности доставки; использование демонстрационных возможностей презентации товара, не ограниченных физическими границами; организацию единовременного доступа к предложению всех продавцов, включенных в сферу цифровой торговли; неограниченную потребительскую аудиторию.

Автором подробно изучены тренды развития цифровой торговли на современном этапе, в том числе применение технологий искусственного интеллекта и автоматизации бизнес-процессов для выполнения рутинных задач, внедрение блокчейн для обеспечения безопасности данных, повышения доверия покупателей и противодействия мошенничеству; развитие методов интерактивных онлайн-продаж, голосовых помощников для облегчения поиска нужных товаров, а также предиктивной аналитики данных пользователей, которая позволяет предугадать предпочтения покупателей и предложить им товар, соответствующий их ожиданиям; взаимную интеграцию различных каналов коммуникации в единую систему для непрерывной связи с покупателями и целевой аудиторией, внедрение технологий виртуальной и дополненной реальности в торговлю, что позволяет оценить товар без необходимости физического посещения магазина, а также платежных инструментов и сервисов, обеспечивающих широкий выбор опций оплаты, доступный покупателям.

**Ключевые слова:** цифровая торговля, современные тенденции, цепочки добавленной стоимости, потребительское поведение, спрос на инновации, регуляторная среда, виртуальная и дополненная реальность.

## Introduction

The current stage of social development is characterized by the decisive impact of digital technologies on all spheres of life. The changes replacing computerization and informatization are not limited to isolated digital transformations. As noted in the report "Digital Trade for Development," prepared by the United Nations Conference on Trade and Development, the International Monetary Fund, the Organization for Economic Cooperation and Development, the World Bank, and the World Trade Organization, the digitalization of the economy is fundamentally changing approaches to communication, production, management, and trade [1]. Thus, the introduction of digital technologies increases labor productivity by reducing production costs, leads to cost savings and increased investment efficiency, stimulates the expansion and diversification of export baskets, and promotes sustainable economic growth by fostering innovation.

The Internet and digitalisation are fundamentally changing the way people, businesses and governments interact. This has led to a new phase of globalisation underpinned by the movement of data across national borders, changing the nature, patterns and actors in international trade in goods and services. Digitally related transactions, either in goods or services, have existed for many years. Yet the current scale of transactions and the emergence of new (and disruptive) players transforming production processes and industries, including many that were previously little affected by globalisation, is of particular importance [2].

**Main body (Discussion)**

According to R. Baldwin international trade has gone through three stages. The first, often referred to as the ‘first unbundling’, or ‘traditional trade’, was spurred by falling transport costs which enabled the separation of production and consumption across national borders. Consumers gained from wider access to new and more competitively priced products from abroad and trade mainly involved final goods. In this context, trade policy was largely concerned with market access to ensure that the benefits from trade in final products could be reaped. The second unbundling, or ‘GVC trade’, arose from continued reductions in transport and coordination costs enabling businesses to fragment processes of production across national borders and to exploit locational comparative advantages. Trade in intermediate products or tasks flourished and global production relocated, in part, towards emerging economies.

Trade policy became more complex, increasingly involving trade facilitation and behind-the-border issues aimed at reducing bottlenecks along the value chain. Digital technologies have made it increasingly feasible for buyers and sellers to place and receive orders on a global scale. They also enable the instantaneous remote delivery of services directly into businesses and homes, including internationally [3].

Businesses and households make increasing use of digital ordering. Many services that traditionally required proximity between producers and consumers are now traded at a distance. In much the same way that reductions in transport and coordination costs enabled the fragmentation of production along global value chains (GVCs), falling costs of sharing information – relaxing in turn some of the traditional constraints associated with engaging in international trade, be this asymmetric information, hold-ups or contract enforcement – are powering the digital trade revolution. Services can now be fragmented across national borders, through collaborative processes, and delivered via digital platforms as never before. At the same time, falling informational barriers, arising from growing digital connectivity, are enabling more physical, or traditional, trade to take place, increasing access to foreign markets for firms in a way that would previously have been unimaginable, particularly for small and medium enterprises. As a result, more trade in services, including in small-value digital services such as streamed music, e-books and online games, is also taking place [4, p. 67].

The digital transformation is further blurring distinctions between conventional cross-border trade in services, consumption abroad and services provided through foreign presence, and is posing new challenges for the way international trade and investment policy-making is made and how international trade, especially in services, is measured. Emerging technologies, such as distributed ledgers, or Blockchain, have the potential to further change how we trade in the future [5, p. 35].

By making international contracts more transparent and enforceable, and facilitating the transfer of value, the Blockchain has the potential of reducing 'hold-ups' in trade and facilitating just-in-time delivery along GVCs. In parallel, additive manufacturing, or 3D printing, can also change how goods are delivered and the structure and operation of supply chains for parts and components [6].

As firms adopt new technologies they are likely to move towards more knowledge-intensive processes of production, giving rise to new sources of comparative advantage. Automation has the potential to reduce the role of labour abundance or skills in determining comparative advantage in trade in goods, from agriculture to manufacturing, and trade in services. Intangible assets and access to knowledge-based capital (KBC) may become increasingly important, potentially fundamentally changing the way factors of production are allocated both within the firm and across borders through global value chains [7, p. 133].

A tentative typology for digital trade according to Organisation for Economic Co-operation and Development is presented in figure.

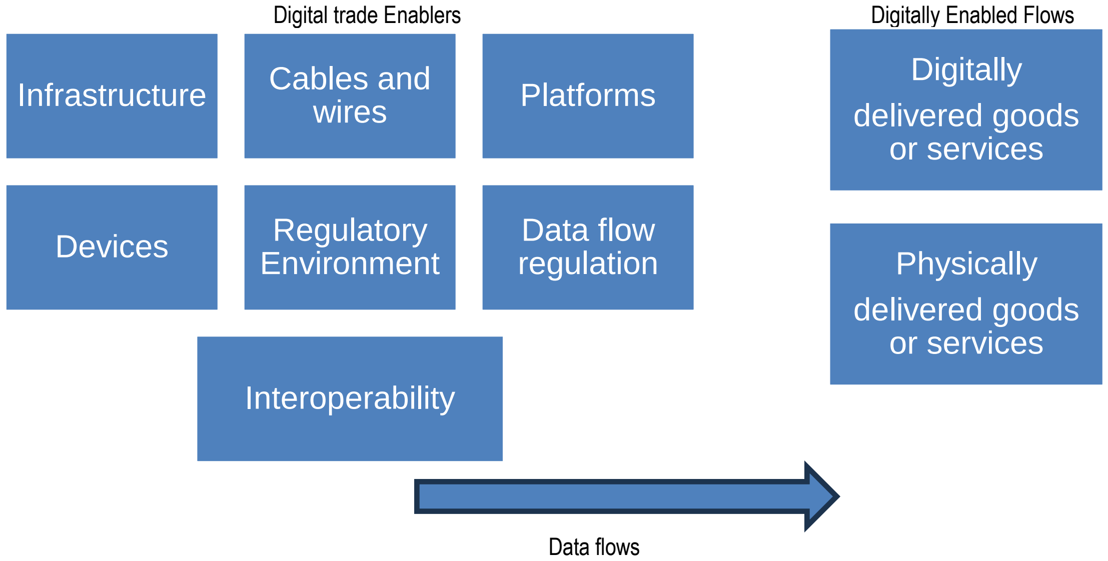


**Figure** – A tentative typology for digital trade [8]

Digital trade also presents significant challenges for policy makers and businesses. For example, the intangible nature of digitalised services has created strong fiscal incentives for their source (country of origin) to be located wherever that may be most advantageous, in turn further blurring already grey distinctions between conventional cross-border trade in services, consumption abroad and services provided through foreign presence, and posing new challenges for the way international trade and investment policy-making is made as well as how international trade, especially services, is measured. In addition, significant income streams can now be generated through data itself, the collection and dissemination of which is subject to myriad national laws, for example, governing privacy. Data flows – even though these are generally not recorded in international trade statistics, particularly intra-firm transactions – underpin modern trade, both in enabling corporations to manage global production networks under global value chains and in automation for trade facilitation [9].

Despite the growing importance of what is commonly referred to as ‘digital trade’, little empirical and internationally comparable information currently exists, inhibiting a full understanding of the scale and policy challenges of digital trade. Moreover, economic effectiveness of companies practicing new business models – such as Airbnb, Facebook and Spotify – raise a number of additional complications, including in relation to the nature of the activity, for (services) trade policy.

E. N. Smirnov states that from a trade policy perspective, the benefits of digital transformation, widely described in scientific literature, depend on the seamless and integrated functioning of systems encompassing goods, services, and digital connectivity. However, market liberalization alone is not enough to reap the benefits of digital trade. New technologies often become available through international trade. Therefore, to increase


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production, access to international markets is necessary, which is only possible for companies with competitive digital advantages. In the digital economy, the success of firms is determined by both the adoption of new technologies and their entry into global markets.

Access to new technologies is ensured by the degree of trade liberalization, but the effective use of such technologies requires slightly different strategies. Data naturally moves seamlessly across the internet, reaching a global audience. This allows all companies (of all types and sizes) to gain new opportunities to create new products and enter new markets. However, to access these consumers and markets, goods and services must comply with certain regulatory requirements, such as technical requirements, electronic payment compatibility, privacy, and consumer protection. Regulatory approaches vary widely across countries, necessitating international dialogue to address these differences and contradictions [10, p. 79].

**Definition of digital trade**

While there is no single recognised and accepted definition of digital trade, there is a growing consensus that it encompasses digitally enabled transactions in trade in goods and services which can be either digitally or physically delivered and which involve consumers, firms and governments. At its most basic, digital trade is underpinned by the transfer of bits and bytes across borders. Data flows connect businesses (e. g. through service links), machines (e. g. the Internet of Things, or IoT) and individuals (i. e. peer-2-peer or social networking) to each other. Increasingly, data itself is generating significant income streams, facilitating the delivery of new, and previously non-tradable, goods and services and, for the latter, blurring the lines between the modes in which these are delivered [11].

To this day there is no generally accepted definition of digital trade. One approach to understanding this concept is to identify its distinctive features or attributes. This approach distinguishes the concept of "digital commerce" from the concept of "traditional commerce," which occurs without the use of the internet (offline commerce).

Firstly, the differences between digital and offline commerce include the composition of the parties involved. Offline commerce is characterized by a large number of intermediaries who provide various services, including lending, freight forwarding, foreign exchange transactions, and others. Digital commerce, on the other hand, is characterized by the possibility of direct exchange between the manufacturer-seller and the buyer.

The next distinction is the subject of trade. In offline trade, the subject matter consists of goods, works, services, and production factors. However, the subject matter of digital commerce includes traditional physical goods, as well as digital products and services sold via the global internet.

Furthermore, the methods of trade and delivery of goods and services also differ. Thus, digital trade takes place on online platforms, and the entire transaction and delivery process is carried out electronically over the global internet. In offline trade, the exchange occurs through physical contact between the seller and buyer, and goods are delivered by various modes of transport [12].

There are also differences in controlling bodies. In particular, there is no unified system for overseeing the global digital trade market. At the same time, the rules for offline trade in goods and services are defined by multilateral agreements of the World Trade Organization and other institutions. The second edition of the Handbook on Digital Trade defines digital trade as all international trade that is digitally ordered and/or digitally delivered. Digitally ordered trade involves the international sale or purchase of a good or service, conducted over computer networks by methods specifically designed for the purpose of receiving or placing orders. Digitally delivered trade only covers services and is defined as all international trade transactions that are delivered remotely over computer networks. This definition goes beyond e-commerce or digital platforms [13, p. 17].

An alternative definition used by the UN Conference on Trade and Development (UNCTAD), focused on services and considered trade in digitally deliverable services.

Such a definition is much broader than digitally delivered services and encompasses trade in services such as insurance and pension services; financial services; charges for the use of intellectual property; telecommunications, computer and information services; research and development services; professional and management consulting services; architectural, engineering, scientific and other technical services; trade-related services; other business services not included elsewhere; audio-visual and related services; health services and education services (excluding those consumed during international travel); as well as heritage and recreational services [14].

That definition could be further broadened by considering all international trade enabled by digital technologies, including those that were not ordered or delivered through computers networks. Further, the expansion of the digital economy has enabled novel combinations of goods and services and their delivery forms. For example, an item can cross a border as a service but becomes a good when it is consumed, as it happens with 3D printing service.

Despite global efforts to harmonize international trade statistics, our understanding of digital trade and its implications remains limited. Digital trade volume refers to the total quantity of goods and services traded electronically across international borders, utilizing digital platforms and technologies.

This concept encompasses various forms of transactions, including e-commerce, digital services, and electronic data transfers, highlighting the increasing role of the digital economy in facilitating global trade. The growth of digital trade volume reflects shifts in consumer behavior, technological advancements, and the integration of online markets into traditional trade practices [15].

**Emerging trends of digital trade**

Digital trade is actively developing due to the latest technologies, including artificial intelligence and virtual reality (VR and AR), making shopping more convenient and interesting. Nowadays consumers are getting used to fast delivery, quality service and safe shopping. The pandemic accelerated the transition of many sellers online, increasing competition. More over new laws protect user data and introduce tax obligations [16, p. 917]. Dynamic growth, customer orientation and demand for innovation define the main trends of digital trade (table 1).

**Table 1** – Emerging trends in digital trade

| № | Trend | Description of trend |
|---|---|---|
| 1 | Artificial intelligence assistants and automation | The main innovation in digital trade is the introduction of AI-assistants (AI-agents), configured to quickly and efficiently perform routine, repetitive tasks. For example, AI assistants can automatically answer frequent customer questions, process claims, form sales reports, analyze reviews. The development of AI assistants and other automation tools will free time and resources for solving more important tasks and optimizing business processes |
| 2 | Creating security and transparency with blockchain | As online shopping continues to grow, so do concerns about data security, fraud and trust between buyers and sellers – this is where blockchain technology comes in.<br>According to Statista, a German online platform that gathers and presents statistical data from various sources on a wide range of topics, the global blockchain technology market will skyrocket from $17 billion in 2023 to over $943 billion by 2032, signaling its rapid adoption across industries, including ecommerce. By providing a decentralized and tamper-proof ledger, blockchain enhances transaction security, prevents fraud, and improves transparency in online shopping [17] |
| 3 | Livestream shopping is taking off | Live commerce is redefining how consumers discover and purchase products online, blending entertainment with real-time shopping experiences. Once a niche trend, livestream shopping is now a mainstream sales channel, with platforms like Whatnot, eBay Live, and TikTok Live leading the charge. According to Statista, US livestreaming ecommerce sales reached $50 billion in 2023 and will grow to $68 billion by 2026. As social media and ecommerce continue to converge, brands are tapping into livestream shopping to engage audiences, showcase products in action, and drive instant sales [18] |

**Continuation of Table 1**

| № | Trend | Description of trend |
|---|---|---|
| 4 | Turning up the volume with voice search | With 75 % of US households owning a smart speaker in 2025, it's no surprise that voice search is an up and coming trend in the ecommerce space.<br>Voice assistants like Amazon Alexa and Google Assistant have transformed the way that consumers interact with ecommerce platforms – like BigCommerce and Shopify – offering a hands-free, convenient way to shop. By simply using a voice command, shoppers can search for products, make purchases, and track orders with ease.<br>Harnessing customer data for personalized shopping experiences.<br>As research shows, personalization drives customer loyalty. In fact, a study from Google and Storyline Strategies found that 72 % of consumers are more likely to be loyal to a brand if they offer a personalized customer experience [19] |
| 5 | Predictive analytics | What if you could anticipate customer needs, before they even ask? Predictive analytics makes that possible by analyzing patterns in customer behavior, purchase history, and browsing data to forecast what they'll want next. Predictive tools are used to identify high-value customer segments, focus retention efforts where they'll have the biggest impact, forecast demand, adjust inventory and supply chains based on predicted trends, personalize recommendations, suggest products likely to convert based on past and peer behavior |
| 6 | Omnichannel | Making purchases becomes more convenient thanks to omnichannel when the boundaries between ordinary and internet stores are blurring. The product can be selected on the site or in the application, and picked up in a store near the house. Or make an order in the store, and arrange payment and delivery via the internet store. Even product returns are now online. To make customers comfortable, companies implement special systems that automatically show the availability of goods in each store and in the warehouse |
| 7 | Immersion | Virtual technologies create an immersive environment, bringing online shopping as close as possible to visiting a regular store. This compensates for the impossibility of physical contact of the buyer with the product. VR (virtual reality) – the technology of full immersion in a virtual environment that imitates the real world. For example, special glasses or helmets that create an interactive three-dimensional picture. AR (augmented reality) – augmentation of the real environment with virtual objects. For example, a mobile application that overlays virtual objects on top of a photo using the smartphone's camera [17] |
| 8 | Increased speed of delivery | The speed of delivery of goods will become one of the main competitive advantages of trading platforms. To achieve this, companies are investing massive amounts of money in improving transportation infrastructure, building specialized distribution centers, and developing high-tech logistics. Buyers will be able to receive orders literally in a matter of hours or even minutes, especially in large cities. Logistics companies use self-driving vehicles and drones for fast delivery, build a network of automated parcel reception and sorting points, allowing to reduce the waiting time of goods from weeks to hours and minutes |
| 9 | Environmentally friendly production | Consumers are demanding environmental friendliness of their products. Therefore, companies are seriously reconsidering their approaches to packaging, materials, and production processes. Products labeled "Eco" and "Organic," packaging made from recycled and biodegradable materials, and products with low carbon emissions are gaining popularity. Companies that support sustainable development policies and participate in waste management and recycling programs have the opportunity to attract customers willing to pay more for high-quality and safe products |
| 10 | New payment instruments | Customers have a wide range of payment options: bank cards, the Faster Payment System (FPS), QR code scanning, and e-wallets [20].<br>The wider the range of payment methods, the easier it is for customers to make purchases, and the easier it is for merchants to increase revenue and improve the customer experience. Limited payment methods and drawn-out processes can be off-putting for customers looking for ease and simplicity. Payment options are evolving, and customers expect multichannel shopping options. Many businesses also offer flexible payment options like "buy now and pay later," mobile wallets, and the option to pay using cryptocurrency |
| 11 | Mobile shopping | More and more shoppers use their phones or tablets over a PC or desktop, and this trend continues to grow. According to data from Forbes, 54 percent of online Black Friday sales took place on a mobile device in 2023. Being on top of this trend means optimizing websites and online stores for seamless mobile use [16, p. 920] |
| 12 | Subscription models | Subscription models are here to stay. Clothes, cosmetics, socks, consumables, and gym wear are just some of the products available for an e-commerce subscription service. This trend means customers return repeatedly without trying to bring them back to your store, and there seems to be no end to the products and even services you can turn into a subscription model |
| 13 | Social media shopping | Over the past couple years, Instagram, Facebook and Tik Tok have grown into more than just social media platforms – now they're also hubs for social commerce. According to Statista 110.4 million people shopped via social channels in 2024. Thanks to the popularity of experiences like one-click-checkout and live shopping, these channels are becoming more and more customer-friendly, making it seamless for customers to search for and purchase products. In addition, social commerce has a low barrier, allowing online businesses, both big and small, to enhance brand awareness, grow their audience, and offer a frictionless buying experience [16, p. 922] |

Note – Source: Compiled by the author on the basis of [17–20].

**Conclusion**

Digital trade is much more than just selling goods online. It offers new horizons for businesses willing to adapt and keep pace with technology. Those who embrace the opportunities offered by virtual and augmented reality, artificial intelligence, ecology, and mobile commerce will discover enormous opportunities for growth and prosperity. These innovations have a significant impact on the formation of business models, the structure and content of technological processes, the forms and methods of trade relations, and the simplification of trade procedures. The key to success in the future is to embrace change and look beyond the typical online store. Success in this dynamic environment requires more than just keeping up – it demands strategic adaptation.

In addition, digital technologies fundamentally simplify and accelerate access to consumers and markets, bring new opportunities for customization and the introduction of new products. By leveraging data-driven insights, adopting new technologies, and prioritizing seamless customer experiences, brands can stay ahead of the curve and thrive in the competitive online marketplace. Digital trade is evolving faster than ever, driven by emerging technologies, shifting consumer expectations, and new ways to shop and engage with brands. From livestream shopping's real-time engagement to AI-powered experiences, the trends shaping 2025 will redefine how businesses connect with customers.



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