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## CIVIL AND ENVIRONMENTAL ENGINEERING

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# METAVERSE CITY: DEFINITION AND DIRECTION DEVELOPMENT FOR URBAN PLANNING AND ARCHITECTURE

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**Abstract**

Technology corporations believe that the Internet in its current form will become irrelevant in the foreseeable future. In its place, the metaverse will come – a global virtual space in which it will be possible to live, work, meet friends and do all other daily activities. Many consider this direction as a continuation of the sustainable development and smart city concept. The article considered the latest data on the metaverse direction, tries to analyze this trend and its relationship with architecture, sustainable development and urban planning with the help of scientific literature, their analysis and the actual stage of this trend.

This analysis led to the conclusion that each city has its own system of consistent urban thinking, and solutions to achieve the goal of sustainable development, including the metaverse direction. In conclusion, based on the entire analysis, the author formulated the relationship of metaverse with the concept of sustainable development, the advantages, risks and disadvantages of metaverse for the city and citizens.

**Keywords:** metaverse, urban development, virtual world, virtual city, urban transition, augmented reality (AR), virtual reality (VR).

## ГОРОД МЕТАВСЕЛЕННОЙ: ОПРЕДЕЛЕНИЕ И НАПРАВЛЕНИЕ РАЗВИТИЯ ДЛЯ ГРАДОСТРОИТЕЛЬСТВА И АРХИТЕКТУРЫ

**М. М. Каширипур**

**Реферат**

Технологические корпорации считают, что Интернет в его нынешнем виде станет неактуальным уже в обозримом будущем. На его место придет метавселенная – глобальное виртуальное пространство, в котором можно будет жить, работать, встречаться с друзьями и заниматься всеми прочими повседневными делами. Многие считают данное направление как продолжение концепции устойчивого развития и умного города. В статье рассматриваются последние данные о направлении метавселенной, делается попытка проанализировать данное направление и его связь с архитектурой, устойчивым развитием и градостроительством с помощью научной литературы, их анализа и актуального этапа данного направления.

Данный анализ позволил прийти к выводу, что каждый город имеет собственную систему последовательного урбанистического мышления и решений для достижения цели устойчивого развития, в том числе в направлении метавселенной. В заключении, на основании всего анализа, автором сформулированы связь метавселенной с концепцией устойчивого развития, преимущества, риски и недостатки метавселенной для города и горожан.

**Ключевые слова:** метавселенная, городское развитие, виртуальный мир, виртуальный город, городской переход, дополненная реальность (AR), виртуальная реальность (VR).

**Introduction**

With the spread of the Internet, people began to perform some of the activities online. Today we play sports on YouTube videos, for learning languages there are online resources that replace language schools, instead of libraries and cinemas, we can use streaming services and applications with books and audiobooks. To make purchases, it is not necessary to leave the house, even the products will be kindly delivered by a cybermarket or a scooter. We use applications to interact with government agencies and can file a tax return online instead of going to the tax office.

By 2026, a quarter of people will spend at least an hour a day in the metaverse, according to a study by Gartner. According to experts, users will visit virtual offices, classrooms and shops, build houses in the digital space and even buy land [1]. Most of the research comes to the conclusion that more than half of the live events by 2030 will take place in the Metaverses – for example, educational and developing. The average Internet user will spend up to 6 hours a day in the digital worlds. According to experts, e-commerce will bring the greatest income in the Metaverses: their development will affect 80% of commerce, and as of August 2022, this is almost 4.7 trillion dollars. A fair question may arise here: for whom is the Metaverse more beneficial? Of course, first of all, for corporations, brands and companies promoting their services. But it is worth noting that everything happened similarly with the Internet. For companies, this is a platform for earning money and advertising, and for the user, it is an opportunity to receive content, create it and share impressions.

The Metaverse should provide the same variety of possibilities as the Internet. New companies, products, and services will emerge to handle everything from payment rocessing to identity verification, hiring, advertising, content creation, security, and so on. As consumer attention shifts more and more to virtual goods, services and experiences. It will also change where we live, our infrastructure, and how different tasks are distributed, both in the physical world and within the Metaverse.

**Research methodology**

Research methodology would be used literature review; pattern recognition; identification and conceptualization methods for contribute the results of study. For this occasion, main stages and methodology of this research are like as follows:

1. Literature review and analysis method: latest scientific literature, interdisciplinary text and documents with a suitable thematic analysis related to metaverse, sustainability, urban development and architecture.
2. Pattern recognition is the ability to see patterns in seemingly random information. The goal is to note the main patterns and concepts in the results of the first step. The second step looks for similarities or patterns in the sample and codes the results by concept.
3. Identification method: to recognize specific, problems and characteristic of metaverse and its relation to sustainability and urban development (results of part one and two).
4. Conceptualization method: in order to find a suitable theoretical connection between the identified concept and its relation to metaverse, urban development, sustainability, architect and architecture.


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**Main part**

The pandemic situation in 2020 has shown us how it can be really boring to work from home and not go out and it's around the clock. Thus, working and living in the metauniverse in this situation definitely helps people to have fun in another world; work, study and do their daily real life there at the same time. Many experts believe that the metaverse will soon become a replacement for social networks, but so far this is just an emerging trend.

## 1 Basic information about Metaverse

### 1.1 What is the Metaverse?

The first idea of the metaverse appeared in 1992 in the science fiction novel Avalanche by Neil Stevenson. According to the plot of the book, in the 21st century, corporatocracy reigns on Earth – all power belongs to the large corporations – and in addition to the real world, which is shrouded in chaos and split into several corporation states, there is another one – a virtual one. There, people interact with each other in the same way. The real and virtual worlds are intertwined: events in one can affect what happens in the other. The same book became the origin of the term "avatar".

The Metaverse is a convergence of physical, augmented (AR) and virtual reality (VR) in a common online space. The prototype of the Matrix in the real world is the Internet. The difference between augmented reality and virtual reality (VR) is that augmented reality only adds individual elements to an already existing world. Virtual reality artificially recreates the whole world. Having created his avatar in the metaverse, a person will be able to do almost everything in VR that he does in the real world, for example, search for information, communicate with friends, work, go for a walk. In short, to live in the new universe the way he wants and own anything (Figure 1) [2].

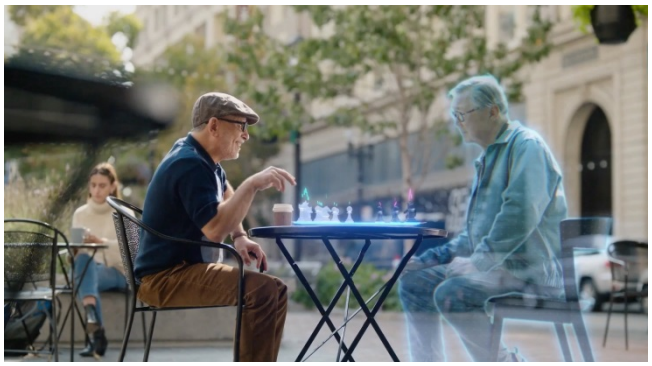

**Figure 1** – Convergence of physical and virtual reality concept

Some people may think that the metaverse equal video games, but the two should not be equated. There are many metaverse concepts, but the most famous one belongs to venture capitalist Matthew Ball. In his presentation, Ball gives seven characteristics of the other world:

1. The Metaverse does not stop: it cannot be restarted, paused, erased or terminated. It's the same as real life.
2. All events within the universe occur in real time, and actions do not depend on external fac-tors. Even though the Meta will have preplanned events, just like real life, it will be a living, holistic experience for one and all in real time.
3. There is no limit to the number of those who inhabit the metaverse.
4. The metaverse has its own economy: people receive "money" for the "work" done, own and manage property. Individuals and businesses will be able to create, own, invest, sell and be rewarded for an incredibly wide range of "work" that generates recognized "value".
5. In the metaverse, you can use elements of the real world: for example, work on your laptop in a virtual space.
6. Data and digital assets from different platforms are combined. There must be absolute compatibility of different "worlds" in the Meta, their data, digital assets and the content that they contain. You can use things from Counter-Strike and Fortnite, buy a car from Need for Speed and sell it to friends on Facebook. As if your Counter-Strike weapon skin could be used in Fortnite or any other game. Today, the digital world is like a shopping mall, where each store uses its own currency, different IDs, own units of measurement, etc.
7. The Metaverse is filled with "content and experiences" created by its users, both individuals and organizations.

The concepts described above form the image of the target state of the Metaverse and the understanding of how it should function. At the moment, there is not a single Metaverse that meets the above criteria. There are many projects that have implemented individual elements of the Metaverse, while the creation of a full-fledged Meta is a matter of more than one year.

### 1.2 Historical background

Despite starting the metaverse idea in 1992, the concept of the metaverse gained attention after Facebook changed its name to Meta in 2021 and announced a major investment in the idea. Then the creation of their metaverses was announced by Microsoft, Epic Games, Roblox and other corporations [3]. But even before this event, the idea of a virtual world and augmented reality was of interest to people, and the concepts of virtual worlds were not invented by IT giants at all, but by science fiction writers.

Also in history, the following key events affecting the Metaverse theme can be distinguished:

1978 – The MUD (Multiple User Dungeon) game is a computer program that users can enter and explore. Each user takes control of a computerized person/avatar/embodiment/character. You can walk around, chat with other characters, explore dangerous areas infested with monsters, solve puzzles, and even create your own rooms, automata, and items.

1982 – The film "Tron" – the film mentions the Metaverse. According to the story, the main character becomes digitized and gets inside the computer, into a completely new world that does not completely copy of reality, but is filled with software abstractions with video game logic.

1984 – The novel "Neuromancer" – the story tells about the world of the near future, where people's bodies are covered with high-tech devices. William Gibson's fantasy warned the very essence of the Internet as a single space for data storage. After the release of the novel, the concept of "cy-berspace" is popularized.

1999 – The film "The Matrix" – it describes the idea of what would happen if humanity existed inside a virtual reality.

2003 – The game "Second Life", which had everything that surprised the Metaverse of the novel Avalanche so much. Players created their own zones with any rules and gameplay. Territories could be bought with money. Large organizations opened their branches in Second Life. At the same time, the economy remained quite free and the in-game currency was easily converted into a real one. In Second Life, you could do real business.

2006 – Roblox is a multiplayer gaming platform that surpassed 55 million daily active users in February 2022.

2018 – Ready Player One film, which takes place in the Metaverse. There the main character fights, plays, earns and loses money and communicates in the virtual world. He returns to the real world, rather, out of necessity.

2021 – Facebook becomes Meta (Figure 2).

Today, not only the Meta Company is engaged in the issue of building the Metaverse. Among the giants that are mastering the new direction are companies such as Amazon, Microsoft, Epic Games, Tencent and Roblox. Thus, Amazon has been working with augmented reality (AR) technologies for several years, from virtual trying on clothes to special glasses. Along the way, the development of software for cloud computing. And we are not talking about the company's smart home devices that can potentially be connected to its "system".

Back in May 2021, Microsoft announced the creation of a corporate Metaverse. They are going to achieve this using the Azure cloud platform, which has services for creating a digital version of anything – from individual items to entire places. All this comes the interaction with the help of mixed reality. So, we can organize remote work or hold meetings with avatars of real people. Do not forget that there is also a gaming division with the Xbox brand in the asset, and some leaders do not hide: in the foreseeable future, entertainment applications and games may become part of the "universe".

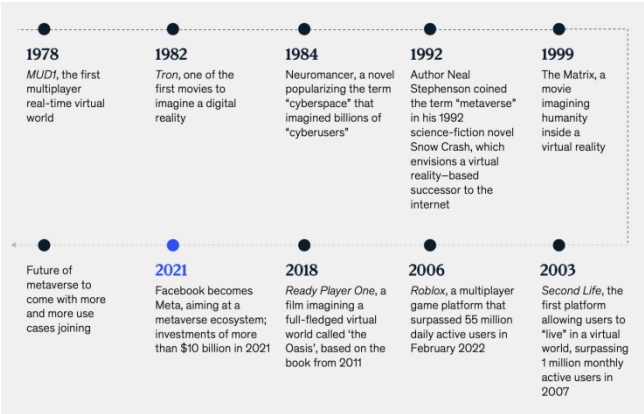


**Figure 2** – Metaverse history timeline

### 1.3 Why metaverse? Why we need it?

Many writers, developers and metaverse fan believes that it can solve real problems of mankind. The main problems that will be solved by metaverse are listed below:

*Problem 1.* Users spend a lot of time on smartphones and laptops, and this affects health.

A sedentary lifestyle, many hours at the monitor, lack of real communication – all this leads, at a minimum, to depression and fatigue, and at a maximum – to real diseases and pathological conditions (physical inactivity, obesity, cardiovascular problems, headaches, visual impairment). In the metaverse, it will be possible to walk around the worlds, gesticulate, move objects with your hands. That is, our physical body will be in motion, which is vital. You don't have to choose between health and the possibilities of the Internet. In the metaverse, it will even be possible to do fitness in the gym among other people, or rather, their avatars. You will see the coach and other participants when you are at home, and they will see you.

*Problem 2.* People are less likely to communicate in real life, and more and more often replace voice communication with correspondence.

Another problem arises when children are given gadgets at an early age – they lose their motivation to explore the real world around them and communicate with their peers, instead they "stick" to Internet videos or scribble messages. Neural connections are formed more slowly, and this is bad for overall development. The Metaverse allows you not to lose your social communication skills. You can meet friends in a virtual cafe and communicate as if you met in a real cafe with your voice and expression of emotions instead of a couple of printed phrases and a Viber/Telegram/WhatsApp emoticon. When communicating on a mobile phone or even a video call, there is still no such effect of presence. You hear a voice or see a 2D image of the interlocutor, and in the metaverse you will have a 3D avatar in front of you, which you can even touch.

*Problem 3.* Distance.

We spend a lot of time to get to work, to the store, to pick up a package from the post office or to get to the theater. We may not see friends for years, because we live in different countries, and we simply do not have time. The Metaverse must remove these boundaries. In it, you can come to a virtual store, then meet friends in a virtual home (even if you live in different cities in reality), then watch a movie together, and so on. The time you save by doing the basic things in the virtual world (work, school, shopping) can be spent on something more valuable than standing in traffic jams. For example, for a real romantic evening with your loved one.

*Problem 4.* Pandemic.

In 2020, we all faced massive restrictions and were locked in our homes. Even in those companies where employees have been transferred to a remote location, some processes have to be solved offline, for example, hold a meeting in the office once a week. This is a risk for employees. Many people have been cut off from their loved ones due to closed borders [4, 5]. There will be no borders in the metaverse and there will be no need for QR codes to enter a virtual shopping center or meet a friend from another country (or rather, with his avatar, of course). There will be no need for offline meetings. You can get together with colleagues in a virtual room, present on a virtual whiteboard, and show digitized documents to superiors. Yes, this can be done now, but you must admit that a meeting in Zoom and a meeting in a large virtual room are not the same thing.

### 1.4 Classification of the Metaverses

Metaverses are divided into the following 4 main categories:

*1. Traditional centralized Metaverses*

These Metaverses do not integrate the blockchain into their mechanism and operate in a centralized system. In other words, these are virtual spaces controlled by a central organization that stores the data of all users. The advantage of these Metaverses is that they have the largest number of users. For example, the game Fortnite collects about 278 million users. For a brand that wants to bet on the number of audiences, this choice of the Meta may be logical. In addition to Fortnite, prominent examples of this group are: Grand the Auto V, Minecraft and Roblox.

*2. Traditional decentralized Metaverses*

This type of Metaverse implies virtual worlds in which all decisions are made by users through voting. Player data is not stored by third parties, but belongs to the account holders. At the moment, this type of Metaverse does not yet exist and most likely will not, since it is difficult to implement without the use of blockchain.

*3. Blockchain based centralized Metaverses*

The Metaverses create a complete digital economy where users monetize their acquisitions and creations. Meta data works with cryptocurrency, but user data is stored at the central organization – the developer. Metas of this type are at an early stage of development. Meta from Facebook can be attributed here, while it is under development.

*4. Blockchain based decentralized Metaverses*

In blockchain-based decentralized Metaverses, decision-making powers do not belong to the central organization, but to users. The so-called DAO (Decentralized Autonomous Organization) system operates there, in which each user who owns the Metaverse token plays a role in managing the virtual world in which he is located, and also follows the rules that are prescribed in the smart contract. Metaverses of this type are also developing a virtual economy based on cryptocurrency. This is probably the most successful form of the Meta, as the concept used most closely embodies what the Metaverse really is. The principle of decentralized Metaverses is an additional opportunity for the user to receive rewards with virtual items or currency. Exactly in these Metas the earning mechanisms such as "Play to earn" and "Create to earn" are most noticeable (Figure 3).

An example of this type of Metaverse is Axie Infinity, which is based on the Play to Earn model. The Decentraland and The Sandbox metas are also examples, but in a more traditional way, where users own land and can do almost anything with it. Brands are already actively using this type of Metaverse. For example, on July 12, 2022, The Sandbox and PlayBoy collaboration was announced, and on July 30, 2021, Coca-Cola's NFT sale took place in the Decentraland Metaverse.

In terms of functionality, all Metas can be divided into the following 3 groups:

- *Gaming:* this is the most popular and developed direction in the Metaverses. Given technology maturity, user fit and content adaptability, games are a great way to explore the Metaverse.
- *Crypto-worlds*: these are immersive virtual worlds with huge social and financial potential.
- *Business, work, and learning:* the Metaverse opens up new opportunities for immersive virtual collaboration in terms of remote work.

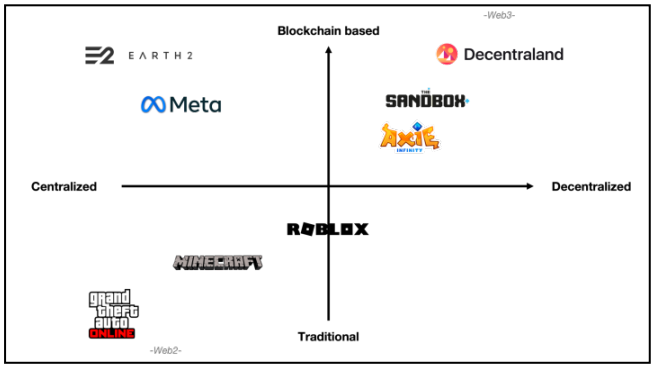


**Figure 3** – Metaverse classification


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We are, as architects, urban planners, or as an ordinary citizen, more interested in the later option, which affects the life of a greater number of the population. But it must be recalled that for all 3 categories, a minimum 3D designer and visualizer is needed, where professional architects and urban planners are more widely needed. Just this space should look and justify like the real world, and definitely needs all the details as it really does for the architecture and urban planning design.

### 1.5 How does metaverse even work?

Designing a metaverse is relevant in the educational and corporate environment, in the field of communications. We need 4 basic factors in order to realize metaverse working: software, equipment, data centers and blockchain.

- *Software:* With the help of 3D engines, projects of the virtual world are created. The most famous of this kind of platforms are Unreal Engine and Unity.
- *Equipment:* These are the user's guides to the metaverse. VR glasses, AR and XR gadgets, and in general everything that will help you interact with the platform. Virtual and augmented reality glasses are optional. The main thing is that the two universes unite, so that it can even be a sound reality without visualization.
- *Data centers:* These are cloud storages for the data of the metaverse, server and network equipment are placed here, and there is a connection to the Internet. The main suppliers are well-known companies such as Amazon, Google and Microsoft.
- *Blockchain:* This thing attaches the data and money of each user to his digital account and allows you to use the purchased products throughout the metaverse.

There are many collaboration and communication services: VR-Chat, Engage, Horizon Work-rooms, as well as games with sandbox worlds like Minecraft, Roblox and Horizon Worlds. However, all of them are still very far from a full-fledged metaverse.

The main criteria that officially presented to the metaverses are listed below:

- *Interoperability* – the ability to work on any device;
- *Decentralization* – independence from any particular company or server;
- *Persistence,* when the world lives its own life, even if you are disconnected from it.

Now companies are looking for solutions: some focus on decentralization and blockchain, others focus on immersive worlds. In the coming years, we should not expect a miracle – except for the active phase of investing in the metaverses direction. The popularity of Meta Quest 2 VR headsets is growing at a rapid pace, but to form the foundation of Meta's metaverse, it is necessary that these devices be in every home, by analogy with a computer or smartphone. There is also the question of available computing power – according to the statements of the CEO of Intel Corporation, there are not enough computing resources in the world to support worlds of this level of detail. And then there are legal and political aspects. The implementation of the Web 3.0 concept will be a global technological revolution that is revising most of the usual processes both on the web and in the physical world. The fact that not only users and centralized individual companies but also states become participants carries great risks. All parties will have to not only launch process updates in parallel, but also agree among themselves by linking their products, regulations and subsystems into a single network. The process of launching such a large-scale mechanism should greatly affect everyone without exception. If all this becomes a reality, people will have to find a balance between the virtual and physical world so that the metaverse does not become the reason for losing touch with reality.

## 2 From reality to virtuality

In the future, the matter will not be limited to one metaverse, the Metaverse world will be as diverse as the modern Internet. In fact, Metaverse is the mobile Internet of the next version. Even if the Metaverse falls short of the vision of science fiction writers, it will generate trillions of dollars in profits as a new computing and media platform. If the concept of the Meta is fully realized, then the Metaverse will become the gateway to much of the digital "impressions" and "experiences", as well as a key component of the physical world. The benefits of being a key player or even the driving force behind such a system are clear. Nobody "owns" the Internet today, but almost all of the leading Internet companies are in the top 10 most valuable public companies on earth. And if the Metaverse truly serves as a "successor" to the Internet – this time with even greater reach, user engagement, and commercial activity – there will be even greater economic benefits. It looks something like this: the user creates an avatar, gives it a certain appearance, then from his equipped virtual home goes to work in a virtual office, where he meets the avatars of colleagues [6]. Physically, they can be anywhere: lying in their favorite sweatpants on the couch or in shorts – on the beach of Sri Lanka.

Now companies that are interested in this area are developing devices for a more complete immersion in the metaverse world. The same Meta announced the work on a high-quality virtual reality headset – the Project Cambria VR helmet. He will be able to recognize facial expressions, read mood, understand the direction of gaze and form augmented reality in front of a person's eyes. The company is also going to introduce augmented reality glasses under the working title Project Nazare. They will be equipped with a holographic display, a projector, chips, cameras, sensors and speakers. Another example of an immersive augmented reality assistant is the Hololens AR headset from Mi-crosoft. It tracks a person's gaze and hand movements to overlay virtual images and icons. This allow you to create usage scenarios – the glasses tell you how to navigate, identify objects and inter-act with the ordinary world in a virtual manner. However, these technologies are not enough. Epic Games founder and CEO Tim Sweeney explains that in the metaverse, users will be able to move from one world to another, retaining their appearance and objects, having different experiences of events, while remaining socially connected with each other. This requires a new programming model that will be like a live and open evolving platform where millions of users move seamlessly from one world to another. Such a model does not yet exist.

An example of how a blockchain-based metaverse works is the Decentraland virtual reality platform based on Ethereum. On it, users buy plots in the virtual world, communicate with each other through digital avatars and attend events created in this space. The blockchain-based experiment includes true ownership and gamified social functionality.

## 3 Virtual world to metaverse

The Metaverse is a publicly accessible virtual space within which people can interact with each other and with all kinds of digital objects using pre-created avatars. Such interaction becomes possible through the use of virtual and augmented reality technologies, as well as the use of special VR and AR equipment. In other words, plunging into the Metaverse, a person receives direct control over his avatar, after which he can perform all kinds of (and sometimes impossible) actions in a pre-created digital reality.

Theoretically, metaverses provide users with the opportunity to lead a full social life. They should have a developed economy for the possibility of mutual settlements, as well as thoughtful systems of virtual interaction and communication. Which excludes it from the true experience of the metaverse, so it's not a smooth movement [7]. You don't start in your house, on your land and go to the venue. You do not look into the distance and see the city spread out before you, ripe for exploration. This will be the next step. The Metaverse must bring it all together, group disparate businesses together, and create an experience that benefits the user both digitally and physically. If you need to go from home to the arena, meet friends along the way and use VOIP chat to communicate, this is one step. If you can buy an NFT poster for your digital bedroom when you arrive, as well as a T-shirt for your avatar – all from a digital avatar vendor – it would be helpful if the physical versions of them were sent to your home.

**4 Effect of Digital on real architecture**

There is no traditional constructive logic in the metaverse, and sometimes you can even change the physics, allowing avatars to jump 10 meters up and walk on the ceiling. Such conditions for creativity will create a new quality of architecture, which, will move from virtual to physical architecture. For those who believe that you can become a real architect only if you build and work with materials, let me remind you that many great architects developed their style and approach precisely on virtual projects – you can remember Cedric Price's Fun Palace or Bulle's utopian projects and Ledoux. Architectural discourse has been in crisis for the last 20 years, because there are no significant, transformative trends. The Metaverse is a new approach, new opinion leaders. Very soon they will create a new visual language, the quality of spaces and change styles.

The Metaverse can also be viewed as a digital layer that is superimposed over the city and read using, for example, a smartphone [8, 9]. Therefore, buildings should have a set of elements that would help not only human vision, but also machine vision: there are already unmanned vehicles, drones and robots that can deliver and other services. In the longer term, the boldness and madness of architects in the metaverse will introduce a new visual habit in humans that will affect the architecture of the physical world. Now the metaverse can serve as a platform for testing ideas that will later be embodied in the physical world. Zaha Hadid Architects designs Liberland's master plan and public presentation spaces.

The digital world should become an experimental space for rethinking what we build in the phys-ical world, taking into account the global impact of the construction sector on the environment. Moreover, the metaverses are more inclusive due to their accessibility and enhanced functionality.

**5 Role of an Architect in Metaverse**

In the modern world, technology companies drive progress, but they are guided by their markers of success: the number of purchases made, the amount of time a person spends on the page, and so on. Acting in their own interests, they can create an environment that is not oriented towards generally accepted social values.

Historically, cities developed spontaneously, but now we are well aware of the problems of self-building, favelas and poor urban planning. Architects must take responsibility for what is already happening in the metaverse, try to create an architectural correction environment there. There are three components necessary for the existence of the metaverse. *The first is the world*, context, three-dimensional space. *The second is the avatar.* And *the third is content* that can be located inside the space and with which the avatar can interact. All these components will be modernized, supplemented, subcategories will appear, but the context will remain the most ambitious and significant. Just like an architect in the physical world, an architect in the metaverse will be able to influence the experience of an entire group of people within a space. The stage of mimicking the physical world should pass quickly or occupy a small part in the architecture of the metaverses, since the challenge lies in new materials, tools and the absence of most of the limitations of the physical world. Now most of the things that have been done are already done by game designers.

The current metaverse prototypes are often similar to cities: the same public spaces, areas that can be built on, buildings, parks and streets. Now it's voxel geometry and low-poly aesthetics – architects are used to a different concept. At the same time, the digital world does not shackle us with norms or physical restrictions, building codes and budgets. In a digital world, the important thing is: "how you work with geometry?"; "how you can optimize it?"; and "what narrative you offer to the user?".

Architecture for the metaverse is open to all users, but freedom of expression in the metaverse comes with its own challenges. Architects are faced with the task of developing systems of interaction and control so that the new quality of the Internet does not turn into chaos. Now technology companies themselves are trying to solve this problem, sometimes involving users, but this is clearly not enough. Architects will have to come up with a language for this digital world. There will be copyright spaces that collaborate with architects, but there will also be spontaneous ones. It is necessary to transfer the expertise of architects to the metaverse.

**6 Metaverse and City**

As we know, pandemic situation in 2020 have many negatives on humans' life, but it helps to know and review many things and daily manner in our life like as: our health and take more times for ourselves, family, close friends, walking, shopping, study, working etc. Without a doubt, COVID-19 had a powerful impact on some the innovation development and digitalization like as: online commerce and robotic delivery, electronic and contactless payments, remote work, distance learning, telemedicine, online entertainment, supply chain 4.0, 3D printing, robotics and drones, 5G and information and communication technologies (ICT) [4, 5]. This list certainly accelerated the emergence, appearance and needs of the metaverse in the present.

Today, there are a large number of separate metaverses in the world. The first and most famous ones are developing on the basis of games (Fortnight, Roblox), gamified blockchain projects (Decentraland) or workspaces (Horizon, Microsoft mesh), which have become necessary since the beginning of the pandemic. But speaking of the metaverse and the unified 3D internet, it is impossible not to talk about cities and the integration of public services, as well as the emerging desire of the authorities of different countries to develop digitalization, laid down by the concept of a smart city and to use the opportunities that the metaverse will provide.

Dubai, Abu Dhabi, and Seoul could be the first cities to appear in the metaverse. Previously, developers created only fictional worlds or individual fragments of real cities, but now they expect to recreate cities, respecting the real scale of buildings [10]. Users will be able to visit cities for the purpose of tourism or shopping, as well as receive public services there. However, experts doubt that they will become popular: it is easier to get banking or government services using the site, and such tourism will become more prepare for a trip than a full-fledged replacement.

The beta version of the project Metaverse Holdings for Dubai and Abu Dhabi is planned to be launched at the end of 2022, and soon after that it will be available to users around the world. The company said: Unlike existing VR projects, where developers create small fantasy worlds, this metaverse will be based on the real world. After the launch of the beta, the metaverse will also recreate the key places of the UAE, which will be "visually, topographically and geometrically" correctly correlated with real objects. Users will be able to visit the metaverse using a VR headset, an application on a smartphone or other device. According to Karin Neidu (strategic advisor at Metaverse Holdings), among the candidates for digitization after the launch of the UAE are Saudi Arabia and Qatar.

The main opportunities of the metaverse for city dwellers consisted of:

- *Availability and effectiveness of the services received:* First of all, this is an opportunity to get more services without a personal visit to various institutions and with great immersion. This, for example, concerns such areas as education and tourism. Of course, we would prefer to do both personally, but the metaverse is able to make these areas more accessible (no need to travel to another country to attend the event). Compared to existing digital tools, the metaverse will provide a livelier communication and presence effect. Video broadcasting an event or recording a lecture and being in a virtual 3D environment is not the same thing. The presence in space (even if it's virtual space) creates a brighter image and contributes to better memorization of information.
- *A new layer in the urban environment:* The digital layer is perceived through glasses. I wanted to play chess with a friend, found any free table and move virtual pieces around the virtual field. User could upload a street design created by another user and now instead of a gray fence you look at an animated painting. Creating content and making it easier to influence the environment around you is another plus. Influencing space on the virtual layer is the realization of the values inherent in civic activism and participatory design – in order to feel like residents and owners of their area, city and people take part in its development (Figure 4).


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**Figure 4** – New virtual layer in the urban environment (concept)

## 7 Metaverse cities realization samples

The government of various countries is interested in the development of their own metauniverses. The following are working on the creation and financing of local platforms:

- The United Arab Emirates – the government of the country announced the launch of the "Dubai Metaverse" strategy. With the help of it, 40 thousand specialists will be attracted and new platforms and technologies will be developed.
- China – The government of the country plans to create its own controlled metaverse. And Hong Kong and Shanghai are already busy developing their own virtual reality educational platforms.
- Spain – The government of the country has allocated $ 4 million in grants for the creation of the metaverse. And Catalonia is busy building its own CatVers platform.
- South Korea – the government of the country in 2022 allocated $ 177 million for the development of the sphere. And Seoul has been building its own Metaverse Seoul since 2021.
- Indonesia – The government has already launched its own MetaNesia platform. Events from the real world are planned to be transferred to the metaverse.

**Seoul – South Korea**

The city of Seoul (the capital of South Korea) announced that it would become the world's first "metaverse metropolis" at the end of 2021. As part of the project – tentatively titled "Metaverse Seoul" – regulators will create a communications ecosystem for all areas of urban life. Quartz reports that the initiative involves the launch of a virtual version of the city, which can be accessed by any inhabitant of the planet using a computer or VR glasses, reports.

The Seoul Metaverse is not an entertainment project, in the manner of VR playgrounds, but part of South Korea's plan to reorganize the economy amid the pandemic. The development of a digital reality includes economic, cultural, tourism, educational and civic services, which will begin to roll out from next year. At the same time, the first Metaverse Seoul structures will start operating at the very end of 2021.

The pilot program will be presented as a virtual bell at the Bosingak Belfry. Traditionally, this bell is only rung at midnight on New Year's Eve, but this time it will ring twice at the same time – in the real world and in a virtual replica of the historic building. The event will mark the start of the new calendar year and the official launch of Metaverse Seoul. Later, the city government will partner with the private sector to help digitize real-world services to support businesses and consumers through virtual reality. Regulators will "build" a virtual city hall, a laboratory for creating new financial technologies, a replica of the Invest Seoul investment fund, and a Seoul campus city. All structures will work at the state level – residents will be able to turn to politicians on issues that concern them and solve them without leaving their homes. In 2023, "the Seoul Metropolitan Govern-ment (SMG)" will open a virtual community service center, the Metaverse 120 Center. Officials will communicate with visitors to the center in the form of avatars, providing advice that was previously only available through the Seoul City Hall center.

Major tourist attractions in Seoul, such as Gwanghwamun Square, Deoksugung Palace, and Namdaemun Market, will also be introduced through the "Virtual Tourist Zone". Within two years, key events in the city, such as the Lantern Festival, will begin to take place in the metaverse and can be accessed from anywhere in the world. Moreover, the metaverse will help South Korea in the process of recreating the cultural heritage – Donuimun Gate, one of the city's gates to the capital, destroyed in 1915, will be transferred to the virtual space in its original form. In parallel with tourism activities, SMG will develop services for socially vulnerable segments of the population. Mixed reality (XR) systems will help people with disabilities receive medical and psychological consultations, as well as allow access to places that were previously inaccessible to people with disabilities.

The city government will use part of the $3.3 billion allocated by Mayor Oh Sehoon for the 10-year plan to modernize Seoul to create the metaverse. Hong's strategy is to create a "digital course for Seoul" – the authorities want to improve the health care system, education and tourism industry, as well as accelerate the development of the economy and introduce a new type of public transport – electric air taxis into everyday life.

**Dubai – UAE**

In the summer of 2022, the United Arab Emirates announced the launch of the Dubai Metaverse strategy. Within 5 years, the government plans to develop platform standards, introduce new technologies and create infrastructure for the metaverses.

The goal of the program is to develop this area and attract new professionals to the Dubai metaverse. In five years, the authorities plan to attract 40,000 developers and content creators of digital platforms. For the development of the metaverse, the UAE is ready to hire local and foreign specialists who will work for technology companies in Dubai. In 2022, more than 1,000 companies were registered in Dubai that are associated with the metaverse. They have already brought $500 million to the country's economy. The government plans to increase this figure to $4 billion. The Dubai Metaverse strategy also has the task of integrating the technologies of the metaverse into the daily lives of citizens. Therefore, the government of the country is developing its own state platforms. For example, at the beginning of 2022, the Arab Health and Medlab Middle East 2022 congress was held in the UAE. At it, the Minister of Health introduced the first customer service center in the metaverse. Users of the MetaHealth platform will be able to communicate remotely with the center's employees and draw up documents. Public services can be obtained from any phone or personal computer. As a rule, public and private organizations do not engage in the development of the metaverse on their own, but turn to agencies specializing in the metaverse. They help to most accurately adapt the concept of a downloader to the possibilities of the metaverse and have the expertise necessary in such a rapidly changing market.

**DEIP Metaverse City**

At the beginning of June 2022, DEIP Metaverse City opened a space in the metaverse for the creative industry. The project brought together artists from all over the world and showed how you can present your art using DEIP technology, one of the first Web 3.0 creative economy protocols.

The author of the digital activation (BALAGAN team) in collaboration with the Arhead.io metaverse ecosystem and the Atrium architectural workshop creators created a city that reflects the values of DEIP in virtual architecture. The project team designed everything from buttons and avatars to buildings and plazas, integrating the branding and color palette into texture and lighting. The basis of DEIP Metaverse City was the rethinking of microchips – those same ones thanks to which the technologies of our devices work.

DEIP Metaverse City consists of five locations: a three-story exhibition area, a labyrinth with dozens of intersecting streets, as well as tunnels and a square with an amphitheater. The main attraction is the Balloon Dog (Blue) installation by Jeff Koons, one of the most expensive American artists whose work can be seen today in leading museums of contemporary art (Figure 5). The sculpture, donated by the Swiss gallery Weng Contemporary and converted into a digital format, was the first piece of art to be officially presented in the DEIP metacity. There are other exhibits in the space: Venus of Willendorf, Nika of Samothrace, Kazimir Semenovich's multistage rocket and Miron Kruger's sensors.

At the very beginning, visitors are greeted by a huge avatar – DEIP Executive Director Alexa Shkora. He accompanies guests throughout the journey: he talks about locations, mechanics and plans for the development of the creative economy. The culmination of the trip is a ray of light launched by the guests over the metropolis, marking the opening of the mainnet (blockchain for monetary transactions). As Konstantin Belyakov, cofounder and creative director of Balagan, noted, more than 70 world media outlets interested in the future of blockchain and the creative economy wrote about the project: "It was important for us to contribute to the development of the creative industry, as we ourselves are its representatives".

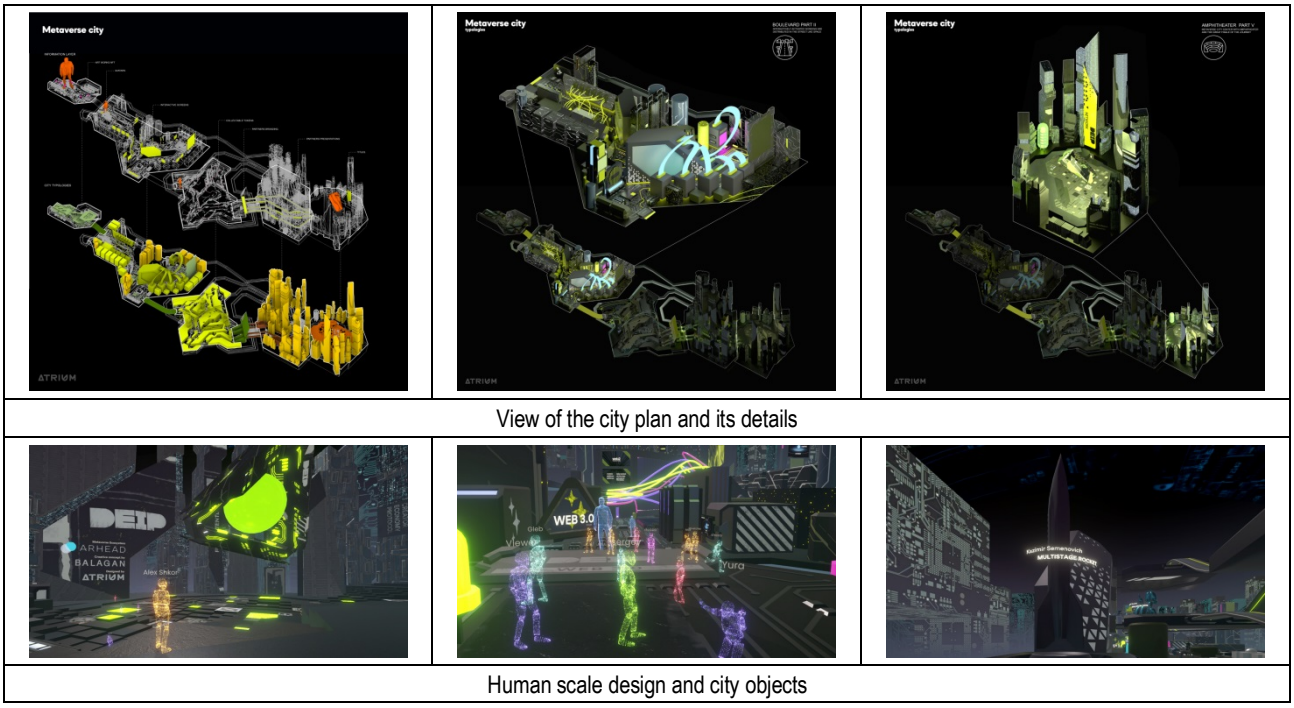


**Figure 5** – DEIP Metaverse City and its details

From the exact vision of other professionals this city can beat very well and generally in today's day is excellent for the creative industry. And there are other sides to see the architecture and urban planners, and their opinion. As can be seen from this sample and the details of the city, many objects of the city and architectural objects and details are missing. Many say this space is too fantastic and generally without green territory, which really influences the soul of a person and his psychological health and character. If we understand this space as a world that a person will participate in a lot of time and life, then the scale of the future problem that connected with these spaces will be great.

## 8 Metaverse and Sustainability

A review of the literature and the direction of the metaverse of the city proves the presence and existence of a strategic plan for cities within the sustainable development of the city. Thus, if this strategy beat sustainable development in the 90th year, then in 2000 until 2015 the strategy received a green or smart city, and so on until today, which is the metauniverse city [11, 12]. Obviously, this process is the continuation of the sustainable development of the city, country, nation and humanity. Therefore, the effect of metaverse on 3 main aspects of sustainable development considered below:

*Social aspect:* if we look at the deeper underpinnings of these trends as sustainable development, we can say that the Metaverse is indeed influencing the social development of citizens, since this pace has received more support in the time of the Covid-19 pandemics in 2020. Moreover, this direction will develop on social networks and communication basis, then we can say that this direction affects the social aspect of sustainable development. There is also a well-known term called metamedicine, which is not limited to the consumption of goods in virtual reality and extends to other areas. For example, prescription games and digital medicine become possible, that is metamedicine. In addition, the emergence of "VR pharmacies" for the treatment of certain diseases is possible.

As part of the direction of metamedicine, games for treatment will develop; VR pharmacies and prescription games may appear. For example, in June 2020, Akili Interactive's game EndeavourRx was approved by the Food and Drug Administration (FDA), making it the world's first video game for treating attention deficit disorder in children. In 2021, the game will be tested as a treatment for COVID-19 patients with brain fog1. Revery raises $2M in 2021 to improve mental health through mobile gaming technology. The project will launch an app that combines cognitive behavioral therapy for insomnia with mobile game concepts. Virtual communication plays an important role in the formation of metalife. According to a Wunderman Thompson report, 83 % of consumers globally believe technology brings people together, while in China, 84 % say technology has strengthened their relationships with friends and family. In particular, games are becoming key places to meet people.

In addition, in the metaverse, virtual platforms are used for large-scale events and small meetings, land is being zoned and sold, plots and houses are purchased, trips with the full effect of being present are possible. New social networks are being created and united by shared values. In particular, IMVU (Instant Messaging Virtual Universe) from Together Labs is a social network for finding friends based on 3D avatars. IMVU is becoming a place to express yourself and build a community.

*Economic aspect:* many literary analyzes and leading directions say that so far investors are coming to the metaverse only for economic interest. Then the metaverse, as a new developing trend and direction of business, affects the economy.

According to a 2021 report by research firm Technavio, the in-game advertising market will grow by $10.97 billion between 2020 and 2024. This growth is fueled by brands building their gaming know-how and incorporating gaming experiences into entertainment and advertising strategies. So, Balenciaga released a 2021 collection with the debut video game Afterworld: The Age of Tomorrow, created by Streamline Media Group. Players navigate the futuristic world as they pass other characters dressed in the brand's new designs. In addition, marketing opportunities will expand and new business models will appear for assessing the demand for virtual things, predicting the quantity, time and place of production in the physical world.


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*Environmental aspect:* as they were impoverished earlier, at the expense of less leaving home and using transport at the expense of household, educational and work processes "at a distance"; the metaverse affects the ecological aspect of sustainable development.

No need to score smart and green city direction according to how much this trend is based on the development of the Internet, information analysis, convenient and efficient system for serving the city population, then the metaverse city is an advanced version of the smart city. The metaverse will be more active and accessible to smart populations. In the coming years, the world will become even more virtual, changing everything from fashion to finance. In addition, there are near-term break-throughs in clean technologies and bioengineering, which could help make progress in tackling cli-mate change and curing disease.

**9 Main advantages of metaverse**

At the moment, the metaverse for architects and urban planners is playing a new trend and oppor-tunities for 3D visualization, 3D designs and their expansion.

On the other hand, the metaverse facilitates the land and transport restrictions of the city due to the possibility of services and virtual spaces. There is such doubt and criticism that the metaverse reflects realities and limits our vision to what we can imagine [5]. In response, it must be reminded that the metaverse is a choice, and not an obligation for each person. Literature reviews shows main advantages and opportunities of metaverse as below:

- This is communication from any corner of the world; and the ability to meet friends and col-leagues in virtual worlds, instead of wasting time on the road.
- The ability to transfer many household processes "to a remote location".
- New working format.
- New jobs will appear, for example, programmers and designers of virtual objects and meta-worlds will definitely be in demand.
- The ability to visualize their projects, for example, inventors will be able to show investors prototypes of their developments not just in the form of drawings or printed 3D models, but as an object of the virtual world.
- It can also change the scope of education and more study opportunities: in history lessons, children will be able to find themselves in the virtual world of ancient Greece or visit the bat-tlefields, medical students will be able to practice and study anatomy on virtual models of people, future architects will be able to create full-sized virtual buildings.
- It could engage virtual influencers and models.
- We can open a shop there.
- New advertising system and platform.
- We can implement outdoor advertising.
- We could hold events and concerts.
- Advertising, buying, Selling Metaverse Objects and Investing.
- Erasing boundaries, the ability to travel through virtual worlds. This will make life easier and better for people with disabilities, low financial status or those who cannot travel due to re-strictions imposed by the state.
- And of course, you can create your own universe and make the space branded, sell your ser-vices in the virtual world and communicate with customers through such an unusual com-munication channel.

**10 Disadvantages and risks of metaverse**

Despite the optimism of the ideologues of the metaverses, many unsolved questions remain. Because of them, the creation of a full-fledged virtual universe will stretch for several years. The main unsolved questions category listed below:

*First of all, related to technology:* now VR glasses and tactile gloves are heavy and uncomfortable and it's hard to stay in them for several hours. Some users get seasick when they use standard VR glasses. Mark Zuckerberg believes that these should be glasses that are close to ordinary glasses for vision, like Google glass. More compact and light weight counterparts are needed. In addition, while the quality of graphics in the VR environment leaves much to be desired (although progress is already noticeable). To feel completely immersed in the process, it is important that we see with our own eyes – a realistic 3D avatar or a pixelated man with a triangular head.

*The second point is the safety* of the physical body while traveling through the metaverse. A person in a VR helmet can easily trip and hit the furniture in their apartment. So, in addition to diving equipment, there must also be safety equipment. As an option, use virtual reality running platforms like Virtuix Omni 2.0.

*The third point is internet.* Life in the metaverse requires stable Internet access. But for many users, this is a problem, which means that these people will be cut off from the opportunity to settle in the metaverse.

*The main disadvantage: Metaverse is not equal to the transition from reality to virtuality!* The advent of online services has not made our streets empty, we still go to sports clubs and group workouts, watch movies in cinemas eating popcorn and personally go out for buns in bakeries. What has changed is that in a situation where you prefer to save time on the road, or today is the day when you don't want to leave the house and smile at neighbors and sellers, you have this alternative. The emergence of the metaverse does not necessarily pull us further from reality. The development of the Internet and Internet services is due to convenience and efficiency, so that a person can spend less resources to get the result, changing the quality of the process. The metaverse faces the same task – to make it possible for people to solve the problems facing them even more effectively. We are already spending the time that we will spend in it online; in some professions, working hours will be added here. "To what extent are existing projects coping with this", that's another question, but we have to start somewhere.

**Risks**

The risks of the metaverse are associated with the desire of users to transfer their values and ethics to the virtual world, and their real identity will have an impact on the physical world and have real negative consequences.

The transformation of perception has a significant cultural impact on society and changes in behavior in society, including the reduction of the importance of morality and ethics through the use of a virtual avatar. This is especially true of the most vulnerable new group in the metaverse, children. In addition, there is the problem of respectful interaction with intellectual property and the use of content.

Another category of risk is associated with the implementation of legislative initiatives in the metaverse and legal jurisdiction, due to the lack of physical boundaries for supply chains that are not regulated by tax codes and regulations. The most important issues relate to the regulation of interaction in the metaverses, which open up new opportunities for manipulation and misinformation, shifting landmarks and changing the perception of the surrounding world.

**Results**

Based on the summary of this study, the following results can be drawn:

1. Digital future, what we once read about in science fiction writers and postmodernists has al-ready become our new reality, and the government is discussing not only cryptocurrencies and mining, but also cybersecurity in the metaverses. There has been a lot of talk about the metaverse since Mark Zuckerberg announced at the end of 2021 that Facebook was renamed Meta and the company was focusing on virtual products. In the Metaverse digital space, a user can be anyone, choose their appearance, contact other players (their virtual avatars) and objects. It is important that the metaverse has all the attributes of the real world, where it has its own digital economy, which allows you buy clothes, real estate, including NFT objects, go to exhibitions, concerts, have parties, watch movies, and much more. Metaverse should become a single virtual ecosystem where all the above principles will be implemented.
2. It seems metaverse would be a good new approach and opinion for architectural discourse. Some scientists believe metaverse is a continue approach of sustainable design and smart urbanism. Although this area is open to all, but freedom of expression in the metaverse comes with its own challenges. Some architects try to design master plan and public spaces for metaverse.
3. Pandemic situation in 2020 helps to know and review many things and daily manner in our life, and powerful impact on some the innovation development and digitalization and finally accelerated the emergence, appearance and needs of the metaverse in our life and city. The main opportunities of the metaverse for city dwellers are: availability and effectiveness of the services received and a new layer in the urban environment.

4. The implementation and plan of the Metaverse City more supports the idea that the Metaverse is a new trend/direction of sustainable development or a smart city, according to how much such an approach has been implemented in cities that have smart city infrastructure and a plan for the implementation of sustainable development aspects.

5. A review of the literature and the direction of the metaverse of the city proves the presence and existence of a strategic plan for cities within the sustainable development of the city.

6. The risks of the metaverse are associated with 3 main criteria (desire of users, cultural impact on society, legislations) that affect the physical world and have real negative consequences.

7. Technology can lead to new mental health issues, an increase in addicted users, an increase in cybercrime, a threat to data and privacy. The list of cons also includes a possible seizure of power by corporations within the platforms. At the same time, the emergence of the metaverse will open up many opportunities: a new level of communication, increased social interaction, increased levels of digital empathy, and improved work processes. In addition, new professions will appear, which will create jobs, and education can move to a completely different quality level.

**Conclusions**

The concept of “metaverse” implies the presence of a new digital infrastructure, which is similar to the Internet and is located in the virtual world. The possibilities of the metaverse apply to all areas of users' lives and offer new options for using virtual reality. In particular, the average user's metalife paradigm needs to take into account consumption, medical care, travel, work, dating, and communication. Virtual communication plays an important role in the formation of metalife, and created a new social network, which united by common values. In addition, in the metaverse, virtual venues are used for large-scale events and small meetings, land is zoned and sold, plots and houses are purchased, travel with the full effect of presence is possible.

The Metaverse is a huge simulation. It cannot completely replace the real world and it's not meant to be. The metaverse will become a continuation or addition to the real world with all its pluses, and for some minuses. If it is implemented as they are promised, it will be a breakthrough in virtual and augmented reality technologies and change the fate of many people. The general understanding from the metaverse is to say that this new trend does not actually reconstruct cities, but on the contrary, a new function of reality appears in the city that people want to see it. Ultimately this should make cities more livable. Will the developers succeed in creating a metaverse or will it remain an unrealizable fantasy – we will see in a few years.

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# MULTI-STOREYED BUILDING SLAB FOUNDATION SETTLEMENT

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**Abstract**

The purpose of this article is to consider slab (raft) foundation settlement of multi-storey buildings, to analyse their occurrence and development, and to propose methods and recommendations for their prevention or minimisation. The article considers engineering-geological conditions typical for the Brest south-west microdistrict-1, and proposes a method of levelling uneven deformations of the slab (raft) foundation base.

**Keywords:** foundation base, foundation settlement, stress-strain state, relative settlement difference, deformation modulus, central and peripheral zones.

## ОСАДКИ ПЛИТНЫХ ФУНДАМЕНТОВ МНОГОЭТАЖНЫХ ЗДАНИЙ

**П. С. Пойта, Н. Н. Шалобыта, Т. П. Шалобыта, Е. Н. Шалобыта**

**Реферат**

Целью данной статьи является рассмотрение осадок плитных фундаментов многоэтажных зданий, анализ их возникновения и развития, а также предложение методов и рекомендаций по их предотвращению или минимизации. В статье рассмотрены инженерно-геологические условия, характерные для ЮЗМР-1 г. Бреста, а также предложен способ выравнивания неравномерных деформаций основания плитного фундамента.

**Ключевые слова:** основание фундаментов, осадки фундаментов, напряженно-деформированное состояние, относительная разность осадок, модуль деформации, центральная и периферийная зоны.

### Introduction

Currently there is an intensive construction of residential multi-storey buildings in the Brest south-west microdistrict-1. The territory of the microdistrict is a wasteland overgrown with shrubs. The landform of the area is flat, the absolute level of which varies from *133.28 m* to *133.98 m*. The geological structure of the territory includes soil formations represented by a vegetation layer with a thickness from *0.1* to *0.4 m*; alluvial and lake-marsh deposits represented by sands of different coarseness: from dusty to medium; sandy loam and loam – weak and medium strength, including weakly peat-covered, with a thickness of up to *1.4 m*; peat and medium peat-covered soils with a thickness of up to *1.0 m*. Beneath alluvial and lake-marsh sediments, lake-alluvial sediments were uncovered, represented by interlaced sands of various sizes from dusty to coarse, sandy loam and loam with plastic, soft-plastic and flowing.

Ground waters are found at a depth of *0.1 – 1.0 m* from the day surface, or at absolute levels of *132.28 – 133.27 m*, their maximum predicted level (according to JSC "Brestproekt") should be taken at the level of *134.5 m* [1].

Taking into account the geological structure of construction sites, when designing the foundations of multi-storey buildings, the characteristics of foundation soils are assumed to be equal to those given in Table 1.

Shallow foundations and driven pile foundations were considered in the option design.

The main variant of foundations for large-panel buildings of different number of storeys (from *5* to *9* storeys) is a solid reinforced concrete slab for the whole building with a height of *500 mm*. The main specificity of this variant is that the soil formations, peats, marshy soils, as well as weak sandy and clayey soils, which cannot be used as foundations without their removal, compaction or consolidation, are embedded from the surface of the site up to the *131.640 m* mark. Taking these factors into account, as well as the adopted depth of the foundation footings, it was necessary to install the sand and gravel pad over the entire thickness of these soils, up to the foundation footing mark. The sand and gravel cushion was poured in layers of *0.2 – 0.3 m* thickness with subsequent compaction of each layer by rollers up to the compaction coefficient $K_{com}$ = *0.95*. Sand cushion thickness was *3.0...4.0 m*.

**Table 1** – Characteristics of subgrade soils

| Name of soil | Specific weight of soil, *kN/m³* | Strength parameters | | Deformation modulus *E, MPa* |
|---|---|---|---|---|
| | | *φ, deg* | *C, kPa* | |
| Sand and gravel mix | 16,0 | 37 | 2,0 | 20,0 |
| Dusty, medium strength sand | 10,2 | 30 | 4,0 | 13,0 |
| Dusty, firm sand | 10,7 | 34 | 5,5 | 26,0 |
| Fine sand, medium strength | 9,8 | 31 | 13,0 | 17,0 |
| Medium sand, medium strength | 10,6 | 37 | 2,0 | 43,0 |

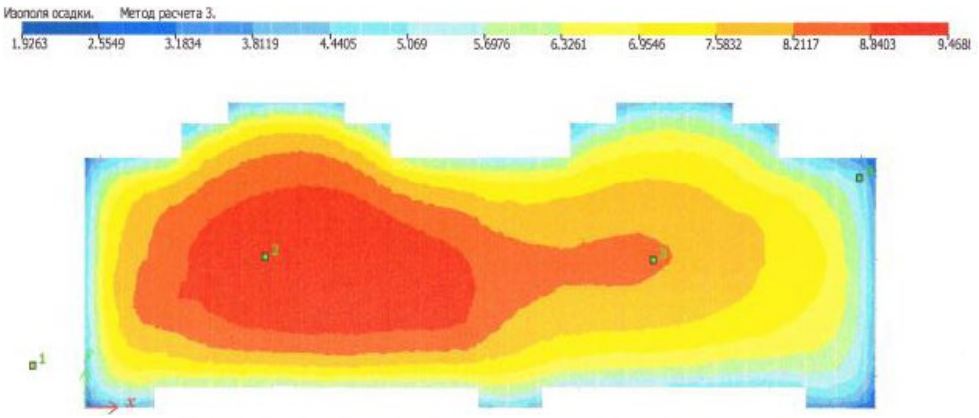
The slab foundation bottom mark is assumed to be *135.400 m* (Project Work Directorate of the Communal Unitary Utilities Enterprise "Brestzhilstroy"). Generally, the foundation slab made of concrete of class C25/30 was built under the house, with separation by expansion joints, within the section.

### Research methodology and results

We have performed calculations of the foundation slab in the engineering-geological conditions specified in Table 1, with the only difference that the layer of flowing loam located at a depth of *5.9...6.9 m*, with a thickness of *1.1* to *1.6 m* in the left section of the house and *1.1...0.2 m* in the right section was taken into account. The calculations were performed using the software packages LIRA-SAPR and PLAXIS 3D, which allow to perform a joint calculation of the system "base-foundation-building" [2, 3, 4].

Isopoles of vertical displacements of the foundation and the character of their development in different sections of the slab are presented in Figures 1 and 2.

a)




b)

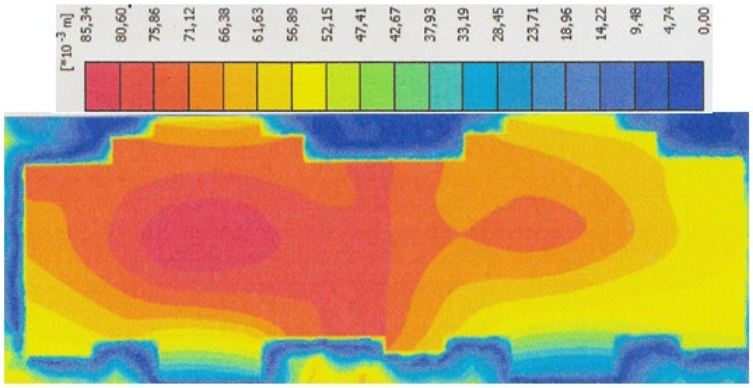



**Figure 1** – Isopoles of vertical displacements of the foundations determined by LIRA-SAPR (a) and PLAXIS 3D (b)

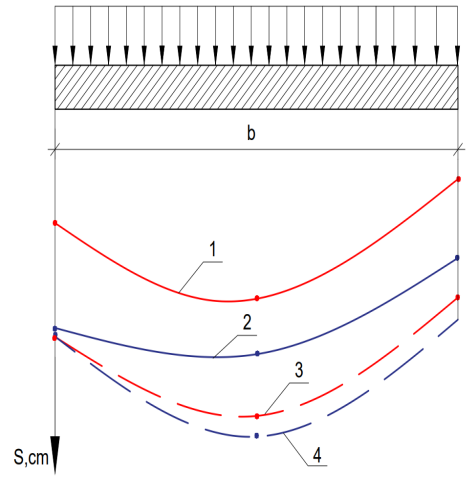



**Figure 2** – Character of slab foundations settlement development
1, 2 - foundation slab settlement at the end and in the middle (PC LIRA-SAPR); 3, 4 - the same, respectively, calculated using the PC PLAXIS 3D

The analysis of vertical displacements shows their significant difference in magnitude and trajectories of propagation both in plan and in cross-sections of the slab.

The settlement obtained with PLAXIS 3D at the same points is slightly greater than that calculated with LIRA-SAPR. The settlement at points along the perimeter of the foundation is almost always less than the settlement at points along the line passing through the centre of the slab along the long side. It is known that when a load is applied to a flexible slab, its centre gives a settlement *1.24...1.60* times greater than the edges [5]. This is explained by the lawful operation of the foundation and its non-uniform stiffness in the central and peripheral zones of the foundation [6]. Taking this into account, as well as the fact that a significant thickness of the foundation footing is prepared artificially, it is obvious that it is possible to prepare the footing in such a way that its stiffness is different within the foundation spot. The implementation of such a solution contributes to the reduction of settlement differences, i.e. their equalisation: an increase of settlement in the edge zones and its reduction in the centre. Thus, the task is to prepare an artificial foundation with different deformability characteristics. The performed calculations have shown that at a considerable thickness of the sand cushion *(2.0 m...7.0 m)*, from *18 %* to *54 %* of the total foundation settlement is formed at the expense of the artificial foundation. Therefore, cushion thickness and the degree of soil compaction [7], i.e. the coefficient $K_{com}$, will have a great influence on the relative settlement difference or on the slab deflection. Using the recommendations of [8] the slab foundation settlement under the centre and midpoints of the sides of a rectangular slab can be determined by the formula

$$S = \frac{bPk}{m_B E_m^{red}}, \quad (1)$$

where $P$ is the average pressure under the foundation footings;

$E_m^{red}$ – average reduced deformation modulus of the base;

$k = k_0$ – coefficient determined from the tables for the basement point under the foundation centre, depending on the ratio of the foundation sides $n=l/b$ and the ratio of the thickness of the removed layer to the foundation half-width $m^{l} = 2H / b$;

$k = k_1$ – same under the centre of the larger side of the foundation;

$k = k_2$ – same under the centre of the smaller side of the foundation;

$m_B$ – coefficient of working conditions of the base, taken for bases with average reduced deformation modulus $E_m^{red} \geq 10$ *MPa* equal to $m_B$ = *1,35* at *10,0 m*, $b \leq$ *15,0 m*.

The degree of variability of the base compressibility in plan is determined by the formula $$\alpha_E = \frac{E^{red}_{max}}{E^{red}_{min}}, \quad (2)$$

If $\alpha_E \leq 1.5$, the foundation is considered to be homogeneous in terms of compressibility. Calculations have shown that $\alpha_E$ determined for the ground conditions of Brest is *1.27*. Therefore, the foundation is homogeneous in terms of compressibility.

Let's denote the foundation settlement under its centre by $S_0$. Then $S_0$ will be equal to $$S_0 = \frac{bPk_0}{m_B E^{red}_m}, \quad (3)$$

The settlement of the foundation under the centre of the larger side of the foundation is equal to $$S_1 = \frac{bPk_1}{m_B E^{red}_m}, \quad (4)$$

Designing a slab with a width of *15.0 m* and taking into account the location of the internal longitudinal walls and the thickness of the slab, we assume the width of the central zone and the peripheral zones located on either side of its centre to be *5.0 m*. This division into sections is justified by the layout of the buildings. For the large-panel buildings designed in the Brest south-west microdistrict-1, the distance between the axes of the internal longitudinal walls is basically *2.1 m*. The next axis of the longitudinal walls is set at a distance of *2.1 m* to one side and *1.1 m* to the other. Then the total distance between the axes of the outermost longitudinal internal walls is *5.3 m*. In calculations, the distance between the longitudinal internal walls furthest from the centre is assumed to be *5.0 m* wide. Then the edge zones along the length of the slab will also be *5.0 m* wide. Taking into account that the compaction of the sand cushion is carried out until $E_0$ = *20,0 MPa*, let's assume that exactly this value of modulus should be provided under the central zone of the slab, width *5,0 m*. Then the edge zones should have a modulus of deformation less than $E_0$. The value of the deformation modulus in the edge zones is denoted by $E_1$. Then the ratio of the reduced average deformation modulus will be as follows $$\beta = \frac{E^{red}_1}{E^{red}_0}, \quad (5)$$

From here $E^{red}_1 = \beta \cdot E^{red}_0$.

Then the difference in settlement between the points in the middle of the slab and on its edge is equal to

$$S_0 - S_1 = \frac{bP}{m_B}\left(\frac{k_0 E^{red}_1 - k_1 E^{red}_0}{E^{red}_0 E^{red}_1}\right) = \frac{bP}{m_B E^{red}_0}\left(\frac{k_0\beta - k_1}{\beta}\right), \quad (6)$$

Obviously, the most acceptable slab conditions will be when the difference in settlement is zero.

Then $$\frac{bP}{m_B E^{red}_0}\left(\frac{k_0\beta - k_1}{\beta}\right) = 0. \quad (7)$$

This expression is zero if $\frac{k_0\beta - k_1}{\beta} = 0$.

From here $\beta = \frac{k_1}{k_0}$.

According to (5) – $\frac{E^{red}_1}{E^{red}_0} = \frac{k_1}{k_0}$.

Consequently, the deformation modulus of the soil in the edge zones of the slab in the middle of the long side is equal to $E^{red}_1 = \frac{k_1}{k_0} E^{red}_0$, (8)

Thus, by specifying the compaction factor of the sand and gravel mixture and the deformation modulus at a point in the centre of the slab, we obtain the required value of $E^{red}_1$ at the edge zone of the slab in the corresponding section.

Determining $k_0$ and $k_1$ according to tables [4] it is possible to determine $E^{red}_1$ for any initial conditions. For more convenient use in practical calculations we have plotted the graphs of change of $E^{red}_1 = f(k_1/k_0)$ (Figure 3). From the graphs we can see that $E^{red}_1$ depends on $E_0{}^{red}$ and does not depend on the aspect ratio. At values $E^{red}_0$ distinct from those shown in the graphs use interpolation.

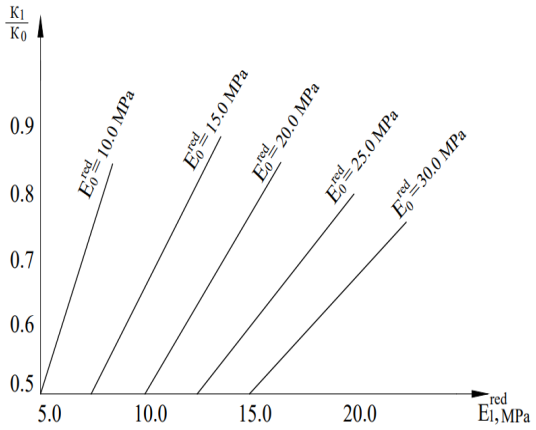



**Figure 3** – Variation of $E^{red}_1$ depending on the $\frac{k_1}{k_0}$

The values of $E^{red}_1$ and $E^{red}_0$ are taken at the points on the edge of the foundation slab and in its centre. Consequently, along the width of the edge zone ($b$ = *5.0 m*) the deformation modulus will vary from $E^{red}_1$ to $E^{red}_0$. This can be accounted by keeping in mind the technology of sand and gravel cushion preparation. If the width of the compacted zone for n passes of the roller is *1.7 m* taking into account overlapping of its traces. Then in the area from the edge of the slab to *1.7 m* the modulus of soil deformation should be $E^{red}_1$.

The next roller trace is also equal in width to *1.7 m*. Then the increase in deformation modulus at this section is $0.54(E^{red}_0 - E_1)$. The deformation modulus of the soil on the second trace of the roller excavation should be equal to $E^{red}_1$ = *15,4 MPa*. Similar calculations are performed for the third section. Modulus of ground deformation at the third track of the roller penetration is $0.9(E^{red}_0 - E_1)$. If the calculations are performed at $E^{red}_0$ = *20,0 MPa*, at the first section the deformation modulus $E^{red}_1$ = *10,0 MPa*; at the second section $E^{red}_1$ = *15,4 MPa*; at the third section – $E^{red}_1$ = *19,0 MPa* (Figure 4).

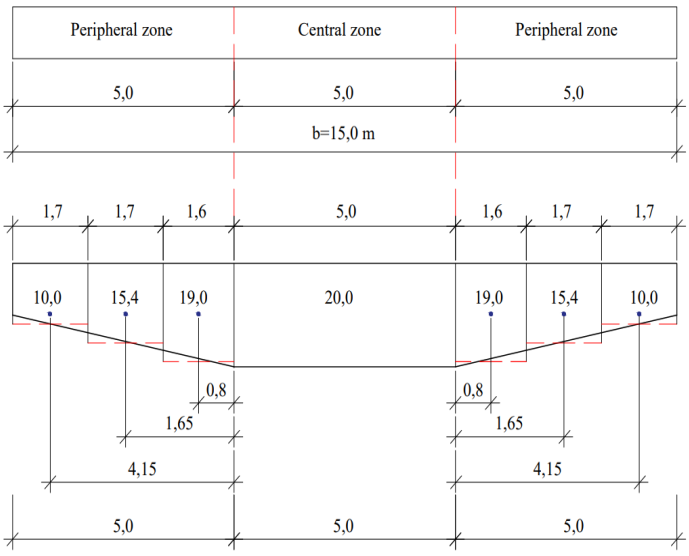



**Figure 4** – Scheme deformation modulus $E_1$ variation in the peripheral zones of a rectangular plate

Foundation slab settlement calculations performed in accordance with the values of $E_1$, which are recommended for edge zones, showed that the slab settlement at points in the middle of the long sides of the foundation is more uniform and varies from *4.82 cm* to *4.87 cm* for the left section. The settlement at the centre of the slab of the left section is *6.27 cm*. Their magnitude is very important and is limited by the current norms [9]. The relative difference in settlement is *0.0019...0.00187*. For the right section, where the load on the foundation is *22 %* less compared to the left section, the settlement of the extreme points varies from *3.79 cm* to *5.37 cm*. The settlement at the centre of the slab is *5.87 cm*. The relative difference in settlement is *0.0007* and *0.0021*. The settlement of the same foundations without considering the change in deformation modulus for the left section ranged from *3.1 cm* to *6.5 cm* and at the centre *8.1 cm*. The relative deflection is respectively *0.0071* and *0.0025*. For the right section, the settlement is more irregular at the extreme points. They vary from *2.3 cm* to *5.9 cm*. The draught at the centre is *6.8 cm*. The relative difference is *0.006* and *0.0012*. Thus, regulating the degree of compaction of the sand and gravel cushion over the width of the future foundation allows to obtain more uniform settlement and, most importantly, to reduce, and very significantly, the amount of deflections and the relative difference in settlement, which naturally affects the amount of internal forces in the foundation slab.

The design of a slab foundation base to exclude non-uniform settlement is a very rational preparation of an artificial base with appropriate parameters of its deformability, ensuring the presence of minimal non-uniform settlement or completely excluding it.

**Conclusion**

When designing slab foundations of considerable thickness on artificial foundations, their deformability should be regulated in order to minimise uneven settlement as much as possible.

The proposed method of artificial base construction makes it possible to significantly equalise the foundation slab settlements, reduce their relative difference by 5–8 times without changing the slab height, i.e. without changing its stiffness.

The construction of foundations with an adjustable deformation modulus is possible when using, as foundations, not only artificially laid embankments, but also in case of building foundations on naturally formed basis.

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UDC 692.21

# STUDY OF METHODS FOR PHYSICO-CHEMICAL TREATMENT OF GROUNDWATER FROM NITRATES

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**Abstract**

Contamination of groundwater by nitrogen compounds is an urgent problem. In Belarus for the water supply of cities, towns, industrial enterprises use groundwater. There is a brief description of the operating conditions of underground water and their quality. It describes the impact of nitrates on human health. The most intensive pollution by nitrates at a depth of 10–15 m in the country side and in home gardens. Also at depths of 40–50 m recorded nitrate concentrations, that exceed the maximum permissible level (45 mg/l for of nitrates content). The article studies methods for removal of ammonium nitrogen, nitrates and nitrites from natural waters, presents the results of experimental studies of water purification from nitrates by ion exchange method for drinking water supply purposes.

**Keywords:** groundwater, nitrates, watertreatment, drinkingwatersupply, ionexchange, anion exchangers.

## ИССЛЕДОВАНИЕ МЕТОДОВ ФИЗИКО-ХИМИЧЕСКОЙ ОЧИСТКИ ПОДЗЕМНЫХ ВОД ОТ НИТРАТОВ

**С. В. Андреюк, М. В. Зань**

**Реферат**

Загрязнение подземных вод соединениями азота является актуальной проблемой. В Беларуси для водоснабжения городов, поселков, промышленных предприятий используются подземные воды. Дана краткая характеристика условий эксплуатации подземных вод и их качества. Описано воздействие нитратов на здоровье человека. Наиболее интенсивное загрязнение нитратами присутствует на глубине 10–15 м в сельской местности и на приусадебных участках. Также на глубинах 40–50 м фиксируются концентрации нитратов, которые превышают уровень предельно допустимой (45 мг/л по содержанию нитратов). В статье изучены методы для удаления аммонийного азота, нитратов и нитритов из природных вод, представлены результаты экспериментальных исследований очистки подземных вод от нитратов методом ионного обмена в целях питьевого водоснабжения.

**Ключевые слова:** подземные воды, нитраты, водоподготовка, питьевое водоснабжение, ионообмен, аниониты.

### Introduction

Groundwater pollution with nitrogen compounds is the problem. In Belarus for the water supply of cities, towns, industrial enterprises use groundwater. Over the past few decades in the field of active agricultural production observed increase in groundwater salinity on the average from 190 (natural background) to 366 mg/l. The average mass concentration of nitrates of 140 mg/l [1], that exceed the allowable concentration of 3 times (45 mg/l) [2].

The presence in water mineral nitrogen (ammonia, nitrates, nitrites) leads to disease development hydrogen-nitrate methemoglobinaemia and different degrees of oxygen deficiency of the organism.

Nitrogen compounds get into groundwater from a variety of sources, natural or man-made. The main natural sources are: soil nitrogen, nitrogen-rich biological deposition and precipitation. The main sources of anthropogenic activities are nitrogen fertilizers, septic drainage water basins, livestock farms, places of business and discharge of industrial wastewater. This has led to a progressive deterioration of the groundwater. Concentrations of nitrates than the allowable concentration of 2–3 times, and sometimes reach 10–16 maximum permissible concentrations [3].

In 2015, the major pollution of ground and artesian waters of Belarus were ammonia nitrogen, nitrate and permanganate oxidation. The largest number of water samples with a high content of nitrate ions found in the basins of the Dnieper rivers (groundwater and artesian water), Western Bug and Pripyat (groundwater) [4].

Brest region has significant reserves of fresh water, and has a problem, as in many other regions of the country.

The most intensive pollution by nitrates at a depth of 10–15 m in the country side and in home gardens. Also at depths of 40–50 m recorded nitrate concentrations, that exceed the maximum permissible level (45 mg/l for of nitrates content).

The increase and accumulation of nitrogen compounds in natural waters of our country and beyond requires a removal of anthropogenic pressure, and improve the quality of drinking water through the use of innovative and cost effective water treatment methods [5].

### Analysis of the current state of water treatment technology from nitrogen compounds

Cleaning groundwater Methods of nitrogenous compounds are divided into physical, chemical and biological. As part of this classification, we analyzed the methods of physical and chemical water purification from nitrates, each of which has its own specific, advantages and disadvantages. Physico-chemical methods: chlorination, air venting, reverse osmosis, ion exchange, electrodialysis.

*Chlorination* allows mainly ammonium hydroxide to oxidize the nitrogen gas through the formation of chloramines. Big difference between the practical theoretical chlorine consumption due to the fact, that not only undergoes oxidation of ammonium hydroxide, but other substances contained in the water and are capable of oxidation. With this method of cleaning the treated water contains a sufficiently large amount of residual chlorine, for which you want to carry out dechlorination, the study showed the presence of the reaction products in the drinking water of toxic volatile halogenated organic compounds.

By means of *air stripping method* selection can be made from water dissolved volatile nitrogen compounds, such as ammonium hydroxide.

Upon contact of water with air dissolved volatile nitro-gen compounds pass into the gaseous form. Along with the benefits (direct transition of ammonium ion to gaseous ammonia), the method has disadvantages:

1) the process efficiency dependence on the temperature and the value of water pH, which should be high, as well as the air flow;

2) changes in the lime-carbon dioxide balance, because of which falls in the carbonate salts precipitate;

3) environmental pollution with nitrogenous compounds, they move from water to air.

*Reverse osmosis* is based on the use of special membranes of cellulose acetate and triacetate, aromatic polyamide and polyesteramide, having selective permeability. These materials are used in the form of modules, which create the maximum surface area per unit volume. The effect of nitrates removal is 85–95 % at 30 and a pressure of 60 bar. The method is characterized by high efficiency, compact installation, but it has the following disadvantages: a significant change in the source water quality, removal is not only harmful but also beneficial to health substances; the need for pretreatment of water in order to avoid contamination and fouling of membranes; the presence of concentrated waste, requiring disposal or recycling. The introduction of this method in practice is ham-pered by lack of selective membranes in the country.

Ion exchange method based on the use of ion exchange resins, which are obtained on the basis of styrene-divinylbenzene copolymer and have as trimethylammonium functional groups (type 1) or dimetilgidroksietilammony (type 2). When selecting the resins should be noted that one type of resin is chemically more stable, type 2 – is relatively more susceptible to degradation, primarily water, containing oxygen. However, type 2 resins have a higher capacity and the regeneration degree.

When using ion exchange solutions require disposal problem of spent regeneration solutions (brine of sodium chloride, hydrochloric acid, sodium hydroxide), and the search of materials with a high, in relation to the nitrogenous compounds, exchange capacity.

Electrodialysis can be used for the removal of nitrate and nitrite from the water potable purposes (effect of removing nitrate ions – up to 40–60 per cent). Implementation of the method on an industrial scale constrain the following disadvantages: the need for a thorough pre-treatment of water; insufficiently high selectivity membranes; presence of waste in the form of concentrated solutions that require additional costs for their elimination. This method is tested only in semi-production conditions.

Known biological methods of removing nitrogen compounds. Used biological processes of nitrification-denitrification. These processes are managed in special facilities, which develop and live microorganisms. Biological processes, which convert nitrogen compounds to nitrogen gas, occur in the presence of a substance capable of oxidation. Such material may be a gas (e.g., hydrogen), solid (sulfur) or liquid (carbon-containing organic compound).

Microbiological methods of nitrification and denitrification are designed for high productivity treatment plants, require specially trained technical staff and continuous monitoring of the process.

Study of the chemical properties of mineral nitrogen compounds, the theoretical analysis of pos-sible methods of removing them from the natural water, quality monitoring the groundwater in natural conditions showed, that under water autonomous objects preferable physicochemical methods, including ion-exchange and sorption [6].

**Investigation of clean groundwater from of nitrates by ion exchange**

Ion exchange method – one of the most common methods of water purification – traditionally used in those cases where the solution contains a small concentration of pollutants, or as a final purification step. For experimental studies of ion exchange were set tasks:

– determining the resource potential of the ion exchange unit;

– study changes in the salt composition of the treated water in the purification of nitrates in highly basic anion exchanger;

– study and optimization of the treatment process in various types of ion exchange resins;

– the choice of the mathematical model of the dynamics of ion exchange for water purification from of nitrates;

– study and optimization of the process of regeneration of ion exchange resins in the purification process involved.

For the study was used a mathematical method for the optimum planning.

As the pollution of underground water, in the first series of experiments used tap water with the addition of nitrates of 20 mg/l for nitrate nitrogen, which corresponds to a concentration twice the maximum allowed for drinking water.

The aim of research was: to receive an experimental statistical model of the ion exchange purification of groundwater from nitrates to predict the efficiency of the installation in any given mode of conducting the ion exchange purification process.

**Results and discussion**

The experimental results were processed on a computer using the program «STATGRAPHIGS-statistical Graphics System». Obtained experimentally-statistical process based on ion-exchange treatment the following variables: 1) loading height and the diameter of the filter; 2) temperatures of water, and 3) filtration rate [7, 8].

In a second series of experiments we used real ground water containing nitrate ions at concentrations up to 100 mg/l. With optimal parameters of the ion exchange process, a high effect of remov-ing of nitrates was confirmed, which was obtained in the first series experimental investigations at model water.

A stronger influence of values of filtration rate of treated water V, m/h, and the factor H/d on the cleaning effect was established (Figures 1, 2). When changing the velocity V, m/h, in the range V = 10 – 32 m/h and fixed values of the factor H/d, respectively, a decrease in the cleaning effect E = f(V) by 20–30 % is observed (Figure 1). At a fixed temperature parameter t, °C, the decrease of the effect (E = f(V) < 50 %) is also observed when the velocity V, m/h, increases, when the factor H/d has a value less than unity. This fact can be explained by the insufficient height of the fixed ionite layer compared to the filtration rate of the solution, when the exchange occurs in nonequilibrium conditions – the degree of ionite utilization decreases, the purification effect decreases.

As a result of increasing the value of the factor H/d, the degree of ionite utilization increases (Figures 2) and the effect of nitrate removal increases: in the range of values H/d = 0,1 – 5, a change in the effect E = f(H/d) up to 19 % is observed. At that, further increase of H/d factor in the interval H/d = 5,5 – 12 leads to decrease of E = f(H/d) up to 30 %, which is determined by layer resistance, tendency of narrow columns to wall effects and channel formation. For efficient use of ionite and ob-taining high purification effect, the velocity parameter V can be varied during operation of the ion exchange column, and the value of the factor H/d can be set initially.

In the region of optimal values, the partial solutions of the obtained experimental-statistical dependences allow estimating the change in the effect of water purification from nitrates taking into account the variation of the factors of ion-exchange column operation by linear regression equations (95 % significance):

– for the factor of treated water temperature t, °C, in the range t = 5–18°C,

$$E = 1{,}03 \cdot t + 78{,}46,\ \%; \quad (1)$$

– for the factor of filtration rate V, m/h, in the interval V = 10–32 m/h,

$$E = -0{,}69 \cdot V + 99{,}28,\ \%; \quad (2)$$

– for the H/d factor, in the interval H/d = 0,1 − 5,

$$E = 3{,}71 \cdot (H/d) + 77{,}77,\ \%. \quad (3)$$


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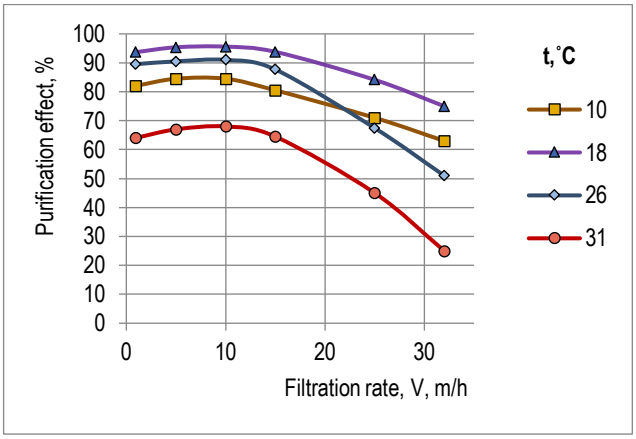


**Figure 1** – Dependence of nitrate removal effect on filtration rate

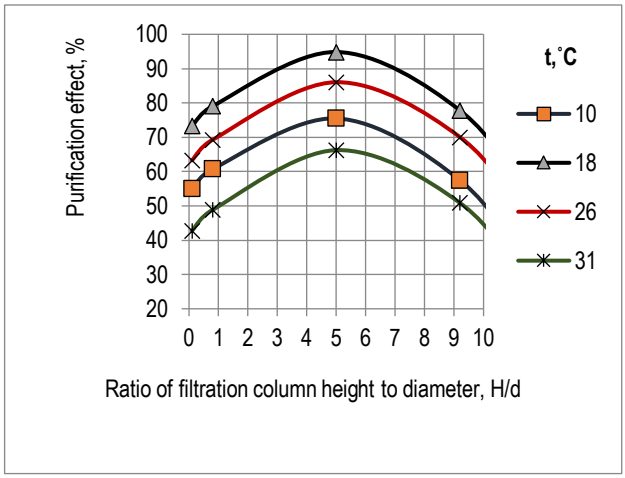


**Figure 2** – Dependence of nitrate removal effect on the H/d factor at a fixed rate value

Sulfate ions compete most with nitrate ions in the ion exchange process (Figure 3). In this case, groundwater ions of the studied region, absorbed by the strong-base anionite, are arranged in the order of affinity as follows:

$NO_3^-$ > $SO_4^{2-}$ > $HCO_3^-$ > $Cl^-$.

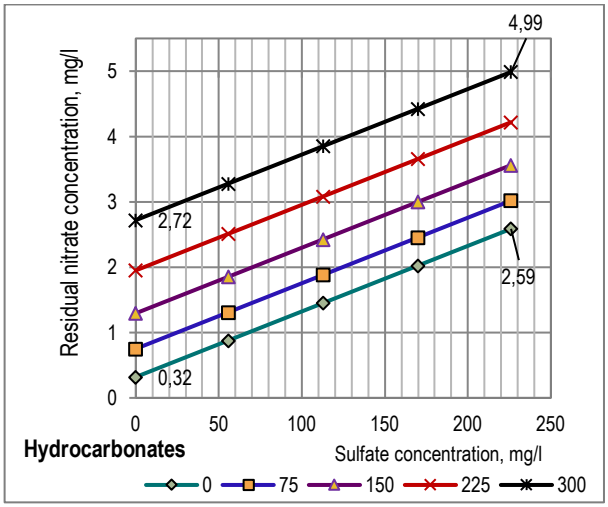


**Figure 3** – Influence of concentration of sulfates on nitrate removal from aqueous solutions of different anionic composition

In general, the change of anionic composition of water in the process of nitrate removal by ion exchange does not deteriorate its natural properties and corresponds to the quality and physiological fullness of drinking water.

**Conclusion**

Explore methods to remove ammonia nitrogen, nitrate and nitrite in natural water. The results of experimental studies of water purification from of nitrates by ion exchange for the purpose of drinking water. These equations allow to predict the efficiency of the ion exchange unit in any given mode of conducting the cleaning process.

The obtained experimental-statistical dependences of the process of purification of groundwater from nitrates by ion exchange method, describing the influence on the effect of nitrate removal filtration rate, temperature of treated water, the value of the ratio of filtration column loading height to its diameter, allowed us to determine the optimal values of these factors V = 13 m/h, t = 18 °C, H/d = 5, which provide the maximum purification effect, taking into account the anionic composition of water. It was found that the greatest influence on the process of ion-exchange purification of groundwater from nitrates is the concentration of sulfate ions in water.

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# ANISOTROPY OF STRENGTH AND ELASTIC CHARACTERISTICS DURING COMPRESSION OF MASONRY OF HISTORICAL BUILDINGS

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**Abstract**

The article presents analytical dependences for calculating the compressive strength and elastic modulus of masonry made of ceramic solid bricks under axial uniaxial compression at arbitrary an-gles to horizontal mortar joints of masonry. Satisfactory agreement of experimental and theoretical values of masonry strength under compression at different angles to horizontal mortar joints is shown. A method for determining the basic variables included in the analytical equations of the computational model of the compressive strength anisotropy of masonry of existing structures, based on tests of specimens-prisms cut from masonry, has been developed and experimentally sub-stantiated. Comparative tests of the strength and elastic characteristics of masonry were carried out using specimens-prisms and standard specimens. It was found that the average values of the initial shear strength of masonry obtained on the specimens-prisms and standard specimens differed by no more than 8 %, and the compressive strength perpendicular to the plane of horizontal joints and the elastic modulus of masonry – by no more than 5 % and 1,2 %, respectively, which indicates the ap-plicability of the proposed method for assessing the strength and elastic characteristics of masonry of existing structures.

**Keywords:** masonry, ceramic brick, anisotropy, modulus of elasticity, compressive strength.

## АНИЗОТРОПИЯ ПРОЧНОСТНЫХ И УПРУГИХ ХАРАКТЕРИСТИК ПРИ СЖАТИИ КАМЕННОЙ КЛАДКИ ИСТОРИЧЕСКИХ ЗДАНИЙ

**А. В. Галалюк, В. Н. Деркач**

**Реферат**

В статье приведены аналитические зависимости для расчета прочности на сжатие и модуля упругости каменной кладки из керамического полнотелого кирпича при осевом одноосном сжатии под произвольными углами к горизонтальным растворным швам кладки. Показано удовлетворительное согласование экспериментальных и теоретических значений прочности кладки при сжатии под различными углами к горизонтальным растворным швам. Разработан и экспериментально обоснован метод определения базисных переменных, входящих в аналитические зависимости расчетной модели анизотропии прочности при сжатии каменной кладки существующих конструкций, основанный на испытаниях, вырезанных из тела образцов-призм. Выполнены сопоставительные испытания прочностных и упругих характеристик каменной кладки по образцам-призмам и стандартным образцам. Установлено, что средние значения начальной прочности на сдвиг каменной кладки, установленные на образцах-призмах и стандартных образцах, отличались не более чем на 8 %, а прочности на сжатие перпендикулярно плоскости горизонтальных швов и модуля упругости кладки – не более чем на 5 % и 1,2 % соответственно, что свидетельствует о применимости предлагаемого метода для оценки прочностных и упругих характеристик каменной кладки существующих конструкций.

**Ключевые слова:** кладка, керамический кирпич, анизотропия, модуль упругости, прочность на сжатие.

### Introduction

Most typical masonry structures work on compression perpendicular to the plane of horizontal joints of masonry. At the same time, there are a number of structures whose compression resistance can be determined by the compressive strength of masonry at other arbitrary angles to the plane of the support joints. Such structures primarily include vaults made of ceramic bricks of various kinds, arched or pointed arched lintels, which are widely distributed in masonry buildings and structures of cultural and historical value. Inspection of old buildings shows that most of these structures do not fit into the theoretical design schemes given in the methodological and regulatory documents due to the degradation of masonry, the loss of part of vertical supports, spring-loaded arches, ties or other elements. Under the action of loads or forced deformation, for example, with nonuniform foundation settlement, the geometric shapes of vaults and arches determine the direction of the force flows arising in them at different angles to the mortar joints of the masonry. As practice shows, the angle of inclination of the compressive force to the mortar joints of masonry in these structures depends on their shape, the ratio of the span to the rising height and is within 10° – 40°. A calculated assessment of the reliability of existing hold-down masonry structures is usually performed by checking the limit states of the bearing capacity by the method of partial coefficients. At the same time, the effects of impacts (the values of the main stresses and their trajectories) are established on the basis of calculations of structures by the finite element method using modern computing systems. Masonry in the calculation models is considered as a homogeneous, isotropic material, and the assessment of the resistance of structures to compression is based on the particular characteristics of the strength of masonry [1–3]. However, the solution of this problem is complicated by the absence in the current norms of the numerical values of the compressive strength of masonry at arbitrary angles to the plane of the supporting mortar joints, as well as full-fledged data on the anisotropy of its elastic characteristics.

### Calculation model of the strength of masonry under compression at arbitrary angles to the supporting mortar joints

In order to experimental evaluation of the anisotropy of the strength and elastic characteristics of masonry, tests were performed on five series of specimens of masonry under the action of compressive force at angles to the plane of the support joints of equal 0°, 22,5°, 45°, 67,5°, 90° (figure 1) [7].


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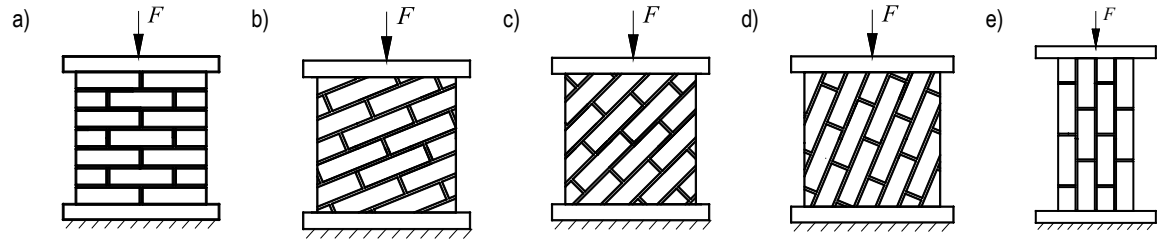



a) – series C-1 ($\theta$ = 0°); b) – series C-2 ($\theta$ = 22,5°); c) – series C-3 ($\theta$ = 45°); d) – series C-4 ($\theta$ = 67,5°); e) – series C-5 ($\theta$ = 90°)

**Figure 1** – Schemes of specimens of masonry

The tasks of the tests included:

– identification of the pattern of cracking and fracture of experimental specimens of masonry;

– determination of compressive strength, as well as elastic modulus and Poisson's ratio of masonry, depending on the orientation of the direction of the compressive force to the supporting mortar joints.

Experimental studies have shown that at angles $\theta$ from 45° to 67,5° the cause of the fracture of the masonry is its shear in the plane of the supporting mortar joints. When the angle is

67,5° < $\theta$ ≤ 90°, the nature of the masonry fracture is determined by the compressive strength of the brick in the direction of the butt surface, and at 0° ≤ $\theta$ < 22,5° – the compressive strength of the brick in the direction of the support surface.

If the angle of inclination of the compressive force to the horizontal mortar joints differs from 0° and 90°, then tangential ($\tau$) and normal compressive stresses ($\sigma$) arise in the mortar joints, the ratio of which varies depending on the angle $\theta$ (figure 2).

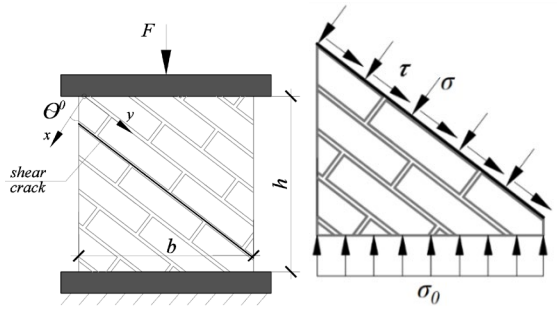



**Figure 2** – Tangential and normal stresses in the supporting mortar joints of masonry

In accordance with figure 2, the values of compressive stresses in masonry at which shear cracks arise in the supporting mortar joints can be determined by the equation (1)

$$\sigma_{0,crc} = \frac{f_{v0}}{\cos\theta \cdot (\sin\theta - \cos\theta \cdot tg\varphi)}. \quad (1)$$

The value $\sigma_{0,crc}$, set by equation (1), should not exceed the value set by equation (2)

$$\sigma_{0,crc} = \frac{0,065 f_b}{\cos\theta \cdot \sin\theta}. \quad (2)$$

Experimental and theoretical studies show that during compression, the formation of shear cracks in mortar joints did not lead to immediate fracture of the masonry. At the same time, the ratio of the compressive strength of masonry $f_\theta$ to the values of compressive stresses $\sigma_{0,crc}$ depended on the angle of inclination of the trajectory of the compressive stresses to the plane of the supporting mortar joints (figure 3).

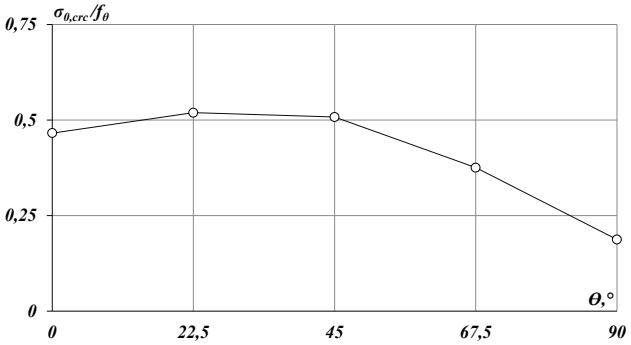



**Figure 3** – Function « $\sigma_{0,crc} / f_\theta - \theta$ »

The compressive strength of masonry at angles $\theta$ in the range of 37,5° – 67,5° can be obtained by multiplying the values of compressive stresses at which shear cracks arise in the supporting mortar joints of masonry $\sigma_{0,crc}$, by a dimensionless coefficient $k$, the value of which should be taken according to the empirical equation (3)

$$k = 0,252 \cdot \theta - 0,0024 \cdot \theta^2 - 4,097. \quad (3)$$

where $\theta$ – the angle of inclination of the supporting mortar joints in degrees.

Taking into account the correction factor $k$, the compressive strength of masonry at angles $\theta$ in the range of 37,5° – 67,5° is determined by the equation (4)

$$f_\theta = k \cdot \frac{f_{v0}}{\cos\theta \cdot (\sin\theta - \cos\theta \cdot tg\varphi)}. \quad (4)$$

The value $f_\theta$, set by equation (4), must not exceed the values set by equation (5)

$$f_\theta = k \cdot \frac{0,065 f_b}{\cos\theta \cdot \sin\theta}. \quad (5)$$

If the values of the compressive strength of masonry $f_\theta$ at $\theta$ = 90° and 0° are known, then the compressive strength $f_\theta$ at angles 0° < $\theta$ < 37,5° and 67,5° < $\theta$ < 90° is determined by linear interpolation.

Figure 4 shows the results of calculating the compressive strength values of masonry $f_{\theta,exp}$ depending on the angle of inclination of the supporting mortar joints $\theta$ according to the proposed calculation model $f_{\theta,calc}$, which are in satisfactory agreement with the experimental data $f_{\theta,exp}$.

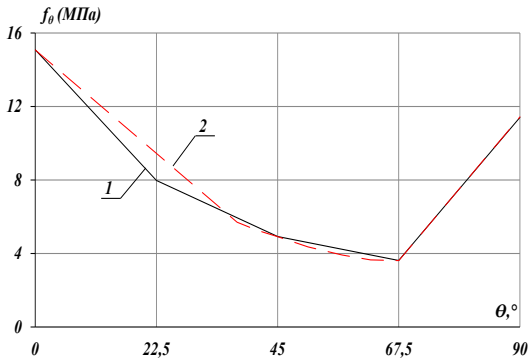
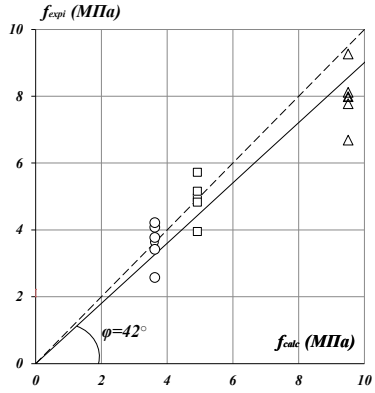



**Figure 4** – Function of the strength of masonry $f_\theta$ on the angle of inclination of horizontal mortar joints $\theta$




«△» – values for the angle $\theta$ = 22,5°; «□» – values for the angle $\theta$ = 45,0°; «○» – values for the angle $\theta$ = 67,5°

**Figure 5** – Comparison of calculated and experimental values of compressive strength at the angle of inclination of the support joints $\theta$

As an illustration of the reliability of the proposed computational model, figure 5 shows a comparison of the results of experimental $f_{\theta,exp}$ and theoretical $f_{\theta,calc}$ values of the compressive strength of masonry for all considered experimental specimens, and also in accordance with [1] the value of the coefficient of variation of the error vector is determined.

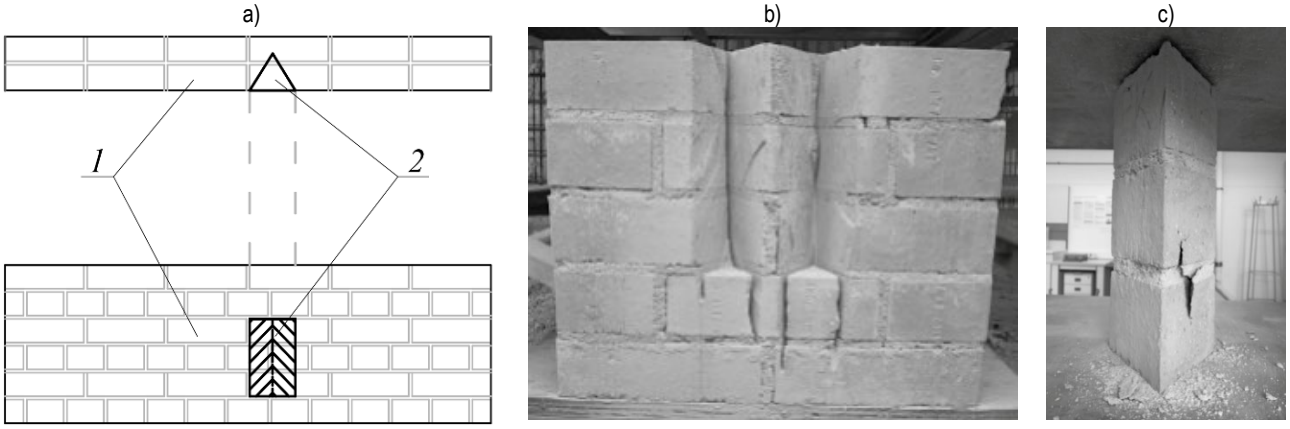
It follows from Figure 5 that the pairs of corresponding theoretical $f_{calc}$ and experimental $f_{expi}$ values of the compressive strength of masonry are located relative to a straight line, the angle of inclination of which to the X-axis was 42°. In this case, the value of the coefficient of variation of the error vector $V_\delta$ = 16,6 %. The results obtained indicate the reliability of the developed computational model.

**Determination of strength and elastic characteristics of masonry of existing structures based on tests of specimens-prisms**

For the analytical calculation of the compressive strength of masonry at arbitrary angles to the plane of the supporting mortar joints in accordance with the proposed calculation model, according to the results of the inspection of masonry structures, it is necessary to obtain the values of the following basic variables:

- value of the initial strength of masonry for shear $f_{v0}$;
- coefficient of internal friction $tg\varphi$;
- normalised compressive strength of bricks $f_b$;
- compressive strength of masonry $f_\theta$ at $\theta$ = 0° and $\theta$ = 90°.

The degree of anisotropy of the compressive strength $f_\theta$ and the elastic characteristics of the masonry of existing structures can be estimated by the results of direct tests with a compressive load of specimens-prisms cut from the masonry. Two vertical incisions are made in the wall at an angle of 60° to its surface, which intersect in the masonry. This creates a prism with a base in the form of an equilateral triangle (figure 6).




«1» – masonry; «2» – test specimen

a) – scheme of specimens selection; b) – masonry after specimen-prisms selection; c) – compression test of the specimen

**Figure 6** – Masonry specimen in the form of a triangular prism [8]

After removing the mortar from the horizontal joints in the upper and lower bases of the prism, the specimen is easily removed from the masonry. The advantage of the proposed method is also that the masonry structure has minor damage during the extraction of specimens, which is very important for objects of historical and cultural value. This method is feasible for wall masonry structures, from the body of which it is possible to cut specimens-prisms at an angle to the direction of horizontal mortar joints other than 90°. If the cutting of specimens-prisms from the masonry is possible only at an angle of 90° to the plane of the supporting mortar joints, then in this case the compressive strength and elastic modulus of masonry are determined on the basis of tests of prisms with a compressive load perpendicular to the plane of horizontal mortar joints, and the initial shear strength of masonry $f_{v0}$ – by tests for prism shear (figure 7).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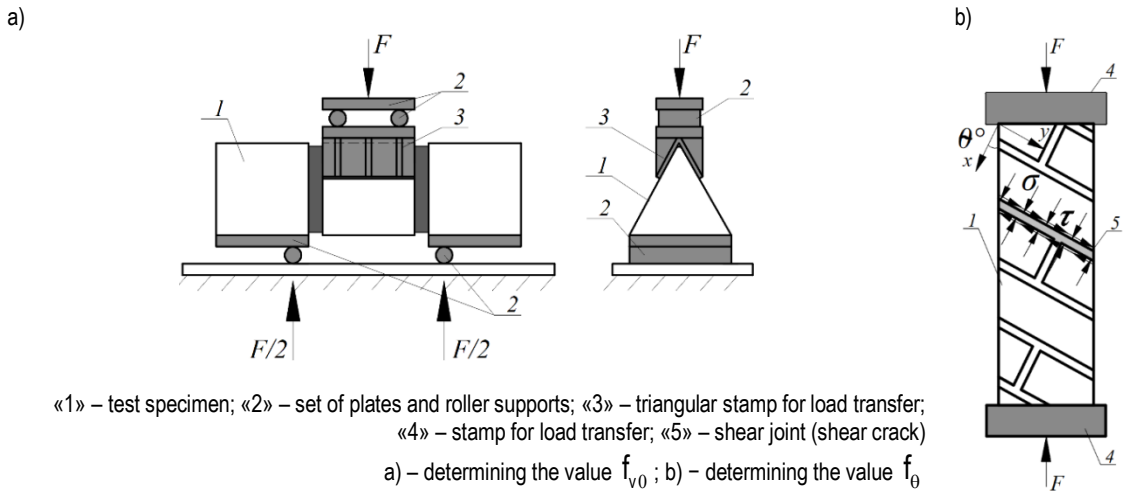


«1» – test specimen; «2» – set of plates and roller supports; «3» – triangular stamp for load transfer; «4» – stamp for load transfer; «5» – shear joint (shear crack)

a) – determining the value $f_{v0}$ ; b) – determining the value $f_\theta$

**Figure 7** – Schemes for testing specimens-prisms

In this case, the calculation of the anisotropy of the compressive strength of masonry is carried out in accordance with the proposed calculation model. The modulus of elasticity of masonry at angles to the supporting mortar joints $E_\theta$ is assumed to be equal to the product of the compressive strength $f_\theta$ by the value of the elastic characteristic $K_E$, the value of which is established according to experimental studies (figure 8).

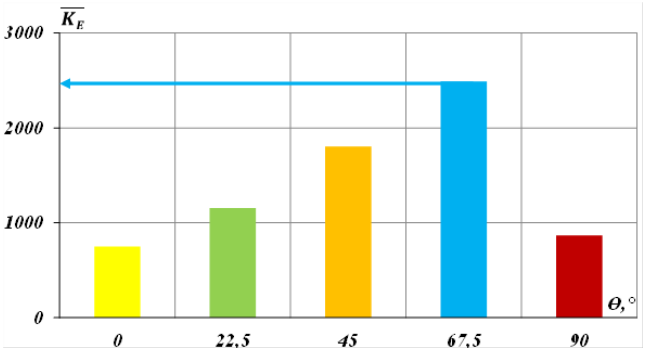


**Figure 8** – Average values of the elastic characteristic $\overline{K}_E$ depending on the angle $\theta$

Experimental studies have shown satisfactory agreement of the results of determining the compressive strength and elastic modulus of masonry specimens-prisms and standard specimens under the action of compressive force perpendicular to the plane of horizontal mortar joints. The difference in the average values of the compressive strength of masonry specimens-prisms and standard specimens did not exceed 5 %, and the elastic modulus – 1,2 %. The nature of the fracture of standard specimens and specimens-prisms at the angles of inclination of the direction of the compressive force to horizontal joints $0° < \theta < 90°$ was the same. At the same time, the difference in the values of the compressive strength of the masonry, established by the two methods, was in the range of 30 % – 40 %, which indicates a more significant effect of tangential stresses on the compressive strength of the masonry standard specimens, compared with the specimens-prisms. The average values of the initial shear strength of masonry obtained on the specimens-prisms and standard specimens differ by 8 %, which indicates the applicability of the proposed method for assessing the shear strength of masonry of existing structures.

**Conclusion**

1. A computational model of the strength of masonry made of bricks under compression at arbitrary angles to horizontal mortar joints of masonry is proposed and experimentally substantiated, taking into account the initial shear strength of masonry, the coefficient of internal friction, the normalised compressive strength of bricks, the compressive strength of masonry perpendicular to the plane of horizontal joints.
2. A method for determining the anisotropy of compressive strength and elastic characteristics of masonry of existing structures has been developed and experimentally confirmed on the basis of tests of masonry specimens in the form of triangular prisms.

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# LIGHTWEIGHT CONCRETE BASED ON BIO-AGGREGATES AND GYPSUM BINDER FOR CONSTRUCTION PRODUCTS

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**Abstract**
Selecting the optimal composition of gypsum concrete with a two-component organic aggregate and glass fiber is a complex task, which in this work was solved using desing of experiment. Adequate mathematical models of tensile strength in bending, compressive strength and water absorption are determined. Based on the mathematical planning of the experiment, the composition of gypsum concrete with the maximum value of tensile strength in bending, which is used in the manufacture of gypsum concrete slabs, was determined. It is shown that gypsum concrete slabs made using casting technology from the developed gypsum concrete composition have a thermal conductivity coefficient K = 0,256 W/(m·K) and provide a noise level reduction to 29,55 dB in the frequency range from 100 to 300 Hz.

**Keywords:** gypsum binder, organic fillers, sawdust, flax fire, glass fiber, gypsum concrete, physical and mechanical properties, optimization of gypsum concrete composition, mathematical planning, gypsum concrete slabs.

## ЛЕГКИЕ БЕТОНЫ НА ОСНОВЕ БИОЗАПОЛНИТЕЛЕЙ И ГИПСОВОГО ВЯЖУЩЕГО ДЛЯ ИЗДЕЛИЙ СТРОИТЕЛЬНОГО НАЗНАЧЕНИЯ

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**Реферат**
Подбор оптимального состава гипсобетона с двухкомпонентным органическим заполнителем и стеклянной фиброй является сложной задачей, которая в данной работе решена с помощью метода математического планирования эксперимента. Определены адекватные математические модели прочности на растяжение при изгибе, прочности на сжатие и водопоглощения. На основе математического планирования эксперимента определен состав гипсобетона с максимальным значением предела прочности на растяжение при изгибе, который использован для изготовления гипсобетонных плит. Показано, что гипсобетонные плиты, изготовленные по литьевой технологии из разработанного состава гипсобетона, имеют коэффициент теплопроводности K = 0,256 Вт/(м·K) и обеспечивают снижение уровня шума до 29,55 Дб в диапазоне частот от 100 до 300 Гц.

**Ключевые слова:** гипсовое вяжущее, органические заполнители, древесные опилки, костра льна, стеклянная фибра, гипсобетон, физико-механические свойства, оптимизация состава гипсобетона, математическое планирование, гипсобетонные плиты.

### Introduction

The development and implementation of environmentally friendly materials into construction practice is one of the priorities of modern construction science. So-called “green” materials can reduce the negative impact on the environment during the construction and operation of buildings, on the one hand, and solve the problem of providing the population with affordable, environmentally friendly housing, on the other hand. In this regard, research aimed at expanding the scope of application of lightweight concrete based on gypsum binder and environmentally friendly organic aggregates is relevant for the development of “green” construction.

Organic aggregate are used for the production of heat-insulating, as well as heat-insulating structural and structural materials and products: wood concrete, cement fiberboard, xylolite, reed concrete, peat boards, heat-insulating boards made from flax, wood fiber and particle boards, etc. [1]. Research on the development of compositions of cement concrete with organic aggregate of various plant species is widely presented in scientific publications. The analysis shows that wood as an organic aggregate is used in the form of crushed wood, machine shavings, sawdust, and wood fiber [2–5]. Flax is used in the form of flax shives and tow [6, 7]. Stems, fibers, husks, cakes of cereal crops, cotton, hemp, reeds, sunflowers, and rapeseed are used as aggregates [8–12]. In terms of the number of publications, the most widely presented in research is the use of organic aggregates based on wood, flax and cereals in concrete. Some scientific studies show the possibility of using beet pulp [13], cactus fibers [14], coconut shells [15], horsetail fibers [16], eucalyptus fibers [17].

The purpose of this research is to develop the composition of a raw material mixture for light-weight concrete based on environmentally friendly and safe materials, such as gypsum, sawdust, flax shives and glass fiber, for the production of gypsum concrete slabs with high thermal and acoustic characteristics. The research was carried out as part of the research work “Lightweight concrete based on bioaggregate and complex gypsum binder for wall structures” (number of state registration 20230695 dated 16.05.2023, grant from the Ministry of Education of the Republic of Belarus).

### Raw materials and research methods

In order to carry out experimental research, the building gypsum «Tayfun Master № 35» grade G–5 III A by GOST 125 was used. The setting time of gypsum is determined by GOST 23789: initial setting time is 9 minutes and 30 seconds, final setting time is 15 minutes. The normal density coefficient is 0.6. The mixing water for binder and gypsum concrete met the requirements of GOST 23732. For fiber reinforced lightweight concrete glass fiber 12 mm long in accordance with TS BY 691581903.001-2018 was used. Sawdust and flax shives were used as organic aggregate. Sawdust is a waste of forestry production "Ostrovetsky Experimental Forestry Enterprise". For experimental studies, sawdust with a particle size of up to 5 mm was used. The bulk density of sawdust was 0,258 kg/m$^3$, humidity 4 %. Flax shives with particle sizes up to 20 mm in length was used. The bulk density of flax shives was 0,154 kg/m$^3$, moisture was 0.5 %.


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The studies using the methods and tests set out in national standards were carried out. Beam samples 40 × 40 × 160 mm in size were made with different contents of organic aggregate and tested for tensile strength in bending, compressive strength, water absorption, water resistance according to GOST 23789, porosity – according to GOST 12730.4, density – according to GOST 12730.1.

Samples-cubes with an edge of 70 mm to determine the physical and mechanical characteristics of optimized composition gypsum concrete were made. The compressive strength of gypsum concrete was determined on a hydraulic press PGM-1000MG4 A according to GOST 10180, water absorption – according to GOST 12730.3. The samples at a temperature of 50 ± 5 °C to constant weight in a SNOL60/300 LFN drying cabinet were dried. The thermal conductivity coefficient was measured using an ITP-MG4 device on slab samples measuring 250 × 250 × 30 mm according to STB 1618. The sound insulation properties of gypsum concrete were studied using a training acoustic chamber according to STB EN ISO 10140-414. Mathematical processing of the research results was carried out in the computer program "PlanExp B-D13", developed in the Microsoft Visual Basic 6.0 programming environment.

**Optimization of organic aggregate compositions using desing of experiment**

When creating lightweight concrete, considerable attention is paid to selecting the composition of the initial mixture. The quality of the resulting material depends on the quality of the raw materials and the correct composition of the mixture. Optimization of the composition of organic aggregates for gypsum concrete was carried out using desing of experiment and processing of factorial experiment data using the computer program "PlanExp B-D13". The content of the following components was considered as factors influencing the physical and mechanical properties of gypsum concrete: glass fiber (X1), sawdust (X2), flax shives (X3). The water-gypsum ratio remained constant in all compositions and was equal to W/G = 0.6.

To carry out the experiment, sample beams 40 × 40 × 160 mm were made, which were tested 2 hours after mixing with water, 7 days and after drying the samples to constant weight at a temperature of 50 ± 5°C. The following physical and mechanical properties of gypsum concrete with organic aggregates were determined as output parameters: tensile strength in bending (Rben), compressive strength (Rcs), water absorption ($W_m$). The levels and intervals of variation of factors are given in Table 1. The experimental plan and the obtained results are shown in the Table 2.

**Table 1** – Levels and intervals of factor variation

| Factors | | Variation Levels | | | Variation Interval |
|---|---|---|---|---|---|
| Natural Value, % by weight of gypsum binder | Code | –1 | 0 | +1 | |
| Glass fiber | X1 | 0,2 | 0,4 | 0,6 | 0,2 |
| Wood sawdust | X2 | 4 | 6 | 8 | 2 |
| Flax shives | X3 | 2 | 4 | 6 | 2 |

**Table 2** – Plan of experiment and Experimental results

| № | Plan of Experiment | | | | | | Rben, MPa, age | | | Rcs, MPa, age | | | $W_m$ % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Coded Factors Values | | | Natural Factors Values | | | 2 hours | 7 days | dry concrete | 2 hours | 7 days | dry concrete | |
| | X1 | X2 | X3 | X1 | X2 | X3 | | | | | | | |
| 1 | –1 | –1 | -1 | 0,2 | 4 | 2 | 2,16 | 2,91 | 3,04 | 2,75 | 3,21 | 5,91 | 26,0 |
| 2 | +1 | –1 | -1 | 0,6 | 4 | 2 | 1,73 | 2,48 | 3,26 | 2,60 | 2,82 | 5,74 | 26,2 |
| 3 | –1 | +1 | -1 | 0,2 | 8 | 2 | 1,95 | 2,70 | 3,13 | 2,50 | 2,69 | 5,73 | 27,1 |
| 4 | –1 | –1 | +1 | 0,2 | 4 | 6 | 2,01 | 2,76 | 3,13 | 2,56 | 2,52 | 5,06 | 26,5 |
| 5 | –1 | 0,19 | 0,19 | 0,2 | 6,38 | 4,38 | 2,01 | 2,76 | 3,24 | 2,66 | 2,59 | 5,45 | 26,1 |
| 6 | 0,19 | –1 | 0,19 | 0,438 | 4 | 4,38 | 1,92 | 2,67 | 3,56 | 2,77 | 2,83 | 5,08 | 26,7 |
| 7 | 0,19 | 0,19 | -1 | 0,438 | 6,38 | 2 | 1,94 | 2,69 | 3,53 | 2,75 | 3,07 | 6,31 | 36,1 |
| 8 | –0,29 | +1 | +1 | 0,342 | 8 | 6 | 1,78 | 2,53 | 2,72 | 2,43 | 2,63 | 5,16 | 27,9 |
| 9 | +1 | –0,29 | +1 | 0,6 | 5,42 | 6 | 1,54 | 2,29 | 2,39 | 2,60 | 2,40 | 5,27 | 28,3 |
| 10 | +1 | +1 | –0,29 | 0,6 | 8 | 3,42 | 1,94 | 2,69 | 3,01 | 2,49 | 2,61 | 5,28 | 27,1 |

As a result of statistical processing of experimental data, assessment of the significance of the coefficients of mathematical models using the Student t-test and the adequacy of mathematical models using the Fisher criterion, the corresponding regression equations in coded form were obtained (1) – (7). Regression equations show the influence of two-component organic aggregate and glass fiber on the physical and mechanical properties of gypsum concrete:

Tensile strength in bending at the age 2 hours:

$$Rben_{2\ hour} = 1{,}948 - 0{,}135 \cdot x_1 - 0{,}107 \cdot x_3 - 0{,}106 \cdot x_3^2 + 0{,}096 \cdot x_1 \cdot x_2 - 0{,}026 \cdot x_1 \cdot x_3 . \quad (1)$$

Tensile strength in bending at the age 7 days:

$$Rben_{7\ day} = 2{,}722 - 0{,}132 \cdot x_1 - 0{,}109 \cdot x_3 - 0{,}119 \cdot x_3^2 + 0{,}112 \cdot x_1 \cdot x_2 - 0{,}035 \cdot x_1 \cdot x_3 . \quad (2)$$

Tensile strength in bending dry concrete:

$$Rben_{dry} = 3{,}547 - 0{,}106 \cdot x_1 - 0{,}125 \cdot x_2 - 0{,}277 \cdot x_3 - 0{,}369 \cdot x_1^2 - 0{,}339 \cdot x_3^2 - 0{,}156 \cdot x_1 \cdot x_3 - 0{,}168 \cdot x_2 \cdot x_3 . \quad (3)$$

Compressive strength at the age 2 hours:

$$Rcs_{2\ hour} = 2{,}811 - 0{,}106 \cdot x_2 - 0{,}077 \cdot x_3 - 0{,}113 \cdot x_1^2 - 0{,}126 \cdot x_2^2 + 0{,}083 \cdot x_3^2 + 0{,}045 \cdot x_1 \cdot x_3 . \quad (4)$$

Compressive strength at the age 7 days:

$$Rcs_{7\ day} = 2{,}85 - 0{,}063 \cdot x_1 - 0{,}084 \cdot x_2 - 0{,}222 \cdot x_3 - 0{,}219 \cdot x_1^2 + 0{,}091 \cdot x_1 \cdot x_2 + 0{,}041 \cdot x_1 \cdot x_3 + 0{,}096 \cdot x_2 \cdot x_3 . \quad (5)$$

Compressive strength dry concrete:

$$Rcs_{dry} = 5{,}605 - 0{,}053 \cdot x_1 - 0{,}429 \cdot x_3 - 0{,}094 \cdot x_1^2 - 0{,}442 \cdot x_2^2 + 0{,}31 \cdot x_3^2 + 0{,}081 \cdot x_1 \cdot x_2 + 0{,}059 \cdot x_2 \cdot x_3 . \quad (6)$$

Water absorption:

$$W_m = 34{,}682 + 0{,}525 \cdot x_1 + 0{,}132 \cdot x_2 - 0{,}784 \cdot x_3 - 7{,}466 \cdot x_1^2 - 1{,}736 \cdot x_2^2 + 1{,}018 \cdot x_3^2 + 0{,}235 \cdot x_1 \cdot x_2 + 0{,}152 \cdot x_1 \cdot x_3 - 1{,}037 \cdot x_2 \cdot x_3 . \quad (7)$$

Analysis of the coefficients of the regression equation for the output parameter of compressive strength shows that a higher content of flax shives (X3) leads to a decrease in compressive strength. The combined use of sawdust with glass fiber and flax shives with glass fiber in the composition of gypsum concrete has a positive effect on compressive strength. With an increase in the amount of flax shives, the water absorption of concrete decreases, as indicated by the negative value of the coefficient of factor (X3) in the mathematical model (7). On the contrary, an increase in the amount of glass fiber leads to an increase in water absorption of gypsum concrete.

The presence of sawdust (X2) in gypsum concrete has a greater effect on compressive strength than on tensile strength during bending. The factor (X2) has the greatest influence on compressive strength at the age of 2 hours; for gypsum concrete at the age of 7 days and for dry gypsum concrete, the influence of this factor becomes less significant, as indicated by the small value or absence of the linear coefficient of the factor (X2) in regression models (4) and (5) respectively.

The effect of factors on the concrete tensile strength in bending are different as can be observed in Figures 1–3. For the tensile strength in bending, the glass fiber content (X1) is one of the most important factors. At an early age influence glass fiber content (X1) is higher, compared to flax shives content (Figure 1, 2). Flax shives content (X3) is the second by its influence on tensile strength in bending. As the concrete dries, the influence of (X3) is increased.

Using regression equations, for a given output parameter, it is possible to determine the composition and predict the physical and mechanical properties of fiber-gypsum concrete with organic aggregates.

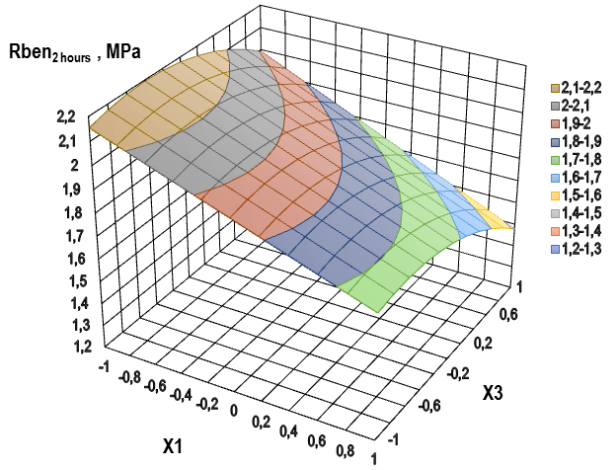


**Figure 1** – Response surfaces for tensile strength in bending at 2 hours vs. glass fiber content (X1), flax shives content (X3), sawdust content (X2 = –1)

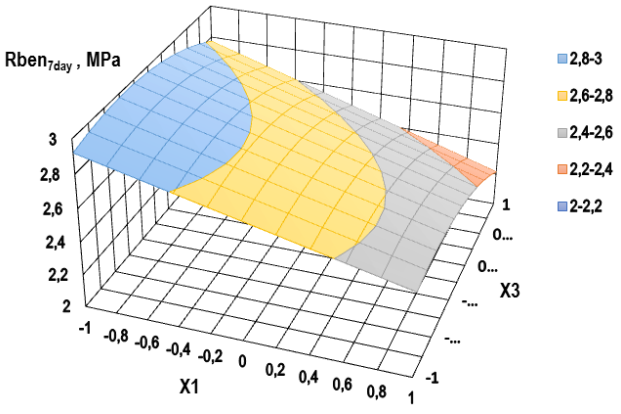


**Figure 2** – Response surfaces for tensile strength in bending at 7 days vs. glass fiber content (X1), flax shives content (X3), sawdust content (X2 = 1)

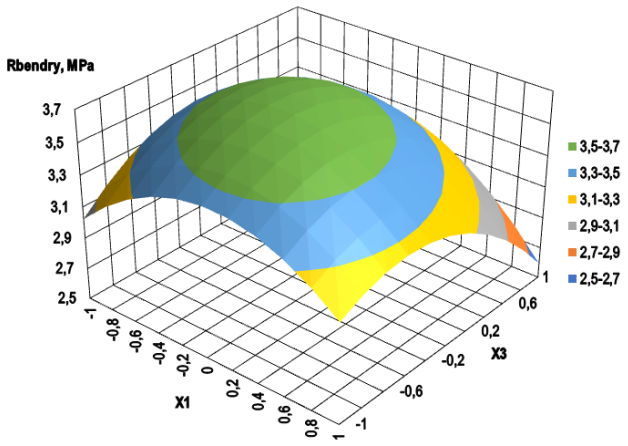


**Figure 3** – Response surfaces for tensile strength in bending dry concrete vs. glass fiber content (X1), flax shives content (X3), sawdust content (X2 = –1)

According to GOST 32614 Gypsum construction boards. Technical conditions, GOST 6266 Plasterboard sheets Technical conditions the tensile strength in bending is the main characteristic for gypsum boards. According to the obtained regression equation (formula 3), the maximum flexural tensile strength dry concrete $Rben_{dry}$ = 3,67 MPa will be achieved at a value of factor X2 = -1, which corresponds to a sawdust content of 4 % by weight of the gypsum binder, and at value of factors: X1 = - 0,084 (glass fiber content 0,383 % by weight of gypsum binder), X3 = - 0,141 (flax shives content 3,718 % by weight of gypsum binder).

Thus, the composition of gypsum concrete with organic aggregates with a maximum tensile strength in bending, includes the following content of components, wt. %: gypsum binder – 59,49; glass fiber – 0,23; sawdust – 2,38; flax shives – 2,21; water – 35,69.

To experimentally confirm the adequacy of the mathematical models, sample beams 40 × 40 × 160 mm were made from gypsum concrete with an optimized composition of organic aggregates. The water-gypsum ratio corresponded to the standard consistency of the gypsum binder W/G = 0.6. The density of the dry samples was 1117 kg/m$^3$.

The obtained actual and calculated values of the physical and mechanical characteristics of gypsum concrete are presented in Table 3.

**Table 3** – Experimental and theoretical values the physical and mechanical characteristics of gypsum concrete with an optimized composition

| The value of gypsum concrete characteristics | Rben, MPa, age | | | Rcs, MPa, age | | | $W_m$, % |
|---|---|---|---|---|---|---|---|
| | 2 hours | 7 days | dry concrete | 2 hours | 7 days | dry concrete | |
| Experimental value | 2,10 | 2,90 | 3,58 | 2,87 | 3,05 | 5,46 | 31,4 |
| The value, calculated with equation (1) – (7) | 2,01 | 2,78 | 3,67 | 2,80 | 2,98 | 5,24 | 32,7 |
| Deviation, % | 4,5 | 4,3 | 2,5 | 2,5 | 2,3 | 4,2 | 4,0 |

Deviations of experimental and theoretical values do not exceed 5 %, which indicates high convergence with the calculation result and confirms the reliability of the obtained mathematical models.


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**Physico-mechanical, sound-proofing and heat-insulating properties of concrete slabs with lightweight fiber-gypsum with organic aggregates**

The samples gained strength under natural humidity conditions at a temperature of 18–20 °C. The tests at the age of 7 days, after drying the samples to constant weight at a temperature of 50±5 °C and in a water-saturated state were carried out. The experimental results are presented in Table 4.

**Table 4** – Physical and mechanical properties of gypsum concrete for gypsum concrete slabs

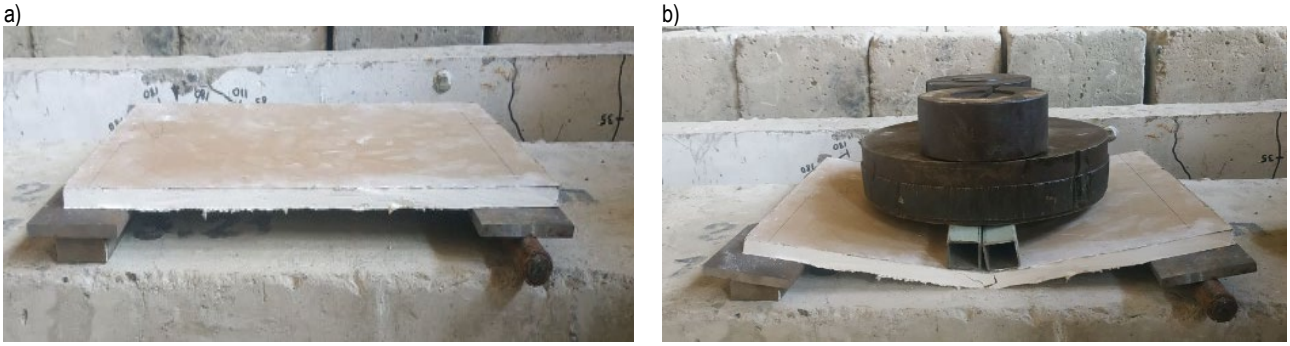
| Density, kg/m³ age | | Compressive strength, MPa, age | | | Softening coefficient | Water absorption, $W_m$, % | Porosity, % |
|---|---|---|---|---|---|---|---|
| 7 days | dry concrete | 7 days | dry concrete | Saturated with water | | | |
| 1388 | 1120 | 4,28 | 5,42 | 3,94 | 0,73 | 30,6 | 34,1 |

To determine the class of compressive strength and grade of average density, sample-cubes 70 × 70 × 70 mm were made and tested from optimized composition gypsum concrete.

According to GOST 25820-2014 the compressive strength class of gypsum concrete corresponds to B3,5; medium density grade – D1100.

Determination of the breaking load and deflection of sheets made of gypsum concrete with optimized composition of organic fillers was carried out according to the GOST 6266 method. The essence of the method is to destroy the sample-slab with a concentrated load applied in the middle of the span according to a single-span pattern. For testing, slabs with dimensions of 400 × 300 mm and thicknesses of 10 mm, 12,5 mm, 15 mm were made. To compare the results, a plasterboard board (GSP-A), 12,5 mm thick, manufactured at JSC BelGips was taken as a control sample.

These slabs are used for constructing partitions and cladding wall surfaces. To conduct the experiment, a sample measuring 400 × 300 mm was cut out of a plasterboard sheet. The device and testing process are presented in Figure 4. The test results are presented in Table 5.



a) location of the slab on supports located at a distance of 350 mm; b) destruction of the slab under load applied in the middle of the span

**Figure 4** – Procedure for testing sample-slabs for bending

**Table 5** – The value of the breaking load when testing sample-slabs for flexural

| Name of samples | Thickness, mm | Breaking load, N | Deflection, mm |
|---|---|---|---|
| Slab JSC BelGips | 12,5 | 300 | 2,0 |
| Slab №1 | 10 | 160 | 3,0 |
| Slab №2 | 12,5 | 240 | 2,08 |
| Slab №3 | 15 | 320 | 3,6 |

Analysis of the test results shows that, with the same thickness, the gypsum slab of JSC BelGips has higher flexural strength than gypsum concrete slab № 2 with an optimized composition of organic aggregate. In the experiment, a sheet of plasterboard with glued layers of cardboard was used; board № 2 was not glued with cardboard. All other things being equal, the experiment did not take into account the influence of the adhesion strength of the gypsum core and cardboard, which can provide an increase in the flexural strength of gypsum plasterboard sheets of JSC BelGips. When the slab thickness increased to 15 mm (slab № 3), the value of the destructive load exceeded that for a 12,5 mm thick gypsum plasterboard.

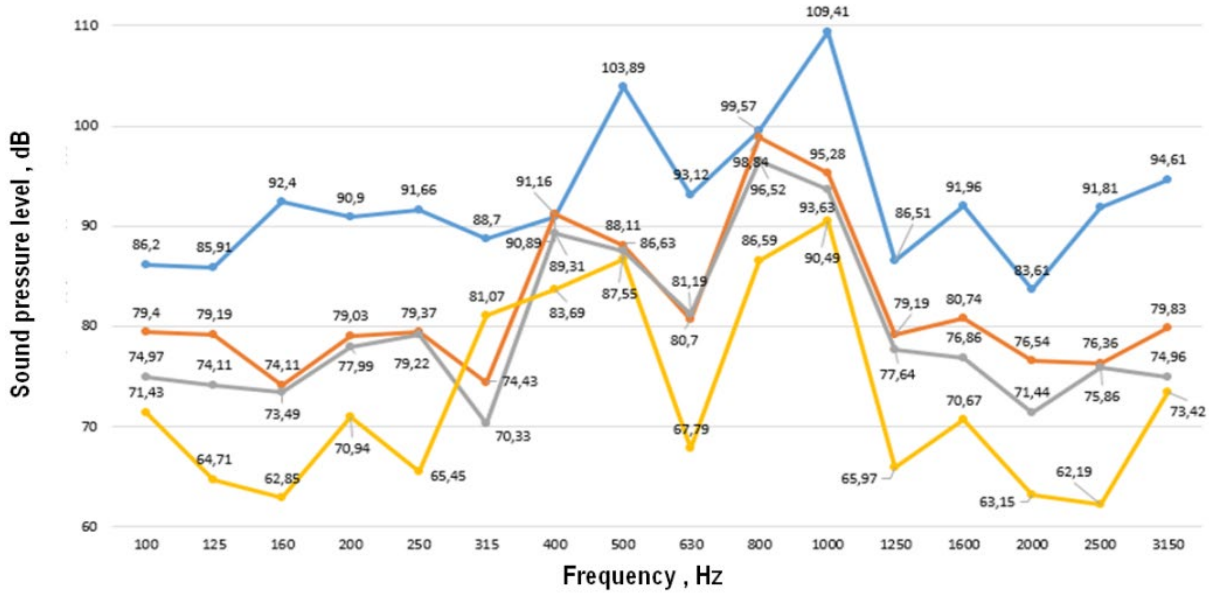
To conduct research to determine thermal conductivity, a slab measuring 250 × 250 × 30 mm was made from a gypsum concrete mixture with an optimized composition of organic aggregates and dried to constant weight. Measurements performed on the ITP-MG4 device showed that the thermal conductivity is 0,256 W/(m·K) with density of gypsum concrete 1120 kg/m³. According to GOST 6266, the thermal conductivity of plasterboard boards should be in the range of 0,22–0,35 W/(m·K).

The sound insulation properties of gypsum concrete slabs were determined using a training acoustic chamber on samples measuring 250 × 250 × 30 mm and 250 × 250 × 12,5 mm. A comparison of sound insulation properties was carried out with plasterboard boards of JSC BelGips, 12,5 mm thick and 250 x 250 mm in size.

Measurements were carried out on sound pressure levels in octave frequency bands with geometric mean frequencies of 100; 125; 160; 200; 250; 315; 400; 500; 630; 800; 1000; 1250; 1600; 2000; 3150 Hz in accordance with SN 2.04.01-2020 Noise protection. Construction standards of the Republic of Belarus. At the first stage, measurements of the sound pressure level were carried out in an empty acoustic chamber ("radiating" compartment). At the next stage, the acoustic chamber was divided into two compartments by a polystyrene foam partition, and the gypsum concrete sample under study was installed in the "window" of the partition. Next, the frequency was changed and the sound pressure level was recorded in the compartment separated from the source of the sound signal by a partition with the material under study ("receiving" compartment).

The efficiency of the soundproofing properties of the material was assessed by the decrease in the sound pressure level in the "receiving" compartment compared to the sound pressure level in the "emitting" compartment. The results of measuring the sound insulation properties of plasterboard slabs and gypsum concrete slabs with organic aggregates are presented in Figure 5.

Analysis of the results obtained shows that gypsum concrete with organic aggregate is superior in its soundproofing properties to the gypsum plasterboard board of JSC BelGips with the same thickness in the frequency range from 100 to 160 Hz. At a sound pressure level exceeding 250 Hz, the samples have comparable values in the amount of reduction in the sound pressure level in the "receiving" compartment. The results obtained show that the sound insulation ability of gypsum concrete slabs with organic aggregate increases with increasing slab thickness. Thus, in the frequency range from 100 to 300 Hz with slab thicknesses of 12,5 mm and 15 mm, the magnitude of the decrease in sound pressure level is, respectively, from 11,23 dB to 18,91 dB, from 14,77 dB to 29, 55 dB. In general, the results obtained allow us to draw a conclusion about the effective sound-proofing ability of gypsum concrete slabs with organic aggregate.




1 – empty chamber (blue line); 2 – BelGips slab 250 × 250 × 12,5 mm (orange line); 3 – gypsum concrete slab with organic aggregate 250 × 250 × 12,5 mm (gray line); 4 – gypsum concrete slab with organic aggregate 250 × 250 × 30 mm (yellow line)

**Figure 5** – Dependence of the sound pressure level in the "receiving" chamber on the frequency of sound when passing through the partition

**Conclusion**

Mathematical dependences of the physical and mechanical properties of gypsum concrete on the amount of organic aggregate have been obtained, which make it possible to optimize and calculate the compositions of gypsum concrete with given properties. A raw material mixture composition has been developed for structural and thermal insulation dispersed-reinforced light-weight gypsum concrete with two-component organic aggregate based on local raw materials of the average density grade D1100, strength class B3,5, thermal conductivity K = 0,256 W/(m·K). Gypsum concrete slabs, made using casting technology from the developed gypsum concrete composition, provide a noise level reduction of up to 29,55 dB in the frequency range from 100 to 300 Hz.

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# APPLICATION OF QUANTITATIVE ASSESSMENT BASED ON FUZZY LOGIC RULES TO THE TECHNICAL CONDITION OF EXISTING STRUCTURES

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**Abstract**

Approaches based on the use of fuzzy logic concepts provide effective solutions to problems containing uncertainties present in the assessment of existing buildings. The article presents the principle of development and implementation of quantitative assessment of the technical condition of existing structures. The process is based on an algorithm in which the input data and information collected at each step are processed and interpreted to determine the next step of the procedure. The result shows that the evaluation of the existing precast concrete building using the proposed fuzzy system is consistent with the evaluation of qualified experts.

**Keywords:** quantification assessment, fuzzy logic, existing structures, technical condition.

## ПРИМЕНЕНИЕ КОЛИЧЕСТВЕННОЙ ОЦЕНКИ, ОСНОВАННОЙ НА ПРАВИЛАХ НЕЧЕТКОЙ ЛОГИКИ, К ТЕХНИЧЕСКОМУ СОСТОЯНИЮ СУЩЕСТВУЮЩИХ КОНСТРУКЦИЙ

**В. В. Тур, Ю. С. Дордюк**

**Реферат**

Подходы, основанные на использовании концепции нечеткой логики, дают эффективные решения проблем, содержащих неопределенности, присутствующие при оценке существующих зданий. В статье представлен принцип разработки и внедрения количественной оценки технического состояния существующим сооружениям. Процесс основан на алгоритме, в котором входные данные и информация, собранная на каждом этапе, обрабатываются и интерпретируются для определения последующего шага процедуры. В результате видно, что оценка существующего здания из сборных железобетонных элементов с использованием предлагаемой нечеткой системы соответствует оценке квалифицированных экспертов.

**Ключевые слова:** количественная оценка, нечеткая логика, существующие конструкции, техническое состояние.

### 1 Introduction

In recent years assessment of existing structures is becoming a more and more important engineering task. The process of assessment and structure management is a decision process which aims to remove any doubts regarding its current condition and future structural performance and/or to identify the most effective interventions required to fulfil the basic requirements. This process must be optimised considering the total service life costs of the structure. The standard ISO 13822, defines *«assessment of existing structures»* as the *«set of activities performed in order to verify the reliability of an existing structure for future use»*. It defines investigation as *«collection and evaluation of information through inspection, document search, load testing and other testing».* Moreover, inspection is *«on-site non-destructive examination to establish the present condition of the structure»*.

According to ISO 13822, the assessment of the existing structure can be initiated under the following circumstances:

- an anticipated change in use or extension of design working life;
- a reliability check (e.g. earthquakes, increased traffic actions) as required by authorities, insurance companies, owners, etc.;
- structural deterioration due to time-dependent actions and influences (e.g. corrosion, fatigue);
- structural damage by accidental actions (ISO 2394).

General principles of sustainable development regularly lead to the need for extension of a life of a structure, in the majority of practical cases in conjunction with severe economic constraints. The purpose for which the concrete structure was designed and developed can change during the lifespan of the building. When this occurs, and concrete structure no longer fulfils its new requirements, a decision is made whether the building will be demolished or transformed. According to [1], *transformation* is different than *restoration* or *renovation* in that it not necessarily strive to maintain the social, political or cultural embodiment of the place. *Transformation* can lead to a switch in the function of the building. For example, a former industrial building can be transformed into social housing.

In general case the estimation procedure of the present conditions of the existing building consists of three main phases which can be singled out as follow:

*Phase A:* Preliminary analysis (visual inspection; basic *in-situ* testing) is aimed at obtaining a coarse estimation but general information of the real present state conditions of the existing structure and defining a rapid mapping of instabilities, damage and vulnerability. Based on the data obtained, it will be then decided if further and more detailed investigation needs.

*Phase B:* Extensive or detailed in-depth investigation, including a complete and systematic survey of the degradation scenery; experimental and laboratory tests, including both destructive and non-destructive *in-situ* methods.

*Phase C:* Interpretation and assessment of the obtained results; formulation of the judgment on the level of damage and reliability; specification of the repair and retrofitting interventions need in order to meet safety format requirements.

As was shown in [2] the diagnostic process for evaluation of the safety level and structural conditions of existing buildings is based on a decisional tree in which the data information collected at each phase are processed and interpreted in order to define the successive step of the procedure.

The investigation, including updating of information, is one of the most important activities in the assessment process. It must take into consideration all available information and, in particular, the influences of present damage and deterioration mechanisms. The aim of a preliminary inspection (designed as Phase A) is to identify the structural system and possible damage of the structure by visual observation with simple tools. The information collected is related to aspects such as surface characteristics, visible deformations, cracks, spalling, corrosion, etc. The results of the preliminary inspection are expressed, traditionally, in terms of a qualitative grading of structural conditions (e.g. none, minor, moderate, severe, destructive, unknown) for possible damage. According to the Recommendation given by [3], the preliminary assessment (Phase A) is organized in three consecutive steps, each of which provides an intermediate judgment: (1) *Typological and structural description and existing original design documentation analysis;* (2) *Visual inspection,* which consists of visual evaluation of cracks (extension an amplitude), concrete condition ( degradation , covering thickness), reinforcing bars conditions (corrosion); (3) *In-situ experimental testing* (non-destructive or destructive).

Thus, preliminary inspection (*visual inspection* + *in-situ testing*) becomes the ruling practice in the management of maintenance, even when the importance of the construction is significant. The process of evaluation of degradation based on the results of visual inspection is heavily affected by subjectivity. It is because most of the assessment approaches are similar in principle but varies in the details.

As was shown above, most practical cases the expert in charge of the inspection writes down on a safety assessment protocol a linguistic statement, which represents the subjective judgment for the degradation under examination. When relying only on visual inspection both the problems of dealing with different levels of expertise of the inspectors and the problems of handling subjective information on degradation raise this information, which needs to be turned into objective and reliable assessments.

To use the visual inspection as a robust and reliable instrument to evaluate the safety level of existing structures of the buildings, it was decided to take advantage of the ability of Fuzzy Logic to treat uncertainty as expressed by linguistic judgments [4, 5].

Following Aristotle's logic: *«It is impossible that the same thing can at the same time both belong and not belong to the same object and in the same respect» (Aristotle, Metaphysics, Principle of non-contradiction).* This law is very helpful if the problems are simple and linear, but the real-life and nature are not as easy as this [6].

The Fuzzy Logic was introduced in the 60's by Zadeh, who stated that the *«key elements of human thought cannot be represented by numbers, but rather are the labels of fuzzy sets, that is to say, linguistic values identifying fuzzy sets».* Fuzzy sets are classes of object characterized by a gradual transition from the membership conditions to the non-membership one, whereas crisp sets (that where the only one known before this new theory) only allow the drastic binary condition membership/non-membership.

Some common theoretical background of the Fuzzy Logic approach to the civil engineering problems described in detail in numerous international publications [2, 7–11].

As it pointed in [2], *«a Fuzzy Logic is a versatile tool, particularly suitable for the management of decisional trees involving the processing of data endowed with «vague» nature (both numerical and qualitative one), and is naturally able to provide a linguistic, qualitative assessment of the health conditions of the building».* In this context, the Fuzzy Logic appears the most qualified tool for the processing of numerical data and uncertain information to obtain a linguistic description of structural damage.

In order to create the multilevel expert system for existing structures assessment based on the diagnostic process outlined above, a Fuzzy Logic-based algorithm is proposed, which exploits the Fuzzy Logic Toolbox package of *MatLab* Software.

**Fuzzy Logic System: Some Background Information**

Figure 1 presents a general view of a Fuzzy Logic system that is widely used for the assessment of the different technical problems. A fuzzy logic system maps crisp inputs into crisp outputs. It contains four basic components: (1) fuzzifier; (2) rules; (3) inference engine and (4) defuzzifier. Once the rules have been established, a fuzzy logic system can be viewed as a mapping from inputs to outputs [7, 12].

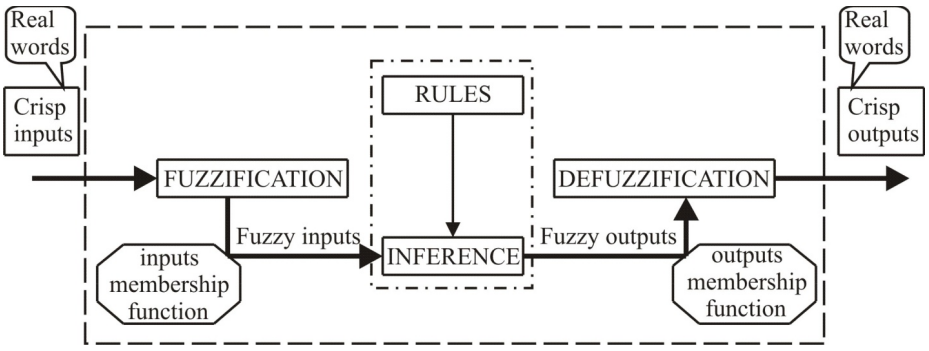


**Figure 1** – Block diagram of Fuzzy Logic system, according to (Khader, 2010)

*Fuzzification* is the process of making of crisp quantity fuzzy. In other words, the fuzzification procedure consists in transforming the numerical value of the considered variable in its corresponding value of membership to the given fuzzy sets through the corresponding membership function. This is done by recognizing that many of quantities, which are considered crisp and deterministic, are not deterministic at all and they carry considerable uncertainty when the variable is probably fuzzy and can be represented by a membership function. Typically, the membership function overlaps so that the values of the variable can partially belong to multiple fuzzy sets. In general case, *the wider the area that overlaps, the more the uncertainty the system includes.*

The procedure of *inference* involves the application of the rules of combination of fuzzy sets. Usually, these are simple linguistic expressions, which are converted to mathematical formalism in the language of the «IF-THEN» logic. This is important because the information gathered through the examination of a given problem can be used without any translation into formulas, which are often of complex determination [13].

On the other hand, rules may be provided by experts or can be extracted from numerical data. In either case, engineering rules are expressed as a collection of «IF-THEN» statements. In general case, each rule contains one or clauses in the «IF» part of the rule, these clauses are known as the *antecedent*, and one (but potentially more than one) clause in the «THEN» part of rules, these clauses collectively are called the *consequent*.

The fuzzy inference engine combines rules into a mapping from fuzzy sets in the input space to fuzzy set in the output space based on fuzzy logic principles.

*Defuzzification* is the conversion of a fuzzy quantity to a precise quantity, just as fuzzification is the conversion of precise quantity to a fuzzy quantity. The output of a fuzzy process can be logical upon for two or more membership functions defined on the universe of discourse of the output variable. The output is also a fuzzy membership value that can be used either «raw» as qualitative assessment or defuzzified as a real number, compatible with nonfuzzy approaches [4, 5, 13–15].

**2 Development Steps of the Expert System**

The expert system should be designed and developed depending on the experience of experts. In this case, the procedure for developing the proposed expert system is divided into two main steps: Designing and Implementation. For each step, there is a list of procedures as shown in Table 1.


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**Table 1** – Scheme of damage assessment expert system [12]

| | | |
|---|---|---|
| **Development of damage Assessment Expert System** | Selecting Assessment Criteria (that indicate structural conditions) | The structural evaluation of building involves several criteria that should be considered. The criteria will be selected based on inspection results and previous records of regular inspections. They will be such basic items that can be inspected by close visual inspections and do not require special testing or long-term investigation. |
| | Estimating the Importance of Assessment Criteria | In the evaluation of any structure decisions must be made on the weighting to be given to the different observations and calculations relating to the strength and serviceability of individual members and to their effect on the overall structure. |
| | Designing of Damage Assessment Expert System | Development an expert system for condition evaluation that includes final state assessment of the building and recommended action. In this expert system, fuzzy sets used and knowledge representation tool. |
| **Implementation State Assessment of Building** | Collecting Information | Collection and evaluation of information through close visual inspection, document search, on-site non-destructive examination etc. |
| | Using Investigations and Inspection Records as Input data | Investigation and inspection records of the previous step used as input data of the expert system. |
| | Assessing the Structural State of the Building | State assessment of the building under consideration. |

**3 Selecting Assessment Criteria. Relations Between the Basic Variables**

It should be noted that not always the excess of information results in a significant improvement of the input data obtained (additional uncertainty reduces the accuracy of estimation). Moreover, it can be uselessly time and finances consuming. As shown in [16] in the practical evaluation, one finds that the influence of the most basic variables is not as important as predicted. Therefore, a more rational approach which restricts the set of input data based on the criteria of simple availability and actual high relevance is suggested. For instance, one originally regards that the deflection increasing and resistance decreasing of each structural member will result in decreased safety in the existing structure as a whole. Resistance is generally satisfied by the specification requirements to materials in the design. Therefore, to simplify the evaluation process, some variables, such as the strength of materials and so on are neglected in the evaluation method. The basic variables utilized in the proposed expert system, are listed in Table 3. The inputs to the system are mostly linguistic variables and some numerical data concerning the selected categories for the assigned criterion. As rule, they extracted from reports of the building assessment. Traditionally, the state conditions for criteria constructed by extracting knowledge mainly from technical books and experts in the domain fields. In the case of the proposed model, the state conditions for criteria and the logic relationships between basis variables (the selected assessment criteria) have been obtained based on the results of the own investigations.

***The relationship between the corrosion level of steel reinforcement and corrosion cracks width***

As it was shown in the numerous publications [17–20] after corrosion initiation, hydrated rust accumulates around the bar, causing pressure and leading to cover cracking. To predict the damage caused by corroding reinforcing bars, knowledge of the state of stress in the surrounding concrete is required, and this can be determined to employ concrete ring or thick-wall cylinder, as it was proposed by most of the researchers, for example [21]. In the last decade, numerous models [18, 20, 22] for corrosion assessment was proposed. Based on the results of the own comparative study [23], the following expression for calculation of the corrosion crack width proposed by [22] has been adopted:

$$w_{cr(l)} = 0,05 + \beta \cdot (x - x_{cr}), \quad (1)$$

where $x$ is the penetration depth (μm);

$x_{cr}$ is the critical penetration depth initiated longitudinal crack;

$\beta$ is the empirical coefficient.

For calculation of the critical penetration depth the following empirical expression [17] has been chosen:

$$x_{cr} = 7,53 + 9,32\frac{c}{\varnothing}, \quad (2)$$

where $c$ is the concrete cover and $\varnothing$ is the bar diameter.

Figure 2 shows the results of the comparison of the theoretical crack width values $w_{cr(l)}$ obtained by the calculations with usage generalized model equation (3) and experimental data. Taking into account statistical uncertainties evaluated by EN 1990, Annex D (b = 0.34; $V_\delta$ = 50.9 %) expression equation (1) can be rewritten as:

$$w_{cr(l)} = k \cdot \left[0,05 + \beta \cdot (x - x_{cr})\right]. \quad (3)$$

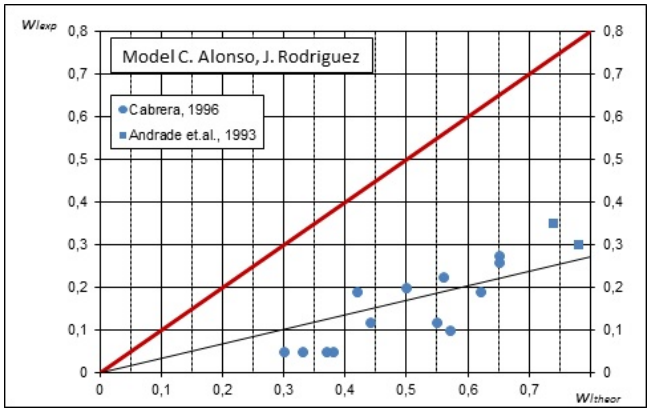



**Figure 2** – Comparison of experimental and theoretical values of the corrosion longitudinal cracks width

The mass loss at a specified depth of corrosion damage propagation is calculated:

$$ML = \frac{r^2 - (r - x)^2}{r^2} \cdot 100\%, \quad (4)$$

where $r$ is the bar radius.

***The relationships between corrosion level of steel, corrosion longitudinal crack width*** $w_{cr(l)}$ ***and flexural crack width*** $w_k$

The parametrical study of the concrete elements with corroded reinforcement for a wide range of combinations of the input variables (concrete compressive strength, ratio $c/\varnothing$, level of the corrosion damage of reinforcement) has been performed with the usage of the developed numerical resistance model and results of the parametrical study presented in detail [23].

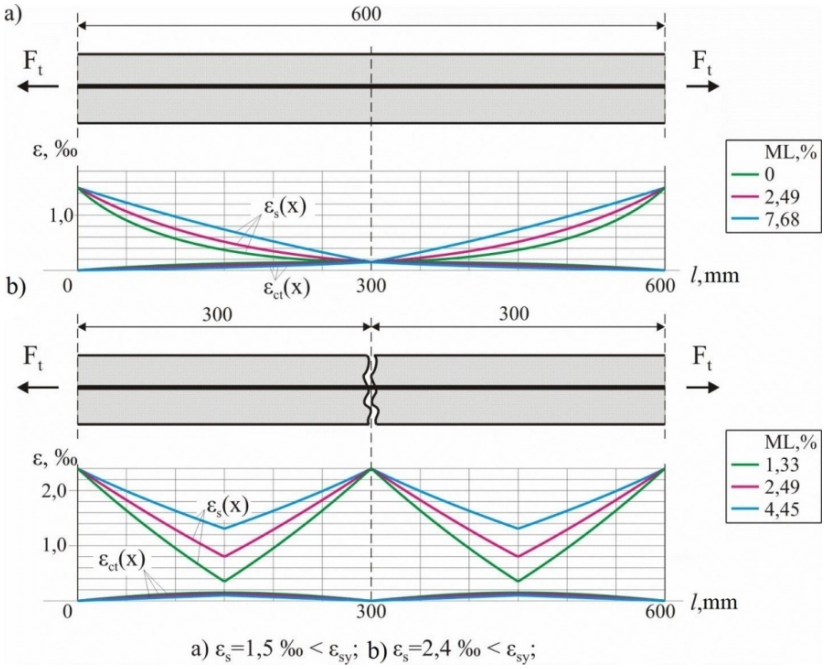



**Figure 3** – The strain distributionsin concrete $\varepsilon_{ct}(x)$ and in reinforcement $\varepsilon_s(x)$ for the different level of corrosion damage and value $\varepsilon_s(0)$ = 1,5 ‰ in cracked section (exploitation stage) (in case $f_{ck}$ = 20 MPa, $\varnothing$ 12 mm, $c/\varnothing = 3{,}5$)
(a) before cracking of the block; (b) stabilized cracking stage

Figure 3 shows an example of the characteristic strain distributions in concrete $\varepsilon_{ct}(x)$ and reinforcement $\varepsilon_s(x)$ for the different level of corrosion damage of the steel reinforcement (ML, %) and constant value of the steel strain in cracked section $\varepsilon_s(0)$ = 1,5 ‰ (for exploitation stage), which were obtained with the usage of developed resistance model [23]. Figure 4 shows the relationship between normal crack width ($W_k$) and level of corrosion damage (ML, %), and Figure 5 shows the relationship between flexural crack width ($W_k$) and longitudinal corrosion crack width ($W_l$) for different corrosion damage level (ML, %), what has been obtained in parametrical study [23] in case of listed input data. The red solid and dashed lines indicate the critical penetration depth which initiates a longitudinal crack.

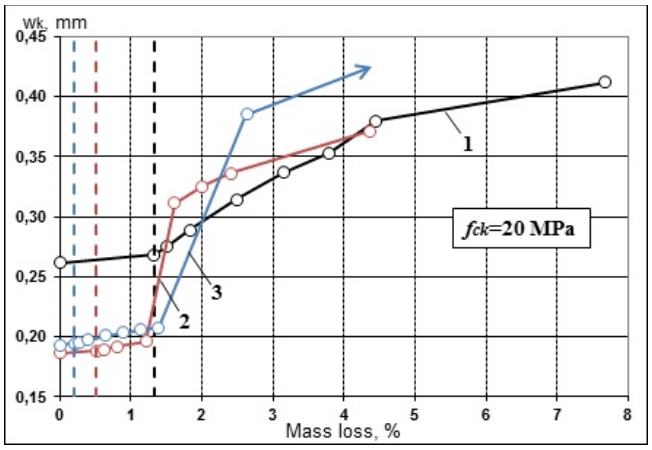



**Figure 4** – The relationships between normal crack width ($W_k$) and corrosion damage level (ML, %) (in case $f_{ck}$ = 20 MPa)
1 – $\varnothing$ 12 mm; 2 – $\varnothing$ 20 mm; 3 – $\varnothing$ 32 mm

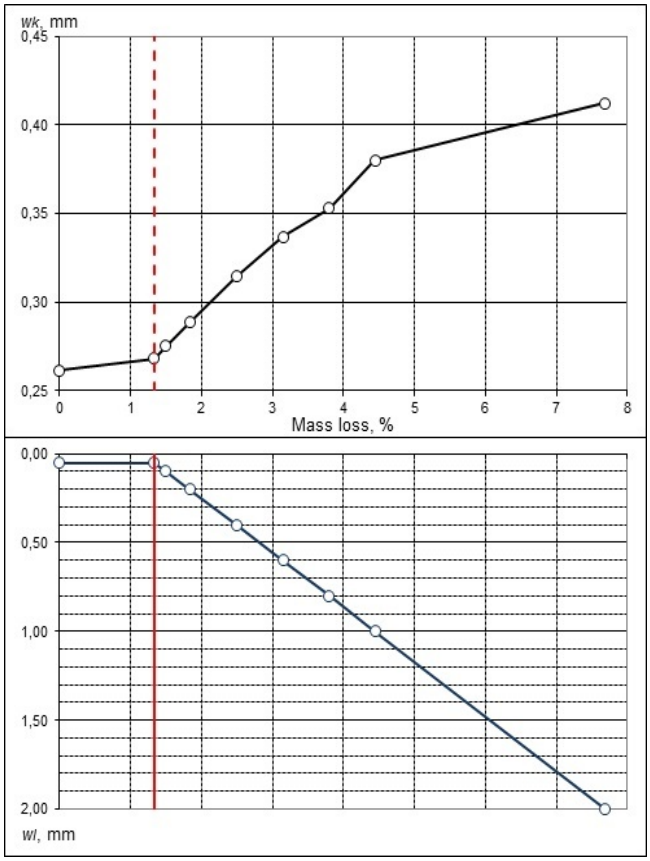



**Figure 5** – The relationship between normal crack width ($W_k$) and longitudinal crack width ($W_l$) for different corrosion damage level (ML, %) (in case $f_{ck}$ = 20 MPa, $\varnothing$ 12 mm, $c/\varnothing = 3{,}5$)

The relationship between deflection ($a / L_0$) and flexural crack width ($w_k$).

Based on results of the investigation [23] performed with the usage of the simplified numerical resistance model (as shown in Figure 6), the following relationship between relative deflection ($a / L_0$) and flexural crack width ($w_k$) has been developed:

$$\frac{a}{L_0} = \alpha_0 \cdot \frac{w_m}{(1-\beta_0)\cdot 300} \cdot \delta \,, \tag{5}$$

where $\beta_0$ is the coefficient calculated from expression:

$$\beta_0 = \alpha_e \rho_l \left( \sqrt{1 + \frac{2}{\alpha_e \rho_l}} - 1 \right), \tag{6}$$

$\alpha_0$ is the coefficient accounting boarding (support) conditions;

$L_0$ is the effective span; wm is the average normal crack width [mm];

$\rho_l$ is the reinforcement ratio $\rho_l = \frac{A_s}{b \cdot d}$;

$\alpha_e$ is the modular ratio $\alpha_e = \frac{E_s}{E_{cm}}$;

$\delta = \frac{L_0}{d}$ is the ratio effective span to the effective depth of the section.

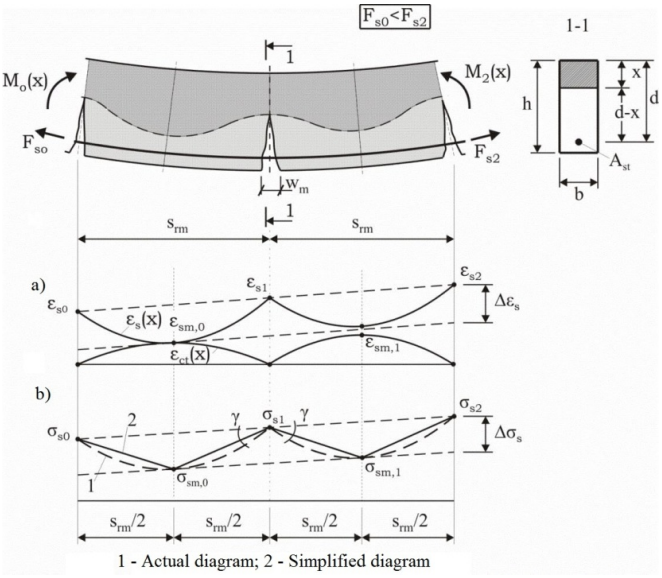



**Figure 6** – The strain distributions in concrete and reinforcement (a) and stresses distribution in reinforcement (b) along the block between adjacent cracks

The proposed expression equation (5) was verified based on the experimental database [24] and compared with the calculation model proposed by [24]. The obtained comparison results are shown in Figure 7 and listed in Table 2. As can be seen from Figure 7 and Table 2 the calculation results obtained using the proposed relationship equation (5) have a good agreement with experimental data. Figure 8 shows the relationship between the relative deflection ($a / L_0$) and normal crack width ($w_k$) obtained based on the proposed expression equation (5) in the case study [23].

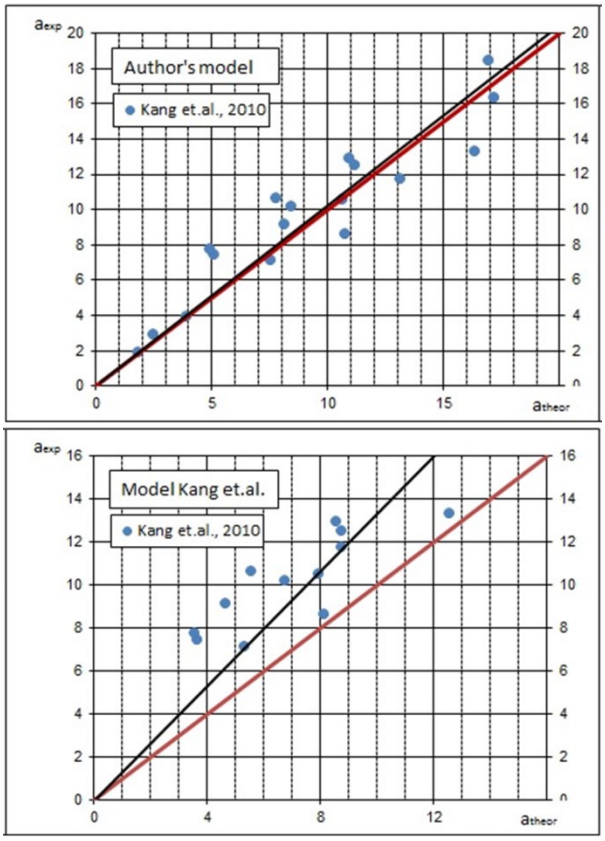



**Figure 7** – Comparison of the experimental and theoretical values of the deflection

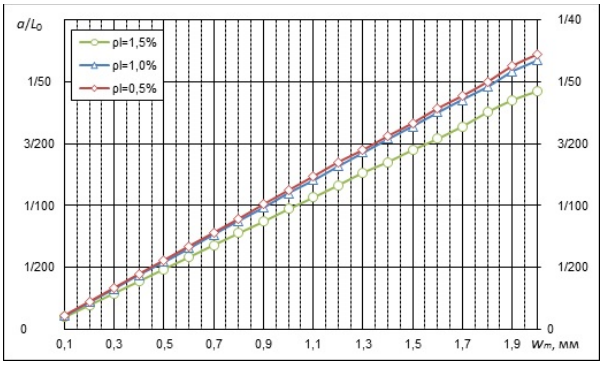
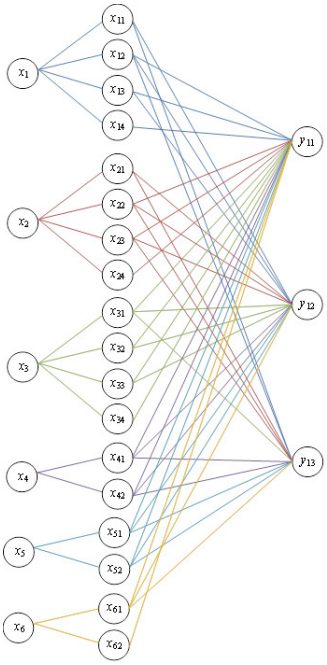



**Figure 8** – The relationship between the relative deflection ($a / L_0$) and normal crack width ($w_k$) obtained based on the proposed expression (5)

**Table 2** – Comparison of the statistical parameters

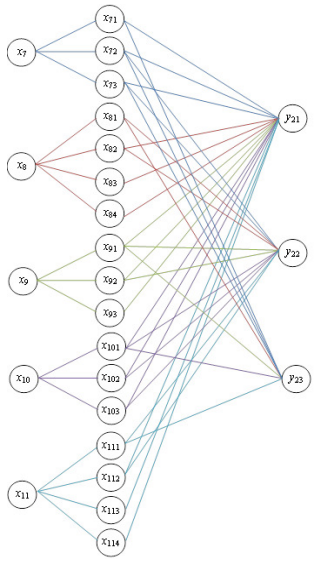
| Model | The statistical evaluation of the model error | |
|---|---|---|
| | b | $V_\delta$, % |
| Author's model | 1.02 | 19.2 |
| Model Kang et al. [24] | 1.34 | 24.3 |

The relationships of the evaluation factors (basic variables) in existing structures, which was obtained based on the classification and established domains $x[0, x_u]$ for each basic variables stated above are shown in Figures 9–11.



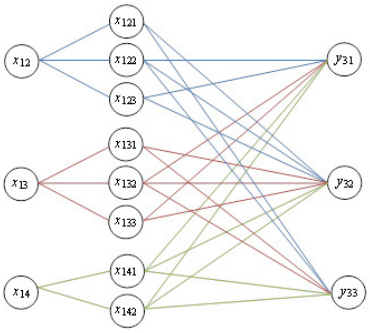
| Basic variable | Level | Linguistic | Range |
|---|---|---|---|
| $x_1$ | $x_{11}$ | no | 0 |
| | $x_{12}$ | single | 0.5-10 % |
| | $x_{13}$ | numerous | 10-40 % |
| | $x_{14}$ | massive | >40 % |
| $x_2$ | $x_{21}$ | no | |
| | $x_{22}$ | mid-span | |
| | $x_{23}$ | near support | |
| | $x_{24}$ | mid-span+ near support | |
| $x_3$ | $x_{31}$ | no | 0 |
| | $x_{32}$ | local | 0.5-10 % |
| | $x_{33}$ | partial | 10-40 % |
| | $x_{34}$ | solid | >40 % |
| $x_4$ | $x_{41}$ | no | |
| | $x_{42}$ | yes | |
| $x_5$ | $x_{51}$ | no | |
| | $x_{52}$ | yes | |
| $x_6$ | $x_{61}$ | no | |
| | $x_{62}$ | yes | |

**Figure 9** – Relationship between basic variables: Phase A: Visual Inspection (A-1)



| Basic variable | Level | Linguistic | Range |
|---|---|---|---|
| $x_7$ | $x_{71}$ | small | <1 |
| | $x_{72}$ | mean | 1-3 |
| | $x_{73}$ | large | >3 |
| $x_8$ | $x_{81}$ | small | no more 0.05 mm |
| | $x_{82}$ | permissible | from 0.05 to 0.4 mm |
| | $x_{83}$ | exceeded | from 0.4 to 1 mm |
| | $x_{84}$ | excessive | more 1 mm |
| $x_9$ | $x_{91}$ | small | no more 0.05 mm |
| | $x_{92}$ | medium | from 0.05 to 1 mm |
| | $x_{93}$ | large | more 1 mm |
| $x_{10}$ | $x_{101}$ | small | no more 1 % |
| | $x_{102}$ | mean | from 1 to 3 % |
| | $x_{103}$ | large | more 3 % |
| $x_{11}$ | $x_{111}$ | small | no more 1/900 |
| | $x_{112}$ | permissible | from 1/900 to 1/250 |
| | $x_{113}$ | exceeded | from 1/250 to 1/50 |
| | $x_{114}$ | excessive | more 1/50 |

**Figure 10** – Relationship between basic variables: Phase A: Basic Testing (A-2)



| Variable | Level | Linguistic |
|---|---|---|
| $x_{11}$ | $x_{111}$ | critical |
| | $x_{112}$ | significant |
| | $x_{113}$ | minor |
| $x_{12}$ | $x_{121}$ | critical |
| | $x_{122}$ | significant |
| | $x_{123}$ | minor |
| $x_{13}$ | $x_{131}$ | no |
| | $x_{132}$ | yes |

**Figure 11** – Relationship between basic variables: Phase A: Damage Class

**4 Realization of the Fuzzy production algorithm in MatLab Software [25]**

*Step 1:* Fuzzification – Input Fuzzy. At this stage, the membership functions for term-sets of input and output linguistic variables are adopted. The most commonly used membership functions are the trapezoidal and triangular one, that will be indeed the functions adopted in the proposed fuzzy algorithm.

*Step 2:* Setting Fuzzy Rules. This is now to need to combine these elements each with the other, to obtain the desired final diagnosis of the existing structures. This performed by introducing proper «fuzzy rules», relating the input data with the final output variable.

*Step 3:* Aggregation is the process by which the fuzzy set that represents the outputs of each rule are combined into a single fuzzy set.

*Step 4:* Activation. A fuzzy «IF-THEN» rule is a connection of two (compound) fuzzy propositions.

*Step 5:* Accumulation. Usually, a rule base is interpreted as a disjunction of rules, i.e. rules are seen as independent «experts». Accumulation has the task to combine the individual «expert statements», which are fuzzy sets of recommended output values.

*Step 6:* Defuzzification – from a fuzzy decision to real decision. As inference results in a fuzzy set, the task of defuzzification is to find the numerical value, which «best» comprehends the information contained in this fuzzy set.

**5 Implementation of the Fuzzy Algorithm**

The starting point, as it has pointed out in ISO 13822, ISO 2394, is the availability of an inventory of data and information derived from the investigation on the analyzed building, the collecting and organization of which is performed by using the survey diagnostic protocol form.

As an example of the implementation of the proposed expert system results of the assessment of the existing building with load-bearing precast concrete elements and masonry walls is presented.

*Structures description.* A main load-bearing element is precast reinforced concrete beam with following geometrical parameters: T-section with height 450 mm, web width 120 mm, flange width 200 mm and length of the span 6 m. Longitudinal main reinforcement is $2 \varnothing 22$ B400, concrete cover 22 mm (ratio $c / \varnothing = 1$). Precast ribbed slabs have the size in plane 1.5x6 m and height of the rib 300 mm. Longitudinal main reinforcement is $\varnothing 16$ B400, concrete cover 32 mm (ratio $c / \varnothing = 2$). Figure 12 shows the characteristic defects and deterioration of the structural elements.

The evaluation factor scores obtained as results of the Visual Inspection and Basic Testing for reinforced structures are listed in the diagnostic protocol (Table 3).

**Figure 12** – Characteristic defects of the evaluated precast beam and ribbed slabs




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**Table 3** – The input data collection (diagnostic protocol example)

| **Phase A: Visual Inspection (A–1)** | | | | |
|---|---|---|---|---|
| **Structural Member** | **Precast beam** | | | |
| General Description | T-section with height 450 mm, web width 120 mm, flange width 200 mm and with 6 m span | | | |
| Propagation of the flexural (bending)/shear cracks, $x_1$ | Parameter: propagation length of the damaged linear size, [%] span length | | | |
| | **no** | **single** | **numerous** | **massive** |
| | 0 | 0.5–10 | 10–40 | >40 |
| *Inspection results* | | | *35 %* | |
| Position of the flexural (bending)/shear cracks, $x_2$ | Parameter: position in span | | | |
| | **no** | **mid-span** | **near support** | **mid-span+near support** |
| | 0 | 1 | 2 | 3 |
| *Inspection results* | | | | × |
| Propagation of the longitudinal corrosion cracks, $x_3$ | Parameter: propagation length, [%] span length | | | |
| | **no** | **local** | **partial** | **solid** |
| | 0 | 0.5–10 | 10–40 | >40 |
| *Inspection results* | × | | | |
| Corrosion damage (deterioration), $x_4$ | Parameter: damage appearance | | | |
| | **no** | **not sure** | **yes** | |
| | 0 | 0.5 | 1 | |
| *Inspection results* | | | × | |
| Surface degradation of concrete (deterioration), $x_5$ | Parameter: damage appearance | | | |
| | **no** | **not sure** | **yes** | |
| | 0 | 0.5 | 1 | |
| *Inspection results* | | | × | |
| Propagation of the longitudinal corrosion cracks in compression zone of the section, $x_6$ | Parameter: damage | | | |
| | **no** | **not sure** | **yes** | |
| | 0 | 0.5 | 1 | |
| *Inspection results* | × | | | |
| ***Damage Level*** | ***1 (critical)*** | | | |
| **Phase A: Basic Testing (A–2)** | | | | |
| Characteristic of the Structure | Parameters | | | |
| | Length, *l* [mm] | | | 6000 |
| | Height, *h* [mm] | | | 450 |
| | Concrete cover, *c* [mm] | | | 22 |
| | Diameter of steel bar, Ø [mm] | | | 22 |
| Concrete | | | | |
| Ratio $c / \varnothing$ (concrete cover/diameter), $x_7$ | Parameter: $c / \varnothing$ | | | |
| | **small** | **mean** | **large** | |
| | <1 | 1–3 | >3 | |
| *Inspection results* | | *1* | | |
| Flexural (bending) cracks, $x_8$ | Parameter: crack width, $w_k$ | | | |
| | **small** | **permissible** | **exceeded** | **excessive** |
| | no more 0.05 mm | from 0.05 to 0.4 mm | from 0.4 to 1 mm | more 1 mm |
| *Inspection results* | | | *0.8* | |
| Longitudinal corrosion crack, $x_9$ | Parameter: corrosion crack width, $w_l$ | | | |
| | **small** | **medium** | **large** | |
| | no more 0.05 mm | from 0.05 to 1 mm | more 1 mm | |
| *Inspection results* | *0* | | | |
| Reinforcement (steel) | | | | |
| Level of the corrosion damage, $x_{10}$ | Parameter: loss of the mass | | | |
| | **small** | **mean** | **large** | |
| | no more 1 % | from 1 to 3 % | more 3 % | |
| *Inspection results* | *0* | | | |
| Deflections, deformations | | | | |
| Deflections, $x_{11}$ | Parameter: relative deflection | | | |
| | **small** | **permissible** | **exceeded** | **excessive** |
| | no more 1/900 | from 1/900 to 1/250 | from 1/250 to 1/50 | more 1/50 |
| *Inspection results* | | | *1/120* | |
| ***Damage Level*** | ***1 (critical)*** | | | |

Table 4 presents the results of the assessment of building under examination using the proposed algorithm, which has been realized by Fuzzy Logic *MatLab* Toolbox. As can be seen from Table 4, obtained estimates comply with the estimation formulated by the highly qualified experts.

**Table 4** – Results of the assessment

| The structural element | Results of the assessment | |
|---|---|---|
| | proposed fuzzy algorithm | highly qualified experts report |
| Precast beams | Severe damage | Severe damage |
| Precast ribbed slabs | Severe damage | Severe damage |

**6 Conclusions**

In this study, an effective structural assessment expert system for evaluation of the existing reinforced concrete buildings using Fuzzy Logic *MatLab* Toolbox was developed and verified on the existing buildings, to assess, in a more objective and reliable way, the real state conditions of the building under examination. It was shown that obtained estimates are in good agreement and compliance with the estimations formulated by the highly qualified experts.

Although the presented expert system based on close visual inspections and simple measurements (Phase an investigation), nevertheless, it may provide substantial assistance to more complicated assessment (for example, evaluation of existing structures based on detailed investigations Phase B).

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# ANALYSIS OF CALCULATION METHODS AND NUMERICAL SIMULATION OF THE STRESS-STRAIN STATE OF REINFORCED CONCRETE ELEMENTS UNDER LOCAL ACTION OF TENSILE FORCES

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**Abstract**
The analysis of methods for calculating the load-bearing capacity of reinforced concrete elements for tearing, given in the domestic technical literature, as well as in the literature countries of near and far abroad, has been conducted. A numerical study of the stress-strain state of the tearing zone under the local action of tensile forces was carried out.

**Keywords:** supporting beam, supported beam, tear-off, finite element analysis, tear-off zone.

## АНАЛИЗ МЕТОДОВ РАСЧЕТА И ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ ЖЕЛЕЗОБЕТОННЫХ ЭЛЕМЕНТОВ ПРИ МЕСТНОМ ДЕЙСТВИИ РАСТЯГИВАЮЩИХ УСИЛИЙ

**Н. Н. Шалобыта, Е. С. Матвеенко, Н. В. Матвеенко, В. И. Рахуба**

**Реферат**
Проведен анализ методов расчета несущей способности железобетонных элементов на отрыв, приведенных в отечественной технической литературе, а также в литературе стран ближнего и дальнего зарубежья. Выполнено численное исследование напряженно-деформированного состояния зоны отрыва при местном действии растягивающих усилий.

**Ключевые слова:** поддерживающая балка, поддерживаемая балка, отрыв, конечно-элементный анализ, зона отрыва.

**Introduction**

Over the last 20 years, both in the Republic of Belarus and in other countries of the post-Soviet era and the Eurasian Union, design standards, including reinforced concrete structures, have been introduced and improved. Taking into account new theoretical and experimental data, as well as developed reliability criteria, changes and addenda were made to a number of standard provisions. However, the analysis of regulatory documents on the calculation and design of reinforced concrete structures, as well as other available sources, showed that the calculation provisions in case of the local action of tensile forces have not changed for more than 70 years.

In the existing technical literature for calculating elements for local action of tensile forces (tear-off), including those in force in the national technical normative legal acts [1] and Eurocodes [2], ensuring the requirements of bearing capacity and serviceability is carried out mainly by direct calculation of transverse reinforcement or by additional constructive measures (installation of structural transverse reinforcement and reduction of the pitch of the main transverse reinforcement). However, the practice of operating reinforced concrete structures shows that this does not meet the requirement for the operational reliability of structures, which manifests itself in the form of their serious damage, especially in load-bearing reinforced concrete structures of buildings and structures – destruction by detachment of reinforced concrete trusses, ridges of gable beams, etc. In this regard, the study and development of a methodology for calculating reinforced concrete structures for tear-off, taking into account the criteria for the reliability of structures, is an urgent task and requires both theoretical and experimental confirmation.

The mechanism of destruction under local tensile forces (tearing) is very similar to the mechanism under local shearing (punching). At the same time, if for the latter continuous experimental and theoretical research is being conducted both in the Republic of Belarus and abroad and changes are constantly being introduced into calculation methods and regulatory documents, then research under the local action of tensile forces in recent decades has been reduced to studies of various anchor elements which work in the condition of the tear-out from the body of concrete or reinforced concrete elements, the mechanics of which differ from that of tearing-off.

**Analysis of methods for calculating the load-bearing capacity of reinforced concrete elements for tearing**

According to construction rules SP 5.03.01-2020 [1], checking the resistance of reinforced concrete elements according to maximum states of bearing capacity under local tension (tear-off) for the case of applying a load to the bottom edge or within the height of the element section (Figure 1) according to clause 8.4.2 is carried out from the condition:

$$F_{Ed} \cdot \left(1 - \frac{d_s}{d}\right) \le \sum \left(f_{ywd} \cdot A_{sw}\right), \qquad (1)$$

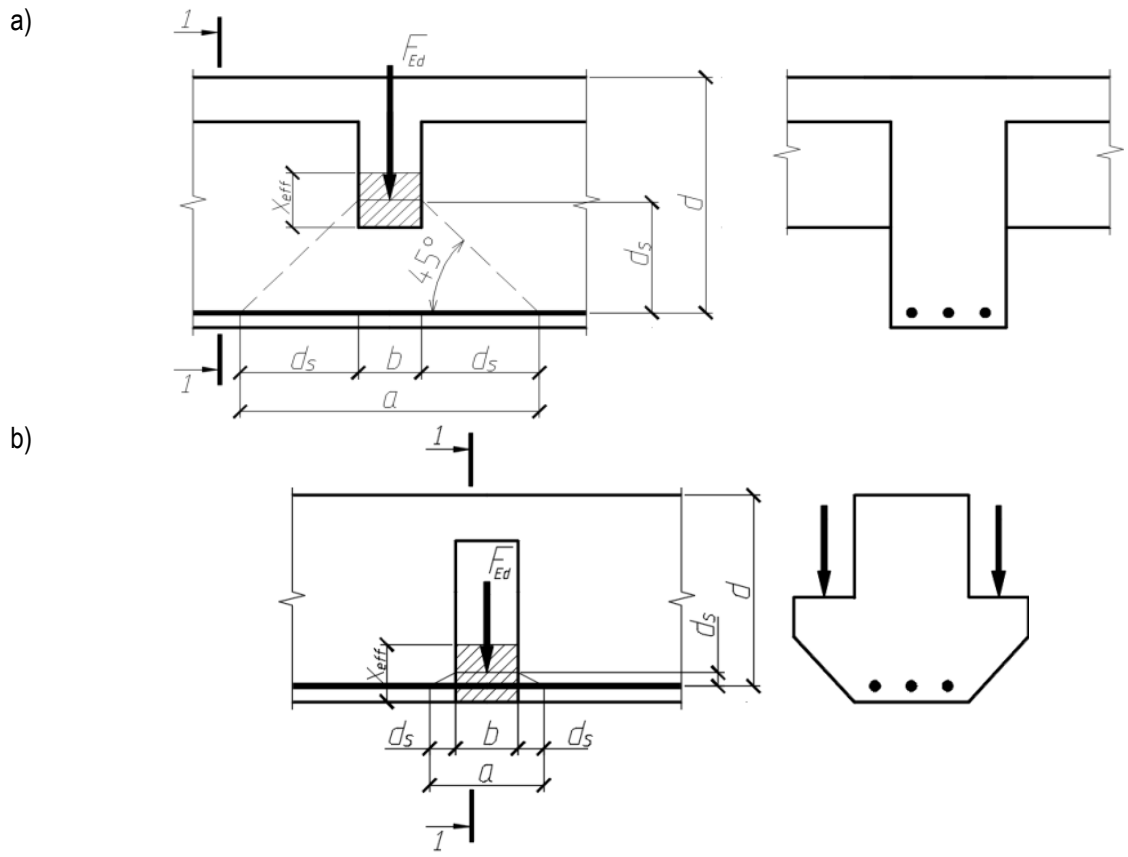
where $F_{Ed}$ – the calculated value of the tear-off force;

$d_s$ – the distance from the level of transmission of the tear-off force applied to the element to the center of gravity of the longitudinal reinforcement section;

$\sum \left(f_{ywd} \cdot A_{sw}\right)$ – the sum of transverse forces perceived by clamps installed additionally along the length of the tear-off zone *a*, determined by the formula:

$$a=2 \cdot d_s+b, \qquad (2)$$

where $b$ – the width of the area for transmitting the tear-off force.




$x_{eff}$ – size of the compressed concrete zone of the supported element

**Figure 1** – Diagram of determining the length of the tear-off zone, when abutted: a) – beams; b) – consoles [3]

The values of the parameters ds and a are established for each specific case and depend on the nature and conditions of application of the tear-off force on a reinforced concrete structure element (through consoles, adjacent elements, etc.). Based on the given calculation, in accordance with the load-bearing capacity requirements, the required amount of transverse reinforcement is established in shear zone.

In technical code for established practices TKP EN 1992-1-1-2009 [2], in accordance with clause 9.2.5, in the case of one beam resting on another beam in the area of the element intersection, installing additional reinforcement is required, which is designed to absorb the mutual reaction, while the supporting reinforcement is clamps, which embrace the longitudinal reinforcement of the support element, some of which may be located outside the volume of concrete which is common to the two beams (zone B, Figure 2). At the same time, the requirements for the diameter and spacing of clamps are not regulated in this normative document.

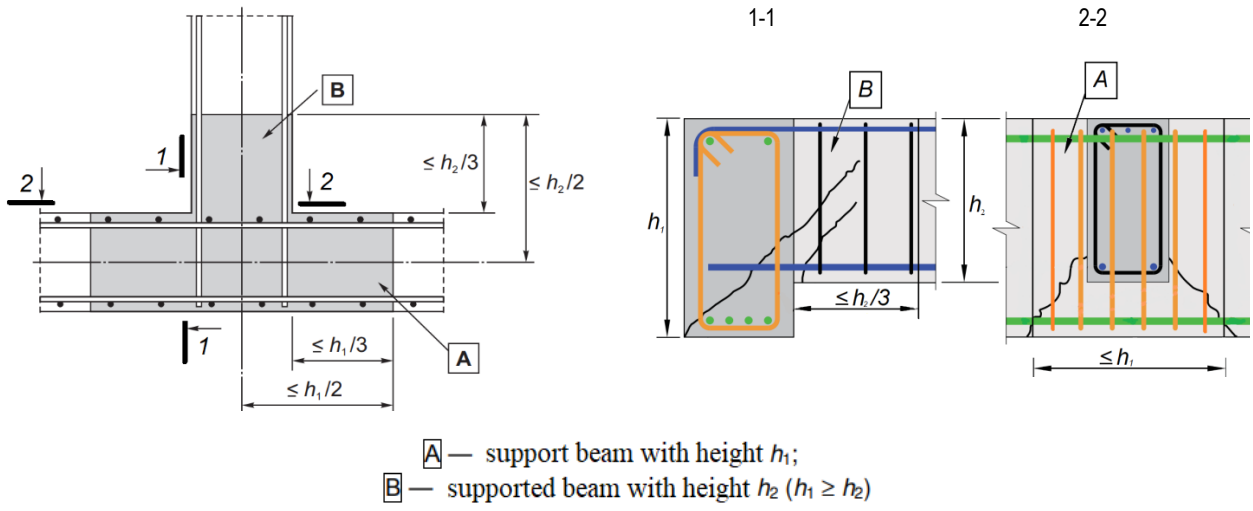



**Figure 2** – Placement of the support reinforcement in the area of the two beam intersection (plan view) [2]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Similar recommendations for the design of the junction of the main and secondary beams are contained in construction rules SP 63.13330.2018 which are current in the Russian Federation [clause 10.4.12, 4], which propose to install additional transverse reinforcement in the form of clamps which cover the longitudinal reinforcement to absorb the reaction from the secondary beam (Figure 3). In this case, in the main beam this reinforcement should be installed on a section $b+2h$ in length, in the secondary beam – on a section $h/3$ in length, where $b$ and h are the width and height of the secondary beam.

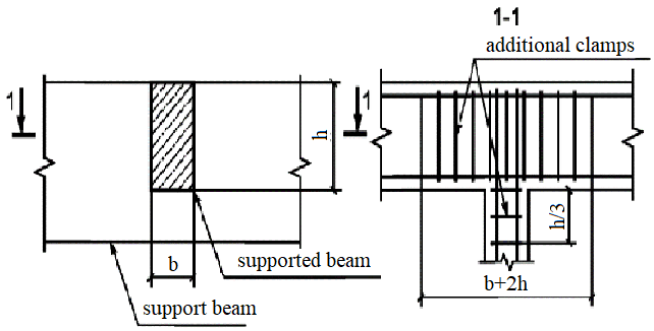



**Figure 3** – Placement of support reinforcement in the area of the two beam intersection [4]

American standards ACI 318R-19 [5] envisage the reinforcement with clamps of only the support (main) beam to absorb the reaction from the supported (secondary) beam in the place of their junction as shown in Figure 4. Additional reinforcement in the beam junction zone may be absent if the following condition is fulfilled:

$$V \le 3b_w d\sqrt{f_c'}, \quad (3)$$

where $f_c'$ – the specified compressive concrete strength;

$b_w$ – width of the supported beam;

$d$ – the effective height of the supported beam.

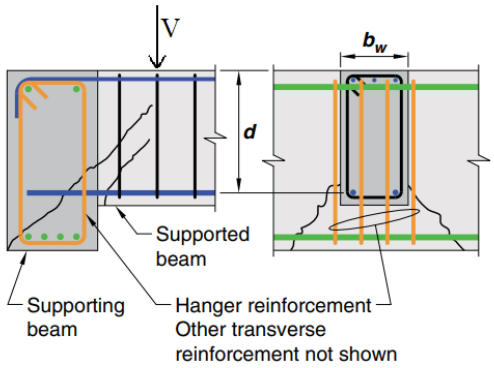



**Figure 4** – Diagram of the support beam reinforcement in the junction zone with the supported beam [5]

Canadian Standard CSA A23.3-04 [6] contains more detailed recommendations for additional transverse reinforcement of a support beam to accommodate the force transmitted from the supported beam, provided that the bottom edge of the given beam is not lower than the bottom edge of the support beam. In this case, the tensile force absorbed by the additional reinforcement is:

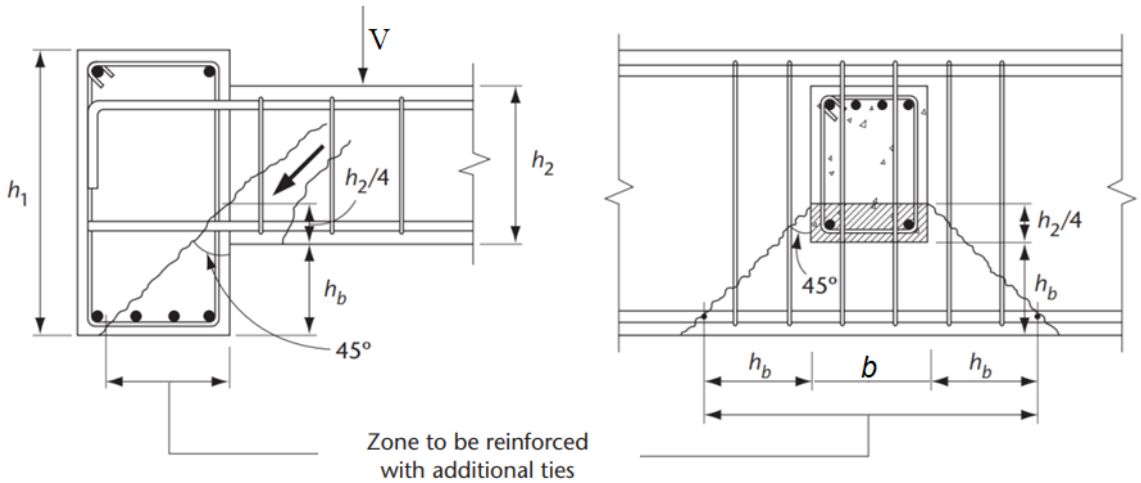
$$F = V \cdot \left(1 - \frac{h_b}{h_1}\right), \quad (4)$$

where $V$ – the transverse force on the prop of the support (main) beam (Figure 5);

$h_b$ – distance from the bottom edge of the supporting (main) beam to the bottom edge of the secondary beam;

$h_1$ – the supporting beam height.

Additional transverse reinforcement must be installed along the entire height of the support beam in such a way so as to cover the tear-off area formed by slanting cracks developing at an angle of 45° from the shear boundary located at a height $(\frac{1}{4})\cdot h_2$ from the bottom edge of the supported beam, to the bottom edge of the support beam.




$h_1$ – support beam height; $h_2$ – supported beam height; $h_b$ – distance from the bottom edge of the support beam to the bottom edge of the supported beam; $b$ – supported beam width

**Figure 5 –** Diagram of the location of additional transverse reinforcement under local action of tensile strength [6]

According to Canadian standards, additional reinforcement of the support beam in the junction area with the supported beam is not required in cases where:

1. the shear boundary passes above the upper edge support beam;
2. the average tangential stresses at the shear boundary exceed

$$\tau \le 0,23\lambda\varphi_c\sqrt{f_c'}, \quad (5)$$

where $\lambda$ – a coefficient that takes into account the performance characteristics of concrete, the density of which does not exceed 1850 kg/m3;

$\varphi_c$ – coefficient of concrete working conditions.

For the purpose of analyzing the factors influencing the actual size of the area where additional transverse reinforcement is installed, which are taken into account in various standards, we will consider three options for pairing the support and supported beams:

– option I – the heights of the main and secondary beams are equal (Figure 6, a);

– option II – the height of the main beam is greater than the height of the secondary beam and their upper edges coincide or the secondary beam is located within the height of the section of the main beam (Figure 6, b);

– option III – the height of the main beam is greater than the height of the secondary beam and their lower edges coincide (Figure 6, c).

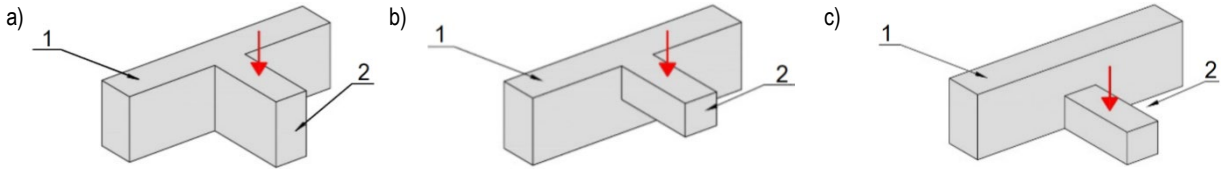



**Figure 6** – Options for the location of the main and secondary beams relative to each other [7]

For each of the above options for the relative arrangement of beams in accordance with the requirements of various standards, Table 1 shows the values of the zone size for installing additional reinforcement.

**Table 1** – Size of the area for installing additional transverse reinforcement

| No. | Name of the regulatory document | Size of additional transverse reinforcement area | | |
|---|---|---|---|---|
| | | Option I | Option II | Option III |
| 1 | SP 5.03.01-2020 [1-1] | $b+2d_s$ | | $b+2d_s$, где $d_s<h_2$ |
| 2 | TKP EN 1992-1-1-2009 [1-2] | $h_1/2$ | | |
| 3 | SP 63.13330.2018 [1-3] | $b+2h_2$ | | |
| 4 | ACI 318R-19 [1-4] | > b | | |
| 5 | CSAA23.3-04 [1-5] | $b+h_2/2$ | $b+2(h_2/4+h_b)$ | $b+h_2/2$ |

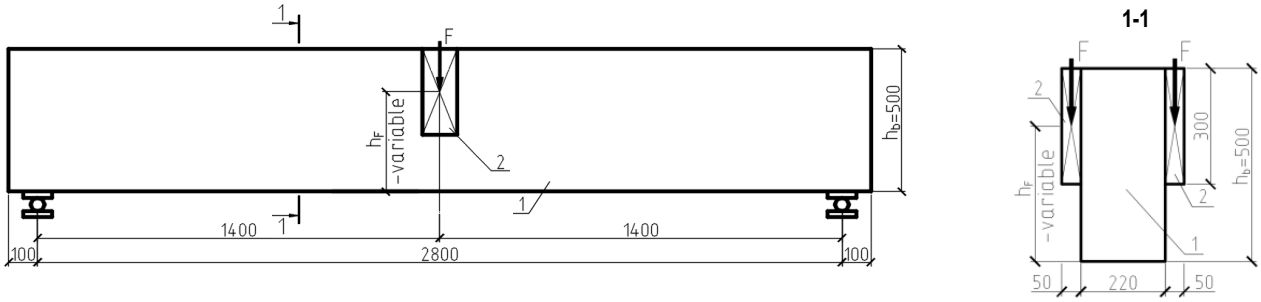
From the analysis of the data in Table 1, it was established that the size of the tear-off zone according to [2], [4] and [5] is not influenced by the relative position of the beams in height relative to each other, while the norms [1] and [6] take this feature into account. However, it is obvious that when calculating the tear-off load-bearing capacity, the location of the point of application of the tear-off force and the angle of inclination of the diagonal crack will be of no small importance.

It is also important to note that none of the considered regulatory documents takes into account the contribution of the concrete work to the tear-off resistance (tensile concrete work [8]), the influence of transverse reinforcement established on the basis of the general calculation of strength along slanting sections, pre-stressing forces, etc.

**Numerical study of the stress-strain state of the tear-off zone under local action of tensile forces**

To obtain data on the characteristics of the formation and development of cracks in the tear-off zone of reinforced concrete elements to which a local tensile force is applied, to reveal the dependence of the angle of inclination of the tear-off cracks and the size of the tear-off zone on the position of the point of application of the tear-off force, a numerical experiment was carried out using the "*Abaqus/CAE*" software complex, which implements finite element method [9].

Finite element analysis was carried out for a sample prepared for experimental research, the testing diagram and reinforcement of which are presented in the Figure 9.




1 – support beam; 2 – supported beam; $h_1$ – height of the support beam; $h_2$ – distance from the center of application of the tear-off force to the bottom edge of the support element

**Figure 9** – Test diagram


https://doi.org/10.36773/1818-1112-2023-132-3-35-40

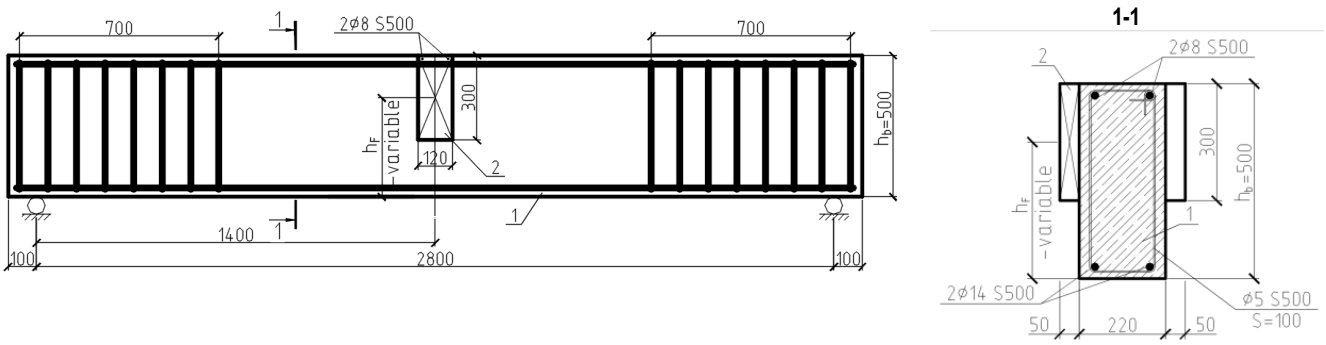



**Figure 10** – General view of the tested junction

The support beam is designed to provide bending resistance for the calculated value of the impact effects $F_u$ in accordance with [1].

In order to analyze the size of the tear-off zone in the case where the lifting load is perceived only by concrete, additional transverse reinforcement in the beam at the point where the tear-off force is transmitted, was not provided.

For numerical analysis, three diagrams of the junction of the supported and support beams (secondary and main) were simulated:

– I – the upper edges of the beams coincide ($h_F$ / $h_b$ = 0,7);

– II – the supported beam is located within the height of the support beam section ($h_F/h_b$=0,5);

– III – the lower edges of the beams coincide ($h_F$ / $h_b$ = 0,36).

Based on the results of numerical experiments, a picture of the stress-strain state in the separation zone and the distribution of tear-off cracks along the height of the section of the supporting element (main beam) were obtained for each of the coupling schemes (Figure 11).

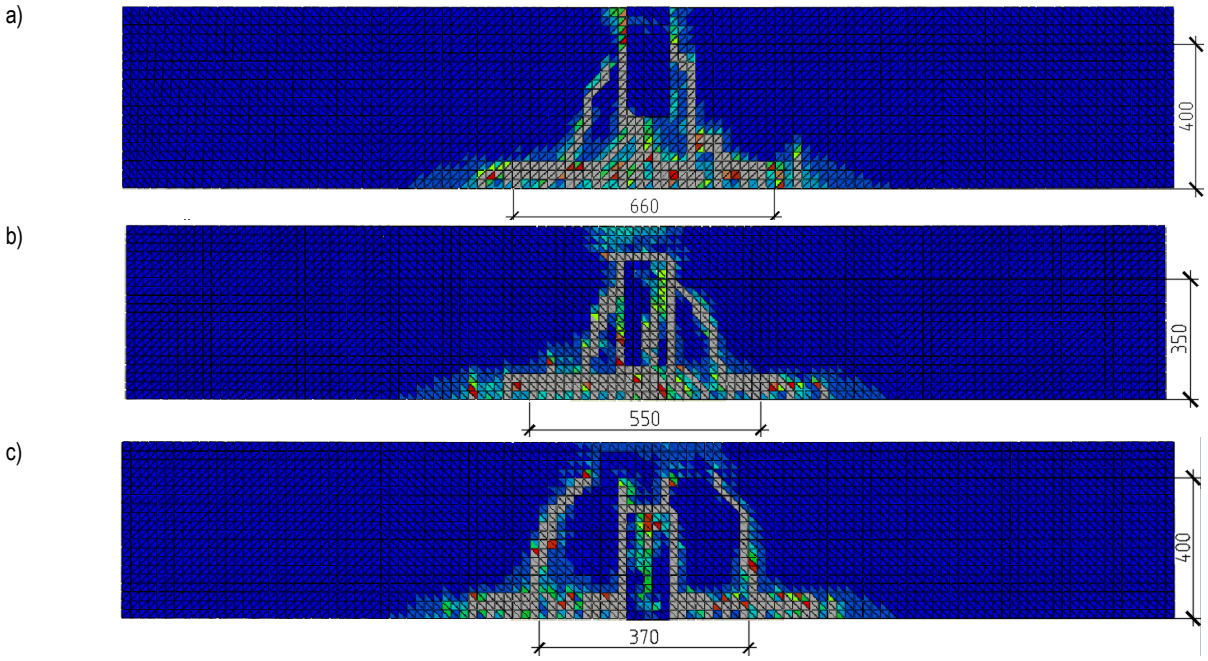



**Figure 11** – Distribution of cracks in the tear-off zone of the simulated beams

As a result of a numerical analysis, it was established that for schemes I and II of the pairing of beams, the first normal cracks in the support beams appeared in the zone of action of the maximum bending moment on the outermost tensile fibers at a load of $0,8F_{Ed,a1}$ and $0,8F_{Ed,a2}$ ($F_{Ed,a1}$ and $F_{Ed,a2}$ is the limiting value of the tear-off force for the first and second beam pairing diagrams, respectively), which is about $0,4F_u$. Further development of normal vertical cracks did not occur due to the perception of acting tensile forces by the longitudinal reinforcement of the tensile zone of the supporting beam. With an increase in load to $0,9F_{Ed,a1}$ and $0,9F_{Ed,a2}$, clearly defined diagonal cracks started in the tensile zone of concrete, oriented toward the center of application of the acting tear-off force. According to the results of the numerical experiment, the angle of inclination of the separation cracks for option I of the beam connection was 36° to the vertical (Figure 11, a), for option II – 31° (Figure 11, b), the dimensions of the tear-off zone are: 400 mm height and 660 mm length of the base of the separation pyramid for option I pairing of beams, and 350 mm and 550 mm – for option II.

Unlike the first two beam pairing diagrams, the third scheme has a different nature of destruction. A local crack in the tensile zone with increasing load has a clearly expressed appearance of a crack normal to the longitudinal axis of the element to the level of the top of the adjacent beam (Figure 11, c). Above the level of the adjacent beam, the crack deviates at an angle of 56° in the direction of the axis of application of the local calculated strength. The destruction occurred at a load of $0,85F_{Ed,a3}$ also as a result of the tear-off of a section of concrete in the form of a pyramid of 400 mm in height and a foundation of 370 mm in length.

The data obtained from the simulation results were compared with the sizes of the tear-off zones obtained by using the calculation methods given in the above-mentioned regulatory documents for each of the beam pairing options (Table 2).

**Table 2** – Calculation of the area for installing additional transverse reinforcement for numerical modeling samples

| No. | Name of the regulatory document | Size of the additional transverse reinforcement area, mm | | |
|---|---|---|---|---|
| | | Option I | Option II | Option III |
| 1 | SP 5.03.01-2020 [1-1] | 750* | 550* | 350* |
| 2 | TKP EN 1992-1-1-2009 [1-2] | ≤500 | ≤500 | ≤500 |
| 3 | SP 63.13330.2018 [1-3] | 720 | 720 | 720 |
| 4 | ACI 318R-19 [1-4] | ≥120 | ≥120 | ≥120 |
| 5 | CSAA23.3-04 [1-5] | 670 | 370 | 270 |
| 6 | Numerical model | 660 | 550 | 370 |
| Note. The center of gravity of the section of the supported beam is taken as the point of application of the tear-off force. | | | | |

As noted earlier, the calculation methods given in foreign regulatory documents [2], [4] and [5] regulate the size of the tear-off zone (installation of additional reinforcement) without reference to the relative position of the beams. While the standards [1] and [6] take into account the influence of the position of the point of application of the tear-off force: when the point of application of the tear-off force moves to the lower edge of the support beam, a gradual decrease in the size of the tear-off zone occurs, and the destruction has a clearly marked character of destruction along the normal section.

Taking into account the fact that the additional transverse reinforcement of the tear zone, provided that $d_s > 0$, accounts for only part of the tear-off force, equal to $F_{Ed} \cdot (1-d_s/d)$ [1], therefore $F_{Ed} \cdot d_s/d$ should be absorbed by the element without additional structural measures. In the process of numerical modeling of the operation of prototypes under the action of a tensile force applied locally, the inclusion of longitudinal reinforcement in the perception of tear-off force was established. From which it follows that when operating elements of reinforced concrete structures under the local action of tensile forces, it is necessary to take into account not only the contribution of the tensile concrete work and the influence of transverse reinforcement established on the basis of the general calculation of strength along slanting sections, but also the work of the longitudinal reinforcement of the element.

**Conclusions**

1. Methods for calculating elements of reinforced concrete structures for tear-off, given in domestic and foreign regulatory documents of the near and far abroad, for the most part, contain general requirements for installing additional structural transverse reinforcement of the main beam, and, as a rule, do not take into account the value of the current tear-off force, and also the tear-off work of concrete (tension) and the influence of transverse reinforcement established on the basis of the general calculation of strength along slanting sections.

2. Analysis of the numerical research data showed that the value of the tear-off force depends on the point of application of the tear-off force relative to the height of the section of the support beam. The results obtained are consistent with condition (1) given in [1], according to which the force perceived by additional transverse reinforcement in the tear-off zone increases when the point of application of the tear-off force is shifted to the lower edge of the element.

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# ASSESSMENT OF UNCERTAINTY MODEL OF RESTRAINED EXPANSION STRAINS OF FIBER REINFORCED SELF-STRESSING CONCRETE AT THE EXPANSION STAGE

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**Abstract**

The article presents an analysis of existing approaches to predicting the self-strains and stresses of self-stressing concrete. The main premises and equations of the modified strains development model for determining the self-strains and stresses of fiber reinforced self-stressing concrete at the expansion stage. This mutual influence model constrains the elements in three directions. The presented model was verified against the background of experimental data. An assessment of the model uncertainties of the modified strains development model of fiber reinforced self-stressing concrete on the 3rd, 7th, 14th and 28th day of concrete age is estimated.

The developed model is applicable for any composition of self-stressing concrete, as well as for various combinations of dispersed reinforcement.

**Keywords:** fiber reinforced self-stressing concrete, restrained expansion strains, self-stressing, volumetric constraint, modified strains development model, model uncertainty.

## ОЦЕНКА ОШИБКИ МОДЕЛИРОВАНИЯ СОБСТВЕННЫХ ДЕФОРМАЦИЙ НАПРЯГАЮЩЕГО ФИБРОБЕТОНА НА СТАДИИ РАСШИРЕНИЯ

**И. П. Павлова, И. В. Белкина, А. А. Лизогуб**

**Реферат**

В статье представлен анализ существующих подходов к прогнозированию собственных напряжений и связанных деформаций напрягающего бетона. Изложены основные предпосылки и уравнения модифицированной деформационной модели для определения собственных напряжений и связанных деформаций напрягающего фибробетона на стадии расширения. Представленная модель учитывает взаимное влияние ограничивающих элементов в трёх направлениях. Выполнена верификация представленной модели на фоне экспериментальных данных. Оценена ошибка моделирования собственных деформаций напрягающего фибробетона на 3-е, 7-е, 14-е и 28-е сутки возраста бетона.

Разработанная модель применима для любых составов напрягающего бетона, а также при различных комбинациях дисперсного армирования.

**Ключевые слова:** напрягающий фибробетон, собственные деформации, самонапряжение, объёмное ограничение, модифицированная деформационная модель, ошибка моделирования.

**Introduction**

Self-stressing concretes occupy a special place in the field of concrete science. The variety of ways to create expansion has led to the emergence of more than 50 types of expansive concretes. Concrete based on alumina cement, as well as Portland cement using sulfoaluminate expanding additives, are widely known. These concretes are used in road surfaces, floors, foundations and massive structures. The main advantage of using this type of concrete is multitasking. During the hardening process, expansion can not only compensate for chemical shrinkage, but also create prestress under construction conditions without prestressing the reinforcement bars. Concrete with expanding binders has high corrosion resistance, waterproofing capacity and frost resistance [1].

However, the use of self-stressing concrete is still quite limited and causes a lot of discussion. Despite the unique properties, instability of compositions remains one of the main problems. Thus, the impossibility of completely eliminating late recrystallization of highly basic calcium hydrosulfoaluminates negatively affects the final properties of the composite. Some patterns of processes occurring in self-stressing concrete remain unexplored to this day.

The lack of reliable models for predicting expansion strains of self-stressing concrete has led to a situation where the main research method is experiment. With this approach, it is quite difficult to establish the cause of failure: incorrectly selected compositions or unforeseen negative processes in concrete during hardening and (or) operation.

One of the problems with expandable composites is unlimited expansion. This process is most dangerous in the later stages of hardening, as it leads to cracking in the cement matrix and a decrease in the strength of the material. The purpose of self-stressing concrete is to create prestresses, which implies some restraints that solve the above problems. As a limiter, various types of rod reinforcement are used, which are placed in one or several planes of the structure. Self-stressing concrete is most effective in structures with triaxial or spatial constraints. Such reinforcement is most often used in floors, slabs, bridges, and pipe concrete.

The next question was to determine the amount of reinforcement needed to achieve the required self-stressing values. At the moment, there is no universal approach to determining self-strains and stresses. Most methods are valid only for the case of uniaxial reinforcement, for example, proposed by the founder of the scientific school “Concrete with expanding binders and structures made from them”, Professor V.V. Mikhailov [2] or the approach set out in regulatory documents (STB 1335, STB 2101).

Prediction of self-strains and stresses for the case of uniaxial constraint is considered in [3]. Scientists from Belarus [4–6], under the guidance of a professor Tur V.V., modified the existing deformation model [3] of self-stressing concrete for the case of uniaxial asymmetrical reinforcement [4], and biaxial constraint [5, 6].

With the development of self-stressing concrete, approaches to controlling processes in its structure have also improved. Researchers have been trying to find a way to reduce the negative effects of expansion and simultaneous declines in strength. Such modifications led to the emergence of self-stressing fiber-reinforced concrete. At first, fiber was used as an addition to rod reinforcement, but at the moment dispersed fiber reinforcement is considered as an independent spatial constraint [7–10].

**The aim of the article** is to present and verify a model for predicting the self-strains and stresses of fiber reinforced self-stressing concrete at the expansion stage.

**MSDM for different types of self-stressing concrete restraint.** There are many approaches to determining restrained expansion strains and stresses in self-stressing concrete. A detailed review of studies on this theme is presented in [11]. Recently, much attention has been paid to models based on the deformation approach [3, 6, 11–16]. The basic provisions of the deformation model of an expanding composite system for different levels of modeling are considered in [12].

In 2004, Ito et al. [3] proposed a model for determining the self-stress of uniaxially reinforced prestressed beams based on the finite element method, which took into account the principle of superposition and the linear dependence of stresses on strains and estimated the stresses and strains of concrete under constrained conditions using Young's modulus models, creep coefficient, changes in autogenous shrinkage and temperature. The proposed method modeled the behavior of stressed concrete beams with high accuracy. At the same time, the model did not take into account the influence of the reaction that occurs in the elastic constraint at the next stages of strain growth.

Subsequently, the authors [11, 13] proposed a deformation model for calculating restrained expansion strains (self-stresses) in elements made of prestressing concrete, based on the hypothesis of the compatibility of deformations, equilibrium conditions and physical laws describing the behavior of self-stressing concrete at an early age, in which, in contrast to [3], the influence in the limiting relation ($\Delta F$) is taken into account (Figure 1).

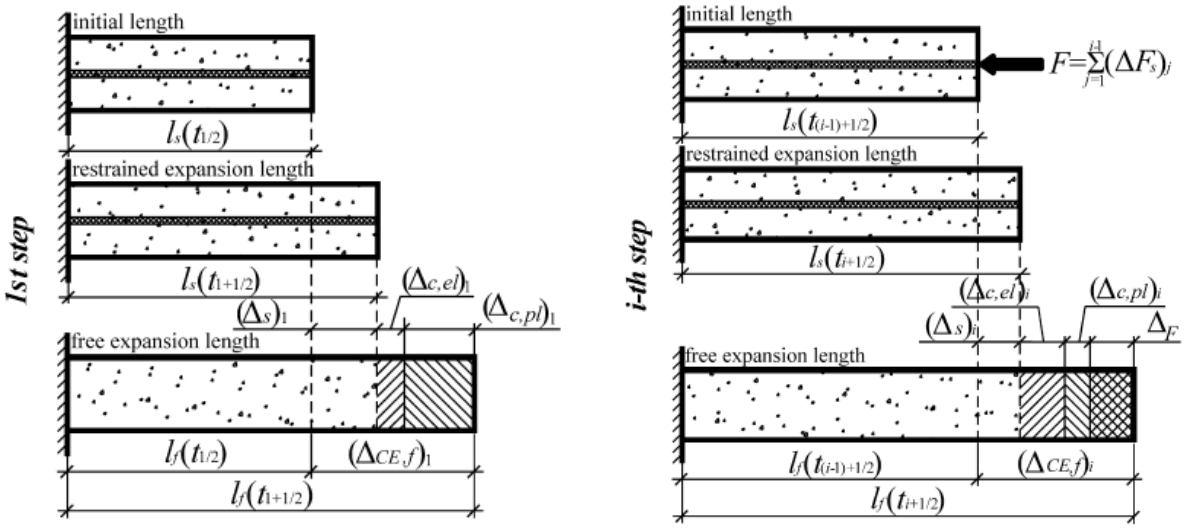


**Figure 1** – Scheme of expansion development under uniaxial symmetrical finite stiffness restraint conditions [13]

The next stage in the development of the deformation model was the transition from structures with uniaxially constrained self-stressing concrete to the case of biaxial constraint. The authors of [6] developed a modified model (2D MSDM) to evaluate the stress and strain parameters of biaxially constrained tensioned concrete elements at an early age, which makes it possible to determine the associated strains and the corresponding self-stresses under arbitrary constraint conditions in orthogonal directions, taking into account the elastoplastic behavior of concrete on expansion stages (Figure 2). A distinctive feature of the proposed analytical model is the consideration of the mutual influence of limiting constraints by introducing Poisson's ratio for concrete at an early age to the selected elastic strains of concrete.

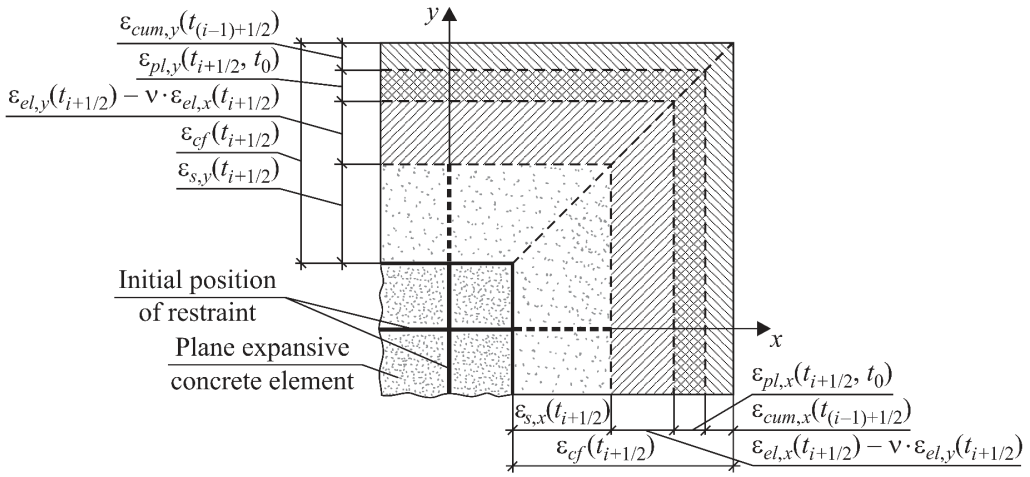


**Figure 2** – Development of strains in the plane expansive concrete element [6]

The final possible option for limiting tension concrete in a structure is a tri-axial (volumetric) constraint. One example of such a constraint is the expansive concrete-filled steel tube (ECFST) structure. The model developed in [14] took into account all previous modifications. However, it is important to note that the radial stress in the steel pipe is not taken into account and the pipe material is in a biaxial stress state (Figure 3).

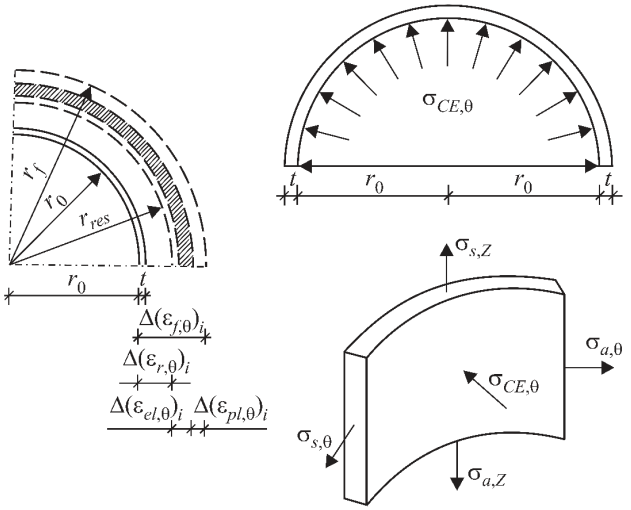


**Figure 3** – Scheme of incremental approach in proposed MSDM for expansive concrete-filled steel tube [14]

**Premises and assumptions of the modified strains development model for the case of a triaxial constraint.** As mentioned above, often FRSSC is usually considered as a modified self-stressing concrete with bar reinforcement. However, this approach to the determination of strains is not correct, since FRSSC represents the following structure – self-stressing concrete with micro-reinforcement. The hypothesis we propose (taking into account the provisions of [3, 6, 12–15]) is as follows:

1. The calculation model is based on the premise that self-stressing fiber reinforced concrete can be represented as a sphere of an expansive concrete core and a homogeneous shell of constant thickness covering it, consisting of fiber material (Figure 4).
2. The ratio of the shell thickness to the radius of the sphere is proportional to the fiber consumption per unit volume of concrete.
3. The shell is connected to the core and does not slip over the concrete surface when the sphere is deformed.
4. The internal forces arising in the expanding concrete core and the internal forces arising in the shell constraining it are mutually balanced.
5. When the sphere of self-stressing concrete expands with radius $r$, the shell perceives a radial uniformly distributed load $q$, as a result, circumferential (equatorial) and meridional stresses arise in the plane of the shell with thick-ness $t$, which due to spherical symmetry, are equal to $\sigma_t = \sigma_m = \sigma$:

$$\sigma = \frac{qr}{2t}. \tag{1}$$

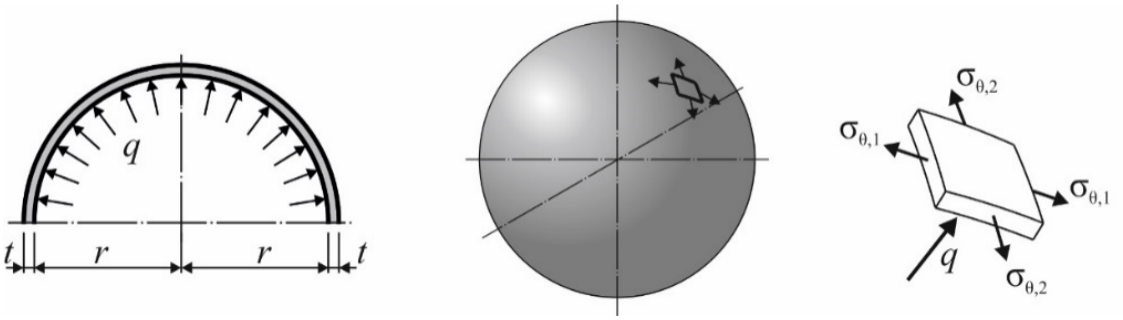


**Figure 4** – Scheme of a spherical shell made of fiber with stresses $\sigma_t$ and $\sigma_m$ arising in it from the action of a radial uniformly distributed load $q$

The circumferential strain $\varepsilon_t$ and the meridional strain $\varepsilon_m$ equal to it are determined in accordance with Hooke's law:

$$\varepsilon_t = \frac{1}{E_s}\cdot\left(\sigma_t - \sigma_m \cdot \mu_s\right);$$
$$\varepsilon_m = \frac{1}{E_s}\cdot\left(\sigma_m - \sigma_t \cdot \mu_s\right). \tag{2}$$

Taking into account the equality $\varepsilon_t = \varepsilon_m = \varepsilon_r$, the strain $\varepsilon_r$ will take the form:

$$\varepsilon_r = \frac{\sigma}{E_s}\cdot\left(1-\mu_s\right), \tag{3}$$

where $\mu_s$ is Poisson's ratio for the shell material; $E_s$ is the modulus of elasticity of the shell material.

6. The expansion of the self-stressing concrete core is uniform in all directions.

7. When determining the elastic strains of self-stressing concrete, the volumetric expansion is taken into account by introducing the Poisson's ratio for concrete at an early age, taken $\mu = 0{,}2$.

8. The restrained expansion strains $\varepsilon_r$ for each orthogonal direction (*X, Y, Z*) are determined by subtracting from the free expansion strains $\varepsilon_{cf}$ the elastic and inelastic strains due to concrete creep ($\varepsilon_{c,el} + \varepsilon_{ac,pl}$), as well as the elastic strains in as a result of the additional elastic constraint reaction $\varepsilon_{acc}$.

To determine the stresses from the action of a radial uniformly distributed load $q$, we use the solution of the problem of a thin-walled spherical shell (Figure 4) loaded with an internal uniform pressure.

From the Laplace equation, we obtain the stresses arising in the shell:

$$q = \sigma_{cf} = \frac{2t}{r}\cdot\sigma_m; \quad \sigma_m = \frac{E_s}{1-\mu_s}\cdot\varepsilon_m;$$
$$q = \sigma_{cf} = \frac{2t}{r}\cdot\sigma_t; \quad \sigma_t = \frac{E_s}{1-\mu_s}\cdot\varepsilon_t. \tag{4}$$

Considering that $\sigma_m = \sigma_t = \sigma$, $\varepsilon_m = \varepsilon_t = \varepsilon$ and assuming that $\varepsilon = \varepsilon_{cr}$, we get:

$$\left(\Delta\sigma_{cf}\right)_i = \frac{2t}{r}\cdot\frac{E}{1-\mu_s}\cdot\left(\Delta\varepsilon_r\right)_i. \quad (5)$$

In the general case, the increment of the restrained expansion strain $\left(\Delta\varepsilon_r\right)_i$ on an arbitrary *i*-th time interval can be represented as follows (Figure 5):

$$\left(\Delta\varepsilon_r\right)_i = \left(\Delta\varepsilon_f\right)_i - \left(\Delta\varepsilon_{el}\right)_i - \left(\Delta\varepsilon_{pl}\right)_i - \left(\Delta\varepsilon_{acc}\right)_i, \quad (6)$$

where $\left(\Delta\varepsilon_f\right)_i$ – increment free expansion strain on arbitrary *i*-th time interval;

$\left(\Delta\varepsilon_{el}\right)_i$ – increment of elastic strain on arbitrary *i*-th time interval;

$\left(\Delta\varepsilon_{pl}\right)_i$ – increment of plastic strain on arbitrary *i*-th time interval;

$\left(\Delta\varepsilon_{acc}\right)_i$ – increment of elastic strain as a result of the action of the elastic constraint reaction on an arbitrary *i*-th time interval.

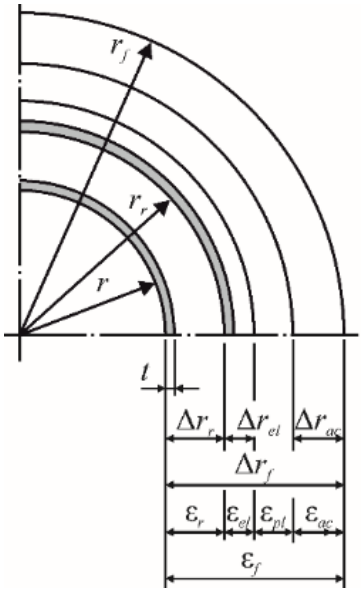


**Figure 5** – Scheme of development of expansion strains in time

The sum of increments of elastic $\left(\Delta\varepsilon_{el}\right)_i$ and plastic $\left(\Delta\varepsilon_{pl}\right)_i$ relative strains on an arbitrary *i*-th time interval can be represented as:

$$\left(\Delta\varepsilon_{el}\right)_i + \left(\Delta\varepsilon_{pl}\right)_i = \left(\Delta\sigma_{cf}\right)_i \cdot J\left(t_{i+1/2};t_i\right) + \sum_{j=1}^{i-1}\left[\left(\Delta\sigma_{cf}\right)_j \cdot \frac{\Delta\phi\left(t_i;t_j\right)}{E_{cm,28}}\right], \quad (7)$$

where $J\left(t_{i+1/2};t_j\right)$ is the concrete creep function:

$$J\left(t_{i+1/2};t_j\right) = \frac{1}{E_c\left(t_j\right)} + \frac{\phi\left(t_{i+1/2};t_j\right)}{E_{cm,28}}, \quad (8)$$

where $E_c\left(t\right)$ is the modulus of elasticity of concrete at a modified age corresponding to the actual age of concrete $t_j$:

$E_{cm,28}$ is the modulus of elasticity of concrete, corresponding to 28 days of the actual age of concrete;

$\Delta\phi\left(t_i;t_j\right)$ is increment of the concrete creep coefficient on an arbitrary *i*-th time interval:

$$\Delta\phi\left(t_i;t_j\right) = \phi\left(t_{i+1/2};t_j\right) - \phi\left(t_{(i-1)+1/2};t_j\right). \quad (9)$$

Modified age of concrete $t_i$, corresponding to *t* days of the real age of concrete, taking into account the influence of the temperature regime at the stage of hardening and expansion of concrete:

$$t_i = \sum_{j=1}^{n}\Delta t_j \cdot e^{13{,}65 - \frac{4000}{273+T(\Delta t_j)/T_0}}, \quad (10)$$

where $\Delta t_j$ is the number of day(s) with temperature *T* (°C); $T_0$ = 1°C.

The modulus of elasticity of concrete at a modified age corresponding to the actual age of concrete $t_j$ can be derived from:

$$E_c\left(t\right) = E_{cm,28}\cdot\exp\left\{s\left[1-\left(\frac{t_{m,28}-a}{t_i-a}\right)^{0,5}\right]\right\}, \quad (11)$$

where $s$ is an empirical coefficient that takes into account the type of binder; $a$ is an empirical coefficient that takes into account the effect of the concrete setting start time.

The concrete creep coefficient $\phi\left(t;t_0\right)$ is calculated using the following formula:

$$\phi\left(t;t_0\right) = \phi_0 \cdot \beta\left(t;t_0\right), \quad (12)$$

where $\phi_0$ is the notional creep coefficient;

$$\phi_0 = 5{,}31\cdot\left[\frac{E_c\left(t_0\right)}{E_{cm,28}} - 1{,}0\right]^2 + 1{,}11, \quad (13)$$

where $\beta_c\left(t,t_0\right)$ is the coefficient describing the development of creep over time after loading.

$$\beta_c\left(t,t_0\right) = \frac{\left(t-t_0\right)}{\beta_H + \left(t-t_0\right)}, \quad (14)$$

$\beta_H$ is the coefficient that takes into account the influence of concrete age:

$$\beta_H \Leftarrow \begin{cases} 0 \le E_c\left(t\right)/E_{cm,28} < 0{,}346; \\ \beta_H = 0{,}000001; \\ 0{,}346 \le E_c\left(t\right)/E_{cm,28} < 1; \\ \beta_H = 40{,}5\cdot\left[E_c\left(t\right)/E_{cm,28} - 0{,}346\right] + 0{,}485. \end{cases} \quad (15)$$


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The increments of elastic strain $\left(\Delta\varepsilon_{acc}\right)_i$ as a result of the action of the elastic constraint reaction on an arbitrary *i*-th time interval can be represented as:

$$\left(\Delta\varepsilon_{acc}\right)_i = \sum_{j=1}^{i-1}\left[\frac{\left(\Delta\sigma_{cf}\right)_j}{E_{cm}\left(t_j\right)}\right]\cdot\frac{E_{cm,aw}\left(t_{(i-1)+1/2}\right)}{E_{cm}\left(t_{(i-1)+1/2}\right)}, \quad (16)$$

where $E_{cm,aw}\left(t_{i+1/2}\right)$ is weight-average modulus of elasticity of self-stressing concrete by the end of the *i*-th elementary time interval:

$$E_{cm,aw}\left(t_{i+1/2}\right) = \frac{\sum_{j=1}^{i}\left(\Delta\sigma_{cf}\right)_j\cdot E_c\left(t_j\right)}{\sum_{j=1}^{n}\left(\Delta\sigma_{cf}\right)_j}, \quad (17)$$

where $\left(\Delta\sigma_{cf}\right)_j$ is the increment of the self-stress value on the *j*-th elementary time interval;

$E_c\left(t_j\right)$ is the modulus of elasticity of the self-stressing concrete at the modified age corresponding to the real age $t_j$;

$E_c\left(t_{i+1/2}\right)$ is the modulus of elasticity of the self-stressing concrete at the modified age corresponding to the real age of the self-stressing concrete $t_{i+1/2}$, which corresponds to the end of the *i*-th elementary time interval under consideration.

Solving together (5) and (6) for each orthogonal direction (*X, Y, Z*), we obtain increments of intrinsic associated strains at each *i*-th time interval:

$$\begin{cases}\left(\Delta\sigma_{cf,x}\right)_i = \dfrac{2t}{r}\cdot\dfrac{E_s}{1-\mu_s}\cdot\left(\Delta\varepsilon_{r,x}\right)_i;\\ \left(\Delta\sigma_{cf,y}\right)_i = \dfrac{2t}{r}\cdot\dfrac{E_s}{1-\mu_s}\cdot\left(\Delta\varepsilon_{r,y}\right)_i;\\ \left(\Delta\sigma_{cf,z}\right)_i = \dfrac{2t}{r}\cdot\dfrac{E_s}{1-\mu_s}\cdot\left(\Delta\varepsilon_{r,z}\right)_i.\end{cases} \quad (18)$$

$$\begin{cases}\left(\Delta\varepsilon_{r,x}\right)_i = \left(\Delta\varepsilon_{f,x}\right)_i - \left[\left(\Delta\sigma_{cf,x}\right)_i - \mu_c\cdot\left(\Delta\sigma_{cf,y}\right)_i - \mu_c\cdot\left(\Delta\sigma_{cf,z}\right)_i\right]\cdot J\left(t_{i+1/2};t_i\right) -\\ -\sum_{j=1}^{i-1}\left[\left(\Delta\sigma_{cf,x}\right)_j\cdot\frac{\Delta\phi\left(t_i;t_j\right)}{E_{cm,28}}\right] - \sum_{j=1}^{i-1}\left[\frac{\left(\Delta\sigma_{cf,x}\right)_j}{E_{cm}\left(t_j\right)}\right]\cdot\frac{E_{cm,aw}\left(t_{(i-1)+1/2}\right)}{E_{cm}\left(t_{(i-1)+1/2}\right)};\\ \left(\Delta\varepsilon_{r,y}\right)_i = \left(\Delta\varepsilon_{f,y}\right)_i - \left[\left(\Delta\sigma_{cf,y}\right)_i - \mu_c\cdot\left(\Delta\sigma_{cf,x}\right)_i - \mu_c\cdot\left(\Delta\sigma_{cf,z}\right)_i\right]\cdot J\left(t_{i+1/2};t_i\right) -\\ -\sum_{j=1}^{i-1}\left[\left(\Delta\sigma_{cf,y}\right)_j\cdot\frac{\Delta\phi\left(t_i;t_j\right)}{E_{cm,28}}\right] - \sum_{j=1}^{i-1}\left[\frac{\left(\Delta\sigma_{cf,y}\right)_j}{E_{cm}\left(t_j\right)}\right]\cdot\frac{E_{cm,aw}\left(t_{(i-1)+1/2}\right)}{E_{cm}\left(t_{(i-1)+1/2}\right)};\\ \left(\Delta\varepsilon_{r,z}\right)_i = \left(\Delta\varepsilon_{f,z}\right)_i - \left[\left(\Delta\sigma_{cf,z}\right)_i - \mu_c\cdot\left(\Delta\sigma_{cf,x}\right)_i - \mu_c\cdot\left(\Delta\sigma_{cf,y}\right)_i\right]\cdot J\left(t_{i+1/2};t_i\right) -\\ -\sum_{j=1}^{i-1}\left[\left(\Delta\sigma_{cf,z}\right)_j\cdot\frac{\Delta\phi\left(t_i;t_j\right)}{E_{cm,28}}\right] - \sum_{j=1}^{i-1}\left[\frac{\left(\Delta\sigma_{cf,z}\right)_j}{E_{cm}\left(t_j\right)}\right]\cdot\frac{E_{cm,aw}\left(t_{(i-1)+1/2}\right)}{E_{cm}\left(t_{(i-1)+1/2}\right)}.\end{cases} \quad (19)$$

Due to the spherical symmetry, the systems of equations (18) and (19) for each orthogonal direction (*X, Y, Z*) can be represented as two equations:

$$\left(\Delta\sigma_{cf}\right)_i = \frac{2t}{r}\cdot\frac{E_s}{1-\mu_s}\cdot\left(\Delta\varepsilon_r\right)_i; \quad (20)$$

$$\left(\Delta\varepsilon_r\right)_i = \left(\Delta\varepsilon_f\right)_i - \left(\Delta\sigma_{cf}\right)_i\cdot\left(1-2\mu_c\right)\cdot J\left(t_{i+1/2};t_i\right) - \sum_{j=1}^{i-1}\left[\left(\Delta\sigma_{cf}\right)_j\cdot\frac{\Delta\phi\left(t_i;t_j\right)}{E_{cm,28}}\right] - \sum_{j=1}^{i-1}\left[\frac{\left(\Delta\sigma_{cf}\right)_j}{E_{cm}\left(t_j\right)}\right]\cdot\frac{E_{cm,aw}\left(t_{(i-1)+1/2}\right)}{E_{cm}\left(t_{(i-1)+1/2}\right)}. \quad (21)$$

**Results and discussion.** To test the main provisions of the model, we used a sample that consisted of data presented in studies [16–18]. Based on the initial data, the values of the associated expansion strains were calculated, which were then compared with the experimental results. To assess the model uncertainties of the computational model, graphs were constructed (Figure 6), which show the values of restrained expansion strains ($\varepsilon_{r,calc.}$) calculated by the model on the 3rd, 7th, 14th and 28th days in relation to the corresponding experimental data ($\varepsilon_{r,exp.}$).

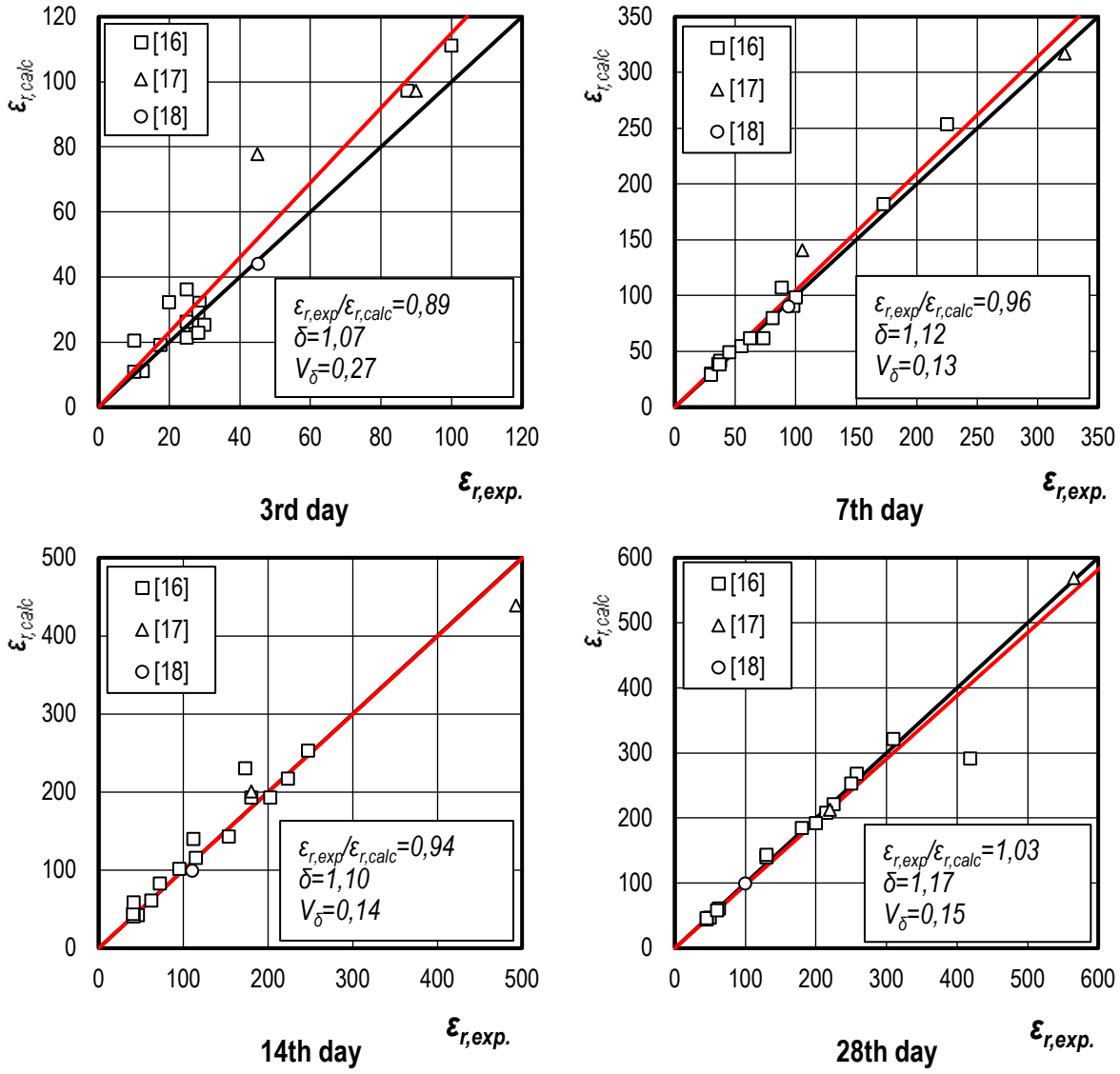


**Figure 6** – Assessment of uncertainty model of restrained expansion strains of fiber reinforced self-stressing concrete at the expansion stage

As follows from Figure 6, the largest scatter between theoretical and experimental data occurs at the early age of concrete – day 3, where the coefficient of variation for the model uncertainties was 27 %. This is explained by the instability of the expansion and shrinkage processes occurring during the period of active action of the expanding additive, which is quite difficult to describe with a model. However, by the time of stabilization, the coefficient of variation decreases (15 %), which indicates more reliable results.

**Conclusion**

The modified analytical model has been developed to determine the restrained expansion stresses and strains at the stage of expansion of self-stressing concrete under conditions of spatial limitation of free strains by dispersed reinforcing elements of arbitrary stiffness. The proposed model differs from existing models in that it takes into account the mutual influence of limiting elements in three directions in the calculations by introducing Poisson's ratio for concrete to the selected elastic strains of concrete. This makes it possible to determine stresses in concrete and strains in the limiting element, represented by dispersed reinforcement, in an arbitrary time interval until the stabilization of free expansion. The model is able to determine the required amount of dispersed reinforcement by the specified values of the restrained expansion strains. The developed analytical model is applicable for every mixes of self-stressing concrete, as well as for various combinations of dispersed reinforcement.

The proposed modified strains development model is quite universal and covers a significant list of compositions suitable for research. It can be concluded that the model allows one to calculate the associated expansion strains of self-stressing fiber-reinforced concrete with a sufficient degree of accuracy. The identified deviations in the experimental and calculated values of strains should be associated with uncertainties in modeling the characteristics of materials.

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# MICROSTRUCTURE DEVELOPMENT OF THE CEMENT PASTE BASED ON THE UNIT CELL MODEL

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**Abstract**

Microstructure development of the cement paste is closely associated with internal processes such as self-desiccation, shrinkage, creep and other internal processes throughout service life of cement-based materials. The ability to accurately model microstructure parameters is key to predicting internal processes of the cement paste.

Currently, the most frequently used approaches to microstructural modeling of cement paste are vector and discrete. Both approaches generate and process a random structure of the cement paste, but at the same time are characterized by high computational complexity and time-consuming. It accounts for the fact, that simplified structural models still remain relevant. A unit cell model, which can be considered as a particular case of the vector approach, is a geometrically simple model that describes microstructure development based on a representative hydrated cement particle.

The paper presents an advanced microstructural model of the cement paste based on the unit cell model.

**Keywords:** cement paste, hydration model, unit cell, pore size distribution, percolation threshold.

## МОДЕЛИРОВАНИЕ МИКРОСТРУКТУРЫ ЦЕМЕНТНОГО КАМНЯ НА ОСНОВЕ МОДЕЛИ ЭЛЕМЕНТАРНОЙ ЯЧЕЙКИ

**В. В. Кравченко**

**Реферат**

Развитие микроструктуры цементного камня тесно связано с такими внутренними процессами, как самовысыхание, усадка, ползучесть и другими процессами на протяжении всего срока службы материалов на основе цемента. Способность точно моделировать параметры микроструктуры является основой прогнозирования внутренних процессов цементного камня.

В настоящее время наиболее часто используемыми подходами к моделированию микроструктуры цементного камня являются векторный и дискретный. Оба подхода генерируют и обрабатывают случайную структуру цементного камня, но в то же время характеризуются высокой вычислительной сложностью и как следствие значительными затратами времени. С точки зрения численного моделирования предпочтительными являются простые в расчетах модели, достаточные для оценки необходимых параметров микроструктуры. Это обуславливает тот факт, что упрощенные модели микроструктуры цементного камня по-прежнему остаются актуальными. Модель элементарной ячейки, которую можно рассматривать как частный случай векторного подхода, представляет собой геометрически простую модель, описывающую развитие микроструктуры на основе репрезентативной гидратирующей частицы цемента.

В статье представлена усовершенствованная модель микроструктуры цементного камня, основанная на модели элементарной ячейки.

**Ключевые слова:** цементный камень, модель гидратации, элементарная ячейка, распределение пор по размерам, порог перколяции.

### Introduction

The cement paste is a crucial phase of cement-based composites whose structure is formed as a result of chemical reactions between cement clinker and water, called a hydration process. During hydration, the cement paste of a plastic consistency turns into a porous solid. Basic properties of cement-based materials, such as mechanical and transport properties, depend heavily on the formed microstructure of the cement paste.

The most effective way to research the microstructure of the cement paste over time is modelling and simulation. Modelling and simulation, taken together, comprise a spectrum of activities that enable the researcher or engineer to compare observations with theory, to extract physical parameters from experimental data, and to predict system behaviors [1].

Despite the fact that a sufficient number of models exist, it remains hard to accurately predict microstructure development of the cement paste due to its extremely complexity.

There are two approaches in modelling microstructure development of the cement paste: discretization and continuous (also called vector) approach.

In the discretization approach the microstructure of the cement paste is approximated as a set of pixels (in two dimensions) or voxels (in three dimensions). Each pixel (voxel) is associated with a specific phase of the cement paste. The key idea of the discretization approach is that at an arbitrary time-step, any pixel (voxel) in a system can change a pre-defined phase state and update it to another according to the taken hydration model. One of the most widely used discretization models was developed at NIST and called CEMHYD3D [2].

In the continuous approach the microstructure of the cement paste is approximated as a set of inclusions in the form of circles (in two dimensions) or spheres (in three dimensions) randomly placed in a representative volume. The circles (spheres) represent an anhydrous phase, and the space between them represents porosity. The hydrate phase appears over time as a layer around each circle (sphere). The key idea of the continuous approach is that at arbitrary time-step, the initial area (volume) of the circles (spheres) in a system decreases, while the hydrate layer increases according to the taken hydration model.

The set of inclusions can consist of either many polydisperse circles (spheres) or a single circle (sphere). The poly-dispersed structure is more preferable, but also much more computationally expensive primarily due to the calculation of the circles (spheres) overlap. Such a structure is used in HYMOSTRUC [3] and μic [4] models.

Meanwhile, there are many observations that point to the agglomeration and flocculation of cement particles, which might result from the adherence of smaller powder particles to the larger ones. In such a case, the average size of the flocculated particles can be considered as the representative size of the particle [5]. DuCOM [5] and unit cell [6] models are based on this idea. Besides, this approach is characterized by a significant reduction in computational costs compared to the polydisperse structure.

This paper presents an advanced microstructural model of the cement paste based on the unit cell model originally described in [6].


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**Hydration model**

A modern model of cement hydration is a complex model that includes at least two parts:

1) Hydration kinetics model.

2) Predicting the volume fractions of the cement paste phases over hydration time.

There are a sufficient number of hydration kinetics models, but all of them are phenomenological. Among the existing models, the Parrot and Killoh model was taken, which provides both sound and practical in spite of its drawbacks [7].

According to the model, the hydration process describes by empirical expressions which varies depending on its stage.

Stage 1. Nucleation and growth:

$$\frac{\partial \alpha_{1,i}}{\partial t} = \frac{k_{1,i}}{n_{1,i}} \cdot (1-\alpha_i) \cdot (-\ln(1-\alpha_i))^{1-n_{1,i}}, \quad (1)$$

Stage 2. Diffusion:

$$\frac{\partial \alpha_{2,i}}{\partial t} = k_{2,i} \cdot \frac{(1-\alpha_i)^{2/3}}{1-(1-\alpha_i)^{1/3}}, \quad (2)$$

Stage 3. Formation of hydration shells:

$$\frac{\partial \alpha_{3,i}}{\partial t} = k_{3,i} \cdot (1-\alpha_i)^{n_{3,i}}, \quad (3)$$

where $\alpha_{1,i}$, $\alpha_{2,i}$, and $\alpha_{3,i}$ – is the hydration degree of the $i$-th clinker mineral ($i \in$ {alite, belite, aluminate, and aluminoferrite});

$t$ – is arbitrary time, day;

$k_{1,i}$, $k_{2,i}$, and $k_{3,i}$ – are the rate constants of the $i$-th phase of the cement clinker, 1/day;

$n_{1,i}$ and $n_{3,i}$ – are the model parameters of the $i$-th phase of the cement clinker.

A lowest value is taken as the hydration rate of the $i$-th phase of the cement clinker ($\alpha_i$):

$$\frac{\partial \alpha_i}{\partial t} = \min\left(\frac{\partial \alpha_{1,i}}{\partial t}, \frac{\partial \alpha_{2,i}}{\partial t}, \frac{\partial \alpha_{3,i}}{\partial t}\right), \quad (4)$$

The kinetics of the pozzolanic reactions is adopted according to the results [8]:

$$\frac{\partial \alpha_i}{\partial t} = \frac{n}{\tau} \cdot \alpha_i^{1-\frac{1}{n}} \cdot (1-\alpha_i)^{1+\frac{1}{n}}, \quad (5)$$

where $\alpha_i$ – is the hydration degree of the $i$-th phase of the pozzolana ($i \in$ {silica, alumina});

$n$ and $\tau$ – are the model parameters, $\tau$ in day.

The overall hydration degree ($\alpha$) of cement (pozzolana) is calculated as a weighted mean by mass fraction of phases.

Predicting the volume fractions of the cement paste phases can essentially be done in only two ways:

1) Based on stoichiometry of hydration reactions of cement (pozzolana) phases [9].

2) Based on the Powers model [10].

In the present study, the first way was taken because it not be related to experimental data, especially since for pozzolana they vary greatly.

The following volume fractions (in m$^3$/m$^3$) are the result of stoichiometry computations: the $i$-th clinker mineral ($f_{cl,i}$), the $j$-th hydrate product ($f_{hyd,j}$), and water ($f_w$).

Proceeding from these fractions, the aggregated phases of the cement paste can be determined:

$$f_c = \sum_i f_{cl,i};\ f_{hyd} = \sum_j f_{hyd,j};\ f_{ch} = 1 - f_c - f_{hyd} - f_w. \quad (6)$$

where $f_c$, $f_{hyd}$, $f_{ch}$ – is the volume fraction of the unhydrated cement, hydration products, and chemical shrinkage, respectively.

It should be noted, that at the initial moment of hydration ($t = 0$):

$$f_c + f_w = f_c \cdot \left(1 + \frac{f_w}{f_c}\right) = f_c \cdot \left(1 + \frac{\rho_c \cdot w/c}{\rho_w}\right) = 1. \quad (7)$$

where $w/c$ – is the water to cement ratio;

$\rho_c$ and $\rho_w$ – is the density of the cement and water, respectively, kg/m$^3$.

**Geometrical model**

*Basic assumptions*

The assumptions of the unit cell model are listed as follows:

1) The cement particles are spherical, uniformly sized, and uniformly distributed over the cement paste.

2) The unhydrated core of each cement particle is equally decreased during hydration.

3) The hydrate products are formed in an equally layer at the surface of each cement particle.

4) Each cement particle is surrounded by the same volume of available free water.

5) A unit cell is a cube with a centred single spherical cement particle surrounded by water.

*Geometrical formulation*

In the original source [6], the evolution of geometry of the single cement particle inside a unit cell is described by three cases (see Fig. 1).

$$\text{Case 1: } r_{cp} \le \frac{1}{2} \cdot l;$$

$$\text{Case 2: } \frac{\sqrt{2}}{2} \cdot l \ge r_{cp} > \frac{1}{2} \cdot l;$$

$$\text{Case 3: } \frac{\sqrt{3}}{2} \cdot l \ge r_{cp} > \frac{\sqrt{2}}{2} \cdot l. \quad (8)$$

where $r_{cp}$ – is the average radius of the single cement particle;

$l$ – is the length of unit cell edge.

The unit cell can be considered in absolute dimensions or dimensionless. In the first case, the length of unit cell edge ($l$) should be expressed in terms of $r_{cp}$:

$$l = \sqrt[3]{\frac{1}{n}}. \quad (9)$$

where $n$ – is the number density of the cement particles in the cement paste 1/m$^3$, which for the case at hand is determined as:

$$n = \frac{f_c}{V_{cp}} = \frac{f_c}{\frac{4}{3}\pi \cdot r_{cp}^3} \quad (10)$$

where $V_{cp}$ – is the volume of the single cement particle, m$^3$.

In the second case, the inverse problem of finding $r_{cp}$ is solved, since $l = 1$.

The principal drawback of the unit cell model in absolute dimensions is that the average radius of the cement particle can vary greatly depending on the way of its determining.

During the hydration process, the volume of the cement particle is computed using the following geometric expressions:

$$\text{Case 1: } V_{cp} = \frac{4}{3} \cdot \pi \cdot r_p^3;$$

$$\text{Case 2: } V_{cp} = \frac{4}{3} \cdot \pi \cdot r_{cp}^3 - 6 \cdot \left(\frac{\pi}{3} \cdot h^2 \cdot (3 \cdot r_{cp} - h)\right). \quad (11)$$

where $h$– is the height of the spherical segment, $h = r_{cp} - \frac{1}{2} \cdot l$.

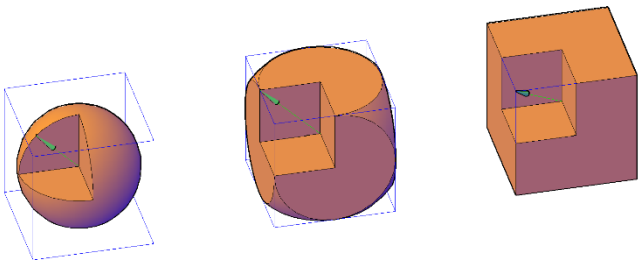

**Figure 1** – The geometry evolution of the single cement particle inside a unit cell

The Case 3 can be neglected, since Case 2 implies $1 - V_{cp}\left(r_{cp} = \frac{\sqrt{2}}{2} \cdot 1\right) = 0{,}035$. Considering the fact that chemical shrinkage in cement-based materials depends on water to cement ratio, but exceeds on average 6%, then the Case 3 is hardly reachable in reality.

One more important geometrical parameter is an available surface of the cement particle ($S_{cp}$) for contact with water:

Case 1: $S_{cp} = 4 \cdot \pi \cdot r_{cp}^2$;

Case 2: $S_{cp} = 4 \cdot \pi \cdot r_{cp}^2 - 6 \cdot (2 \cdot \pi \cdot r_{cp} \cdot h)$. (12)

*Adjustment of hydration kinetics*

The serious problem of the Parrot and Killoh model (as well as other existing models) is that it does not take into consideration several key factors in the hydration process: environment temperature, reduction in available free water and pore space for the deposition of hydration products. Moreover, this model suffers from an inability to account for the fineness of cement.

All these factors heavily affect the hydration rate. The following relation should be used to adjust the original models (4) and (5):

$$\left(\frac{\partial \alpha_i}{\partial t}\right)' = \frac{\partial \alpha_i}{\partial t} \cdot \frac{f_w(t)}{f_w(t=0)} \cdot \frac{S_{cp}(t)}{S_{cp}(t=0)} \cdot \frac{FN}{FN_{ref}} \cdot \exp\left(-\frac{E_{a,i}}{R} \cdot \left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right). \quad (13)$$

where $\left(\frac{\partial \alpha_i}{\partial t}\right)'$ – is the adjusted hydration rate of the $i$-th phase of the cement clinker (pozzolana);

$FN$ – is the actual fineness of cement, m²/kg;

$FN_{ref}$ – is the reference fineness of cement, 385 m²/kg [7];

$E_{a,i}$ – is the activation energy of the $i$-th phase of the cement clinker, J/mol (it can be taken from []);

$R$ – is the universal gas constant, 8,314 J/(K·mol);

$T$ – is the actual temperature, K;

$T_{ref}$ – is the reference temperature, 293,15 K.

It should be pointed out that the ratio $\frac{f_w(t)}{f_w(t=0)}$ is best suited for modelling at low water-to-cement ratios. At water-to-cement ratios more about than 0,35 water transport processes due to moisture diffusion become increasingly important in the cement paste. Therefore, it is preferable to use a ratio based on relative humidity instead of the ratio $\frac{f_w(t)}{f_w(t=0)}$, for instance, one of the most well-known [1]:

$$\begin{cases} \left(\frac{RH(t)-0{,}55}{0{,}45}\right)^4 & at\ RH(t) \geq 0{,}55 \\ 0 & at\ RH(t) < 0{,}55 \end{cases}. \quad (14)$$

However, it also requires to construct a moisture diffusion model to evaluate relative humidity over time in cases like this.

*Microstructure evolution*

Since, the model is based on a single cement particle, the overall radius of the particle is the sole parameter that needs to be determined during hydration. This is easily done by solving the following equation for $r_{cp}$:

$$V_{cp}(r_{cp}) = \left(f_c(t) + f_{hyd}(t)\right) \cdot l^3. \quad (15)$$

The initial radius of the particle ($r_0$) is determined from the following equation:

$$V_{cp}(r_0) = f_c(t=0) \cdot l^3. \quad (16)$$

As it has been mentioned, $V_{cp}$ varies depending on the geometric case.

**Pore size distribution**

The overall pore size distribution ($V_p(r)$) of the cement paste is given by:

$$V_p(r) = \sum_i f_{p,i} \cdot \phi_i(r). \quad (17)$$

where $f_{p,i}$ – is the volume fraction of the $i$-th type of porosity of the cement paste;

$\phi_i(r)$ – is the distribution fraction of the $i$-th type of porosity up to pore radius $r$.

Currently, this issue is the most difficult in modeling microstructure of the cement paste. The measured pore size distribution is dependent on many factors: the laboratory technique used, sample preparation, curing conditions, drying procedure, etc. Typically, the mercury intrusion porosimetry is widely applied to determine the pore size distribution.

However, even the measured values are not always comparable with the actual pore distribution. It is primarily related with «ink-bottle» effect which influences the measurement and distorts the final result. It makes it difficult to establish an analytical function of the porosity distribution, that is why continuous probability functions with minimal parameters are preferred to facilitate calculations.

The simplistic unimodal Raleigh–Ritz distribution function is considered as one of the possible ways to provide the representative pore size distribution [5]:

$$\phi_i(r) = 1 - \exp\left(-B_i \cdot r\right). \quad (18)$$

where $B_i$ – is the pore structure parameter corresponding the peak of porosity distribution on a logarithmic scale, 1/m.

One more frequently mentioned function is described in [3]:

$$\phi_i(d) = a_i \cdot ln\left(\frac{d}{d_{min}}\right). \quad (19)$$

where $\phi_i(d)$ – is the distribution fraction of the $i$-th type of porosity up to pore diameter $d$;

$a_i$ – is the pore structure parameter;

$d_{min}$ – is the smallest capillary pore, m.

There is no exact solution for the above pore structure parameter $B_i$ and $a_i$. In practice, the relationship obtained by fitting the pore structure parameter to the measured pore size distribution function is used.

The Raleigh–Ritz distribution was chosen between these two models primarily due to its function to be better than that in (19), where it is assumed to be a straight line in a semi-logarithmic space.

Assuming that pores are cylindrical and no surface other than the inner walls of the pores exists, the follow expression for the representative pore radius can be obtained ($r_{i,peak}$):

$$r_{i,peak} = 2 \cdot \frac{V_{p,i}(r_{peak})}{S_{p,i}} = 2 \cdot \frac{f_{p,i} \cdot \phi_i(r_{peak})}{S_{p,i}}. \quad (20)$$

where $S_{p,i}$ – is the pore surface area per unit volume, m²/m³.

Using the equation (18) jointly with (20), the pore structure parameter ($B_i$) can be approximately computed as:

$$B_i = -\frac{S_{p,i}}{f_{p,i}} \cdot \frac{\ln\left(1 - \phi_i(r_{peak})\right)}{2 \cdot \phi_i(r_{peak})}. \quad (21)$$

Assuming that the Raleigh–Ritz distribution has a symmetric density function regardless of the type of porosity, it is not difficult to determine $\phi_i(r_{peak}) = 0{,}5$.

From the point of view of moisture transport, the overall porosity of the cement paste can be divided into two components: macropores and micropores. Macropores are empty spaces between partially hydrated cement particles, while micropores are located in the high-density structure (abbreviated HD) of C-S-H particles.

In view of the above, the surface area of macropores ($S_{p,mac}$) and micropores ($S_{p,mic}$) per unit volume can be determined as:

$$S_{p,mac} = \frac{S_{cp}}{l^3}; \qquad S_{p,mic} = S_{hd} \cdot \rho_{hd} \cdot f_{hd} \cdot f_{csh}. \quad (22)$$

where $S_{hd}$ – is the specific surface area of HD C-S-H, 247 m²/g [11];

$\rho_{hd}$ – is the density of HD C-S-H, 1750 kg/m³ [11];

$f_{hd}$ – is the volume fraction of HD phase of C-S-H;


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$f_{csh}$ – is the volume fraction of C-S-H of the cement paste.

The approach presented in [11] is used to determine the volume fraction of HD phase of C-S-H ($f_{hd}$).

The volume fractions of porosity are computed by the following expressions:

$$f_{p,mac} = f_w + f_{ch}; \qquad f_{p,mic} = 0{,}28 \cdot f_{csh}\,. \tag{23}$$

**Threshold of solid percolation**

The main concept of percolation theory is an idea of connectivity. The percolation threshold is defined by the value of some parameter, say volume fraction of the structure in the box, right at the point where the structure either achieves or loses continuity across the box [12].

Inherently, the percolation threshold is a time point of hydration at which a plastic paste turns into a solid (called the set point).

According to the geometrical representation of the model, the percolation threshold is the value of the hydration degree ($\alpha_{per}$) at which the radius of the growing particle reaches the unit cell faces:

$$\alpha_{per} = \alpha\left(r_p = \tfrac{1}{2}\cdot l\right). \tag{24}$$

Actually, the above condition is not optimal, since with a decrease of the water to cement ratio, the cement fraction increases. It brings out the fact that at the initial moment of hydration ($t = 0$) the initial radius of cement particle ($r_{p,0}$) may already satisfy the following condition:

$$r_{p,0} \geq \tfrac{1}{2}\cdot l. \tag{25}$$

The most suitable solution to avoid such a problem is to add one more condition:

$$\alpha_{per} = \alpha\left(r_p = \tfrac{1}{2}\cdot l, f_{hyd\_sol} \geq f_{hyd\_sol,cr}\right). \tag{26}$$

where $f_{hyd\_sol}$ – is the fraction of hydration products in the solid phase, $f_{hyd\_sol} = \frac{f_{hyd}}{f_{hyd}+f_c}$;

$f_{hyd\_sol,cr}$ – is the critical fraction of hydration products in the solid phase which provides the formation of stable bonds for connectivity when the particle radius reaches with the faces of the unit cell.

The critical fraction of hydration products in modelling is assumed to be 0,1.

**Modelling results**

Two types of the cement paste based on ordinary Portland cement (OPC) and blended cement (BC) were used for the simulation.

The considered characteristics of the cement paste are reported in Table 1.

**Table 1** – Characteristics of the cement paste

| Name | Mix proportions, kg/m³ | | | Water to Binder ratio |
|---|---|---|---|---|
| | Portland Cement | Water | Fly Ash | |
| OPC | 370 | 185 | – | 0,5 |
| BC | 450 | 155 | 50 | 0,31 |

The characteristics of cement paste constituents are reported in Table 2.

**Table 2** – The characteristics of cement paste constituents

| Name | Density, kg/m³ | Fineness, m²/kg | Mineral (chemical) composition (mass %) |
|---|---|---|---|
| Portland Cement | 3150 | 345 | $C_3S$: 54,5; $C_2S$: 17,3; $C_3A$: 8,9; $C_4AF$: 7,6; Gypsum: 5 |
| Fly Ash | 2270 | 337,5 | Silica (S): 56,7; Alumina (A): 21,2 |

The parameters in equations (1)–(5) were taken from the above references for the corresponding model.

Sets of Portland cement hydration reactions and phase characteristics contained in [11] were taken to carry out the stoichiometry calculations.

The principal reaction scheme for pozzolana is S[1]+H+CH=C-S-H and A+CH+H=C-A-H [13].

Based on this, the following chemical reaction were taken for fly ash [7, 8]:

$$S + 1{,}1 \cdot CH + 2{,}8 \cdot H \rightarrow C_{1,1}SH_{3,9}\,. \tag{27}$$

$$A + 3 \cdot CH + 3 \cdot H \rightarrow C_3AH_6\,. \tag{28}$$

The phase characteristics for pozzolana reactions were used given in [7]. The pozzolanic activity of flay ash is assumed of 60%.

The initial average radius of the single cement particle was computed as expected value of the Rosin-Rammler probability distribution. The parameters of the Rosin-Rammler probability distribution as a function of the cement fineness were taken from [3]

The found value of the initial average radius of the single cement particle was additionally specified by the equation (16).

The actual temperature was assumed to be 20 °C. The hydration degree of blended cement was computed as weighted mean:

$$\alpha = \frac{\alpha_{pc}\cdot m_{pc} + \alpha_{fa}\cdot m_{fa}}{m_{pc}+m_{fa}}. \tag{29}$$

where $\alpha_{pc}$ and $\alpha_{fa}$ – is the hydration degree of Portland cement and reaction degree of fly ash, respectively;

$m_{pc}$ and $m_{fa}$ – is the content of Portland cement and fly ash in the mix, respectively.

The modeling results are presented in Figures 1–5.

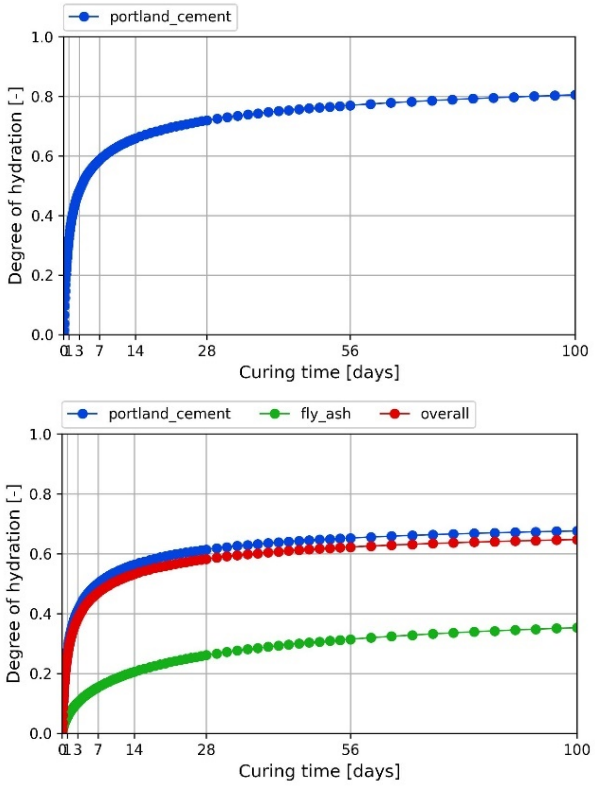


**Figure 1** – The predicted degree of hydration of the cement paste (Left: OPC; Right: BC)

[1] Cement chemistry notation is used here to write chemical compounds


**Figure 2** – The evolution of unit cell geometry for OPC
(The estimated percolation threshold $\alpha_{per} = 0{,}23$)

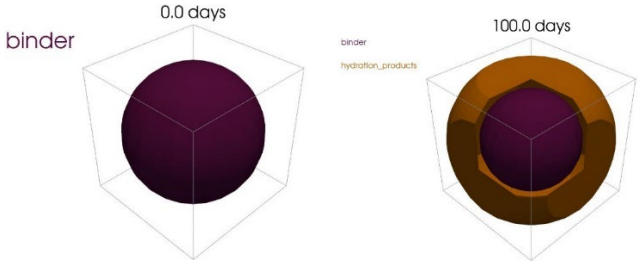


**Figure 3** – The evolution of unit cell geometry for BC
(The estimated percolation threshold $\alpha_{per} = 0{,}06$)

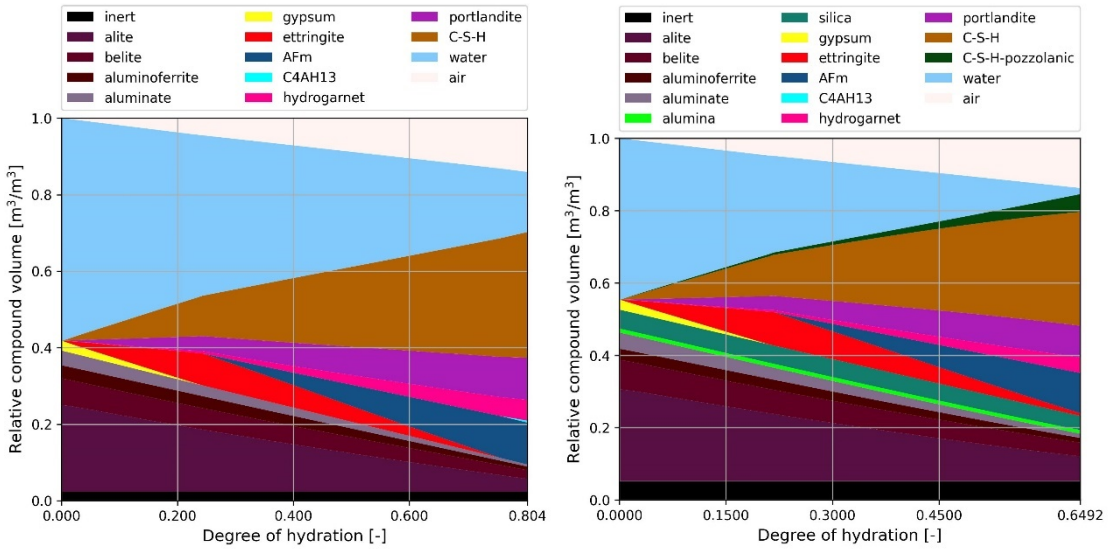


**Figure 4** – The predicted phase composition of the cement paste under sealed conditions
(Left: OPC; Right: BC)

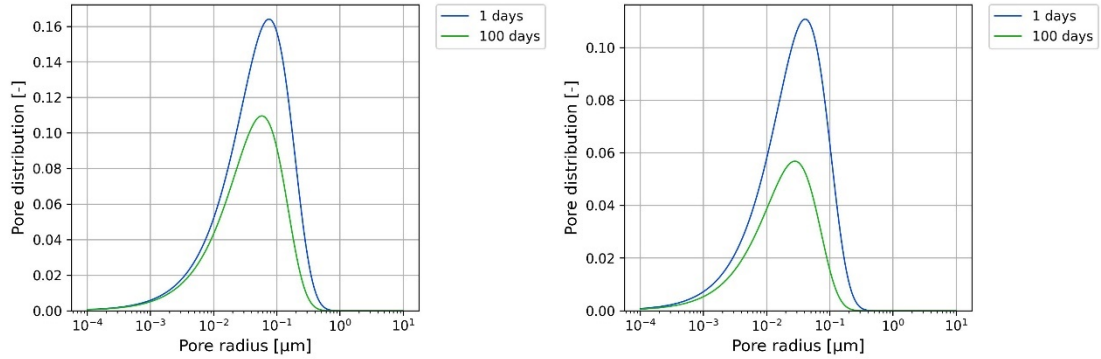


**Figure 5** – The predicted size distribution of macropores of the cement paste
(Left: OPC; Right: BC)

**Conclusions**

1. The presented model of microstructure development of the cement paste is characterized by computational simplicity, but provides all the basic structural characteristics: phase volume composition, evolution of geometry, pore size distribution, and percolation threshold. The simplicity of the model is important, because it facilitates to be incorporated into more complex computational models (for instance, to predict the mechanical properties of cement-based composites over time).

2. The model includes considerable assumptions that may decrease its accuracy. Since, the microstructure of the cement paste is extremely complexity and highly heterogeneous, it is quite difficult to validate such a model. It can be said that accuracy of the presented model is an open issue.

3. The principal drawback of the model is lots of types of averages that can be used to determine the radius of the cement particle.

4. It is impossible to extract a histogram of the frequency distribution of pore sizes from the model i.e., the pore size distribution is strictly limited by the given probability distribution function.

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# 2D CONVOLUTIONAL NEURAL NETWORK IN THE DESIGN OF MONOLITHIC SELF-STRESSED SLABS ON BASE

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**Abstract**

The purpose of this paper is to demonstrate the capabilities of convolutional neural networks in mechanics-related problems, in particular, in the design of monolithic self-stressed slabs on the base. In order to simplify the procedure of designing and calculating the displacements of slabs on the base has been developed a method that combines the advantages of theoretical models, and neural network technologies. The paper shows the possibility of using "soft computing", and also points out the promising potential of convolutional neural networks in predicting forced displacements in slabs of different geometrical shape.

**Keywords:** convolutional neural network, neurons, slabs on base, self-stressed concrete, hybrid.

## ДВУМЕРНАЯ СВЁРТОЧНАЯ НЕЙРОСЕТЬ ПРИ ПРОЕКТИРОВАНИИ МОНОЛИТНЫХ САМОНАПРЯЖЕННЫХ ПЛИТ НА ОСНОВАНИИ

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**Реферат**

Целью настоящей статьи является демонстрация возможностей свёрточных нейросетей в задачах, связанных с механикой, в частности при проектировании монолитных самонапряжённых плит на основании. С целью упрощения процедуры проектирования и расчета перемещений плит по основанию был разработан метод, сочетающий в себе преимущества теоретических моделей и нейросетевых технологий. В статье показана возможность использования "мягких вычислений", а также отмечен перспективный потенциал свёрточных нейронных сетей в прогнозировании вынужденных перемещений в плитах различной геометрической формы.

**Ключевые слова:** свёрточная нейронная сеть, нейроны, плиты на основании, самонапряженный бетон, гибрид.

**The aim is to obtain an improved method for slab design**

The ultimate goal of this research is to create a slab design method that combines the advantages of neural network technologies and theoretical models. This paper discusses the first step in realizing this goal – the creation of a so-called hybrid, which should combine the advantages of theoretical models, finite element methods, biosimilar models, and neural network technologies. The step-by-step realization of the goal requires:

1. To illustrate the possibility of convergence of mechanics and neurotechnology.

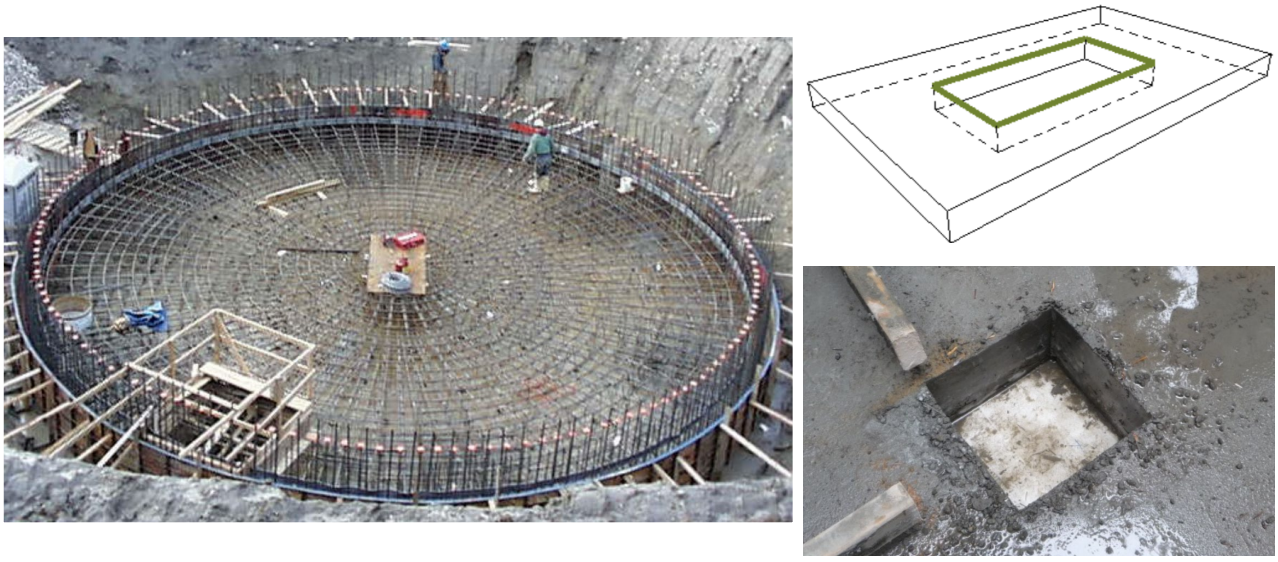

**Figure 1** – Design of slabs with holes of different shapes [1]


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2. To show the possibility of using "soft computing" with the application of deep learning in tasks related to design.

3. To show the advantages of convolutional neural networks in predicting forced displacements in slabs on a base when there is a deficit (or absence) of initial data on displacements in the area of technological holes.

**Key prerequisites**

In some cases, even at the design stage, the slab design provides for the presence of holes of various shapes, both along the contour and in the body of the slab (Fig. 1). Thus, for example, when installing slabs in the shops of production buildings, machine shops of nuclear power plants, at other facilities, in already existing premises, it is necessary to provide in advance how the slab will behave in the area of the enveloped holes.

The solution of such problems on determination of displacements, stress-strain state (SSS), in closed form is either very labor-intensive or not achievable at all.

The existing approaches related to the use of finite element models are known to have certain and sometimes very significant disadvantages. Among them we can mention: 1 – application of temperature effects to describe the free deformations of concrete during curing; 2 – nonlinear kinetics of concrete curing (in the time period up to 28 days) is not taken into account; 3 – nonlinear change of concrete temperature during the course of chemical reactions in the initial period of curing is not taken into account.

**Hard & Soft Computing - from competition to synthesis**

In order to simplify the procedure of designing such slabs, we propose a joint application of a spectrum of methods. For this purpose the main role is given to the development and training of a 2D convolutional neural network (CNN) capable of working with multidimensional data matrices [2].

**Problem statement**

At the first stage, the task of intelligent solution search was set for a displacement in test slabs (slabs on which the neural network's prediction ability was tested). At the same time, when training the neural network, there was no information about displacement in the area of holes in the central part of the slabs. In other words – in all training slabs technological holes were made along the perimeter. In the test ones, the holes were located in the center.

For this purpose, using the solution obtained in the closed form [3] for strip-slabs, displacements in characteristic points along the length of a number of strip-slabs were determined, from which, at the next stage, slabs of different geometric shapes were made up.

At the same time, the samples differed in the shape and location of holes. Next, two-dimensional matrices describing the displacements of the nodal points of the slabs were compiled.

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The location of the nodal points was determined using radius vectors drawn from the geometric center of the slab to a specific grid intersection with a step of 0.4x0.4 m.

It was required to determine the displacements in OXY axes for the test slabs with dimensions 4x4x0.1 m., having technological holes in the center – 1.2x1.2 m., as well as 0.4x0.4 m.

**Preparing samples for training**

To train the convolutional neural network, a sample of 21x7 different slabs was created (Fig. 2, the slab without holes is not shown).

Two types of data were used: topology of the nodes of the coordinate grid "breaking" the slab and shape parameters of the slab with holes; the second type included geometric characteristics of the slab as a whole, physical and mechanical characteristics of the self-stressing concrete and characteristics of the contact layer in the slab-base system.

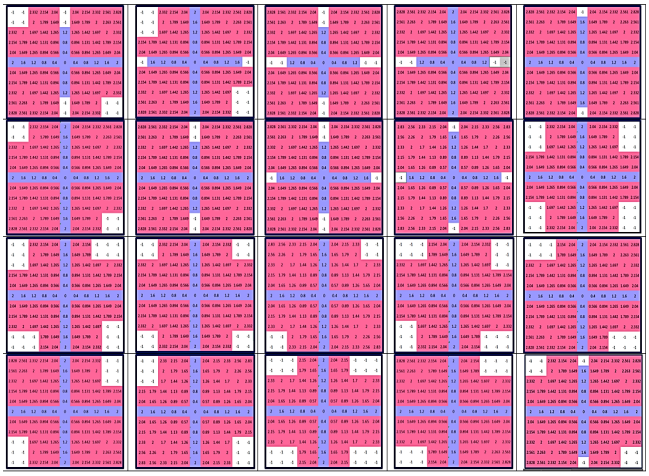

**Figure 2** – A sample of 20 different slabs with peripheral holes for training the convolutional NN

To obtain the slab parameters, the slabs were marked into 11x11 points (nodes) with values of distances from the slab center and displacements defined for each grid node. The displacements of the grid nodes were used as target output values of the CNN. The resulting data were recorded as matrices that were fed to the input of the CNN. Data were stored in separate directories with csv files (each of the 7 directories contained 21 subdirectories with files for coordinates and displacements). This study tested several options for coding data describing slab holes (through "0" and through "–1").

**CNN framework for predicting displacement**

A convolutional neural network combines three approaches in image processing. These are the use of a local receptive field for each neuron of the convolutional layer, the formation of convolutional layers as a set of maps whose neural elements have identical synaptic connections, and the presence of subsampling layer maps that increase the network's resistance to distortions [4, 5, 6, 7].

One of the reasons for high CNN performance, according to the authors [4], is the use of identical neurons in each map, which makes it possible to reduce the number of customizable synaptic connections of the network.

From a technical point of view, this task is similar to image transformation. Therefore, the Pix-to-pix architecture was used [8]. The Pix-to-pix architecture consists of two blocks, an encoder and a decoder with connections between them (fig. 3).

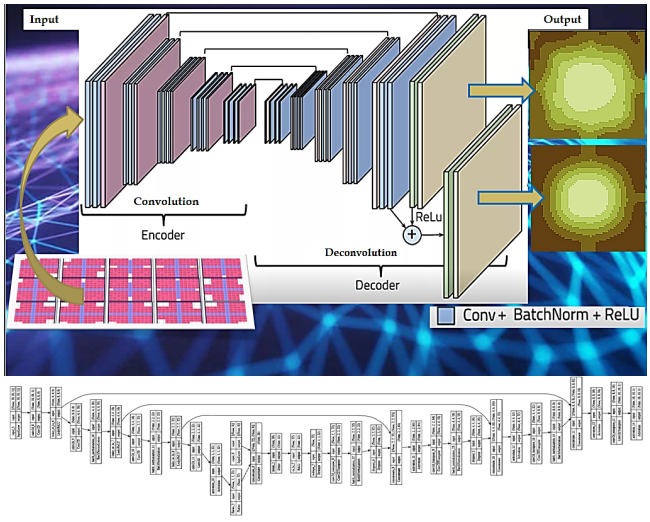


**Figure 3** – Convolutional neural network with Pix-to-pix architecture [9], and diagrams of displacements in slabs with small and large center holes at the "output" of the CNN

All the steps of creating the convolutional NN, training and validation were implemented using the Python programming language and the Tensorflow framework [10].

Due to the pix-to-pix nature of the CNN, the two-dimensional data was enlarged to the number of grid nodes, 16x16 (with total 256 features), before being submitted for training. Two models were investigated, model #1 used the value "0" in the process of holes coding, model #2 used "–1". Simultaneously the task was set to identify the most optimal ratio between validation and training samples, as well as the number of training epochs. Thus, in both models from 50 to 100 training epochs were assigned. In models with 50 training epochs for optimal regularization, 75 % of the initial data for the training dataset were selected (randomly), and 25 % of the data were left for testing the quality of the model. In models with 100 training epochs, the ratio between the validation and training samples was 20 % versus 80 %.

The developed two-dimensional convolutional neural network works as follows: a list with three-dimensional matrices for training describing the features inherent in the slab is fed to the input. The first dimension is responsible for the "length coordinates of the grid points", the second for the "width coordinates", and the third for the "distance" of the grid nodes from the center of the slab.

At each layer, the encoder block wraps up the three-dimensional matrix, reducing the number of points of the slab grid by half and increasing the number of features responsible for the characteristic features of deformation in individual patterns – grid nodes. The convolution continues until a single point remains.

Then the inverse de-convolution to the previous size starts, where the output of the CNN "waits" for a matrix of displacements at characteristic points of the slab. The “sliding window” method is used for image scanning [4]. A sliding window is otherwise called a local receptive field or filter kernel for the corresponding (usually one) neuron of a feature map (each receptive field in the input image space is mapped to a separate neuron in each feature map). If the filter scans the image with stripe – ***s***, the number of neurons in each feature map is generally calculated by the formula:

$$D(C_1)=\left(\frac{n-p}{s}+1\right)\times\left(\frac{n-p}{s}+1\right). \quad (1)$$

Where: ***p*** x ***p*** is the size of the filter kernel, ***n*** x ***n*** – the dimensionality of the original image.

As follows from the last expression, the use of a convolutional network reduces the total number of configurable synaptic connections compared to a multilayer perceptron due to the use of identical neurons in each feature map [4].

The convolution layers of the encoder block have the following sequence of the number of feature maps and corresponding neurons in them: 8@8x8, 16@4x4, 32@2x2, 32@1x1. Similarly for the decoder block (fig. 3). The grid pitch of one filter kernel – 4x4 (fig. 4a). The filter kernels in this study work like independent neural networks. The filter kernel "passes" over the slab image (a grid with a certain step or stripe) shifting (at each step) by 2 values (thus, the "stripe" parameter was set equal – "2"). A "same padding" method (fig. 4c) was applied to the input data. Padding adds rows and columns of zeros around the data, which allow the kernel filter to start from the corner of the data and keep the size of the output data.

To determine the number of neurons in the first feature map (after the filter kernel passes through an image of size – 16x16), taking into account the padding method, one value is added to the existing 16x16 grid from the right and left, as well as from the top and bottom. Hence the final dimension of the incoming map is 18x18. Applying formula (1) [4] we obtain the number of neurons of the first feature map: $D(C_1)=\left(\frac{18-4}{2}+1\right)\times\left(\frac{18-4}{2}+1\right)$ = 8x8. Proceeding in a similar way for subsequent maps, we obtain – 4x4, 2x2, 1x1 neurons in convolutional layer maps.

The decoder layers are followed by a layer – "dropout" (Fig. 4b), which "disconnects" the filter neurons with a probability of 50% to minimize the overtraining of the network.

In the current study, the number of trained parameters exceeds the number of samples on which the model is trained, which is a drawback of the model. For the model to be built, the number of sample slabs should be at least 65000. At the moment the data of missing samples are being generated, which will be reflected in the nearest works.

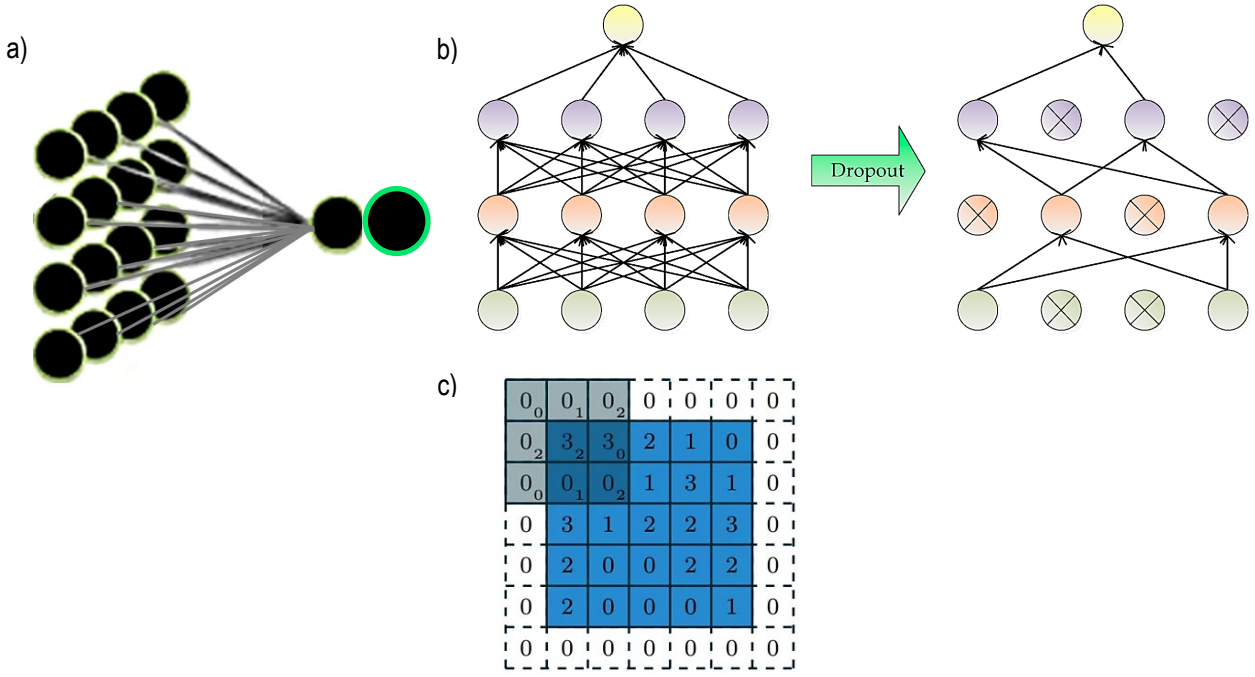


**Figure 4** – Schemes: a) 4x4 filter kernel structure, b) "dropout" operator [11], c) “padding method” [12]


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**Mechanism of operation of ANN and a filter**

Each filter neuron is considered as an operator that changes the input data [4, 13, 14]. The ANN receives the values of grid node coordinates as input, while the signal at the output of the neuron is defined as follows:

$$y_i = f_{act}\left(\sum x_i \cdot w_i + b\right). \quad (2)$$

Where: ***x*** and ***y*** – input and output signals of NN, ***w*** – weight parameter of synapse, ***b*** is a bias, $f_{act}$ – the neuron activation functions – *LeakyReLu* for encoder and *ReLu* for decoder. Since all data fed to the input and outputs of the convolutional neural network were normalized using Z-normalization, the activation of the last layer was performed using the function – *Tanh*. After training the neural network, the data was returned to the normal dimensionality using the "invers transformation".

The value of the transformed function (1) at the output of the resulting neuron of the filter (in given case – 1 neuron, Fig. 4a).

**Normalization**

A number of methods are known in mathematical statistics: decimal scaling, minimum normalisation, normalisation by mean (Z-normalisation) and others [15]. In this paper has been applied normalisation by mean (to compare values of different dimensions, as well as to bring the data to a more convenient form for training a neural network). Z-normalisation sets the mean (mathematical expectation) and variance of the data and is represented by the formula:

$$z = (x - \mu)/\sigma, \quad (3)$$

where: $\mu$ and $\sigma$ – mathematical expectation (mean) and standard deviation, respectively.

**Quality criteria for ANN performance**

When testing the neural network, the mean absolute error with L1 norm [16, 17] was used, as this metric reflects the accuracy of the prediction result quite well. The loss function was defined as:

$$E = \frac{1}{n}\sum\left|Y_{target} - Y_{predicted}\right|, \quad (4)$$

where: $n$ – number of examples, $Y_{target}$ – actual initial data, $Y_{predicted}$ – predicted values of the predicted parameter.

**Parametric optimization, gradient descent algorithm**

As optimizer has been used the method for stochastic optimization "Adam". Adam [18] is a first-order-gradient-based algorithm of stochastic objective functions, based on adaptive estimates of lower-order moments [19].

The goal of parameter optimization is to find the minimum value of the loss function E. At each iteration, the algorithm updates the weight parameters $w$, as showed in function (5).

$$\omega_{n+1} = \omega_n - \frac{\alpha}{\sqrt{\hat{v}_n} + \varepsilon} \cdot \hat{m}_n, \quad (5)$$

where: α=0.001 is the learning rate parameter, $g_t^2$ – indicates the element-wise square $g \odot g$. $\beta_1 = 0.9$, $\beta_2 = 0.999$, and $\varepsilon = 1 \cdot 10^{-7}$. All operations on vectors are element-wise. With $\beta_1^t$ and $\beta_2^t$ are denoted $\beta_1$ and $\beta_2$ to the power *t* (*t=0* at the first initializing). The 1st moment vector at the first initializing – $m_0 = 0$, 2st moment vector at the first initializing – $v_0 = 0$, $\omega_0$ – initial parameter vector, initializing by random generator. The weights are updated until the current and previous values converge.

Was used the next algorithm [19]:

1) $t \leftarrow t + 1$;

2) $g_t \leftarrow \nabla_w f_t(w_{t-1})$ – Get gradient w.r.t. stochastic objective at time-step t, i.e. the vector of partial derivatives of $f_t$, w.r.t $(w)$ evaluated at time-step t;

3) $m_t \leftarrow \beta_1 \cdot m_{t-1} + (1 - \beta_1) g_t$ – Update biased first moment estimate;

4) $v_t \leftarrow \beta_2 \cdot v_{t-1} + (1 - \beta_2) g_t^2$ – Update biased second row moment estimate;

5) $\hat{m}_t \leftarrow m_t / (1 - \beta_1^t)$ – Compute bias-corrector first moment estimate;

6) $\hat{v}_t \leftarrow v_t / (1 - \beta_2^t)$ – Compute bias-corrector second row moment estimate;

7) $\omega_t = \omega_{t-1} - \alpha \cdot \hat{m}_t / (\sqrt{\hat{v}_t} + \varepsilon)$ – Update parameters.

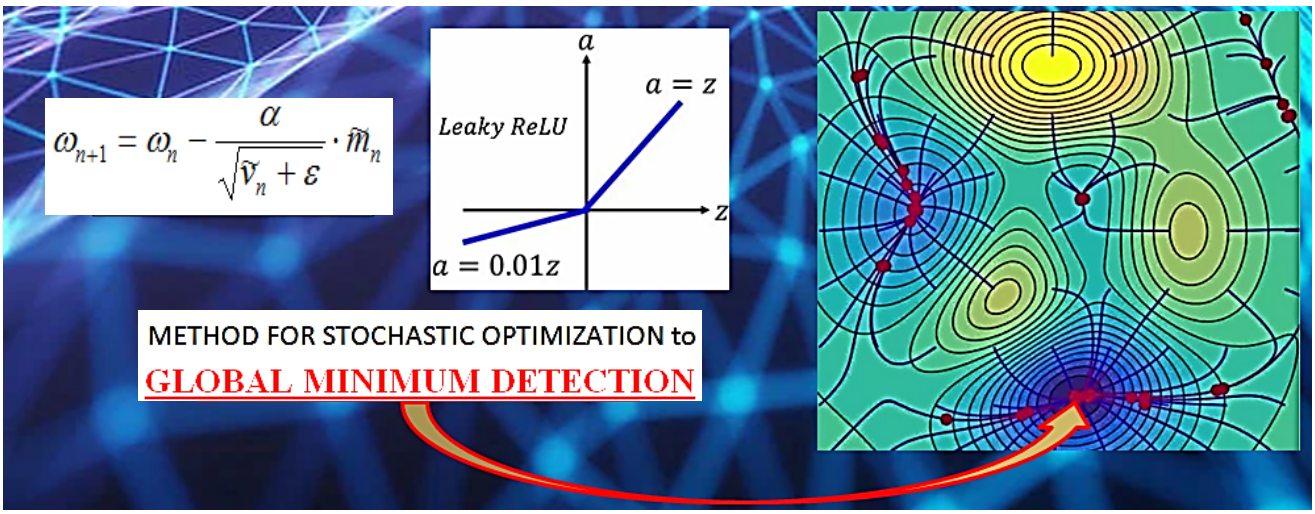


**Figure 5** – Gradient descent on the loss hypersurface [20]

where: $f(w)$ is a noisy objective function: a stochastic scalar function that is differentiable w.r.t. parameters $\omega$.

After acquiring loss function value, the antigradient is computed, updating the synapse weights. Thus, using the gradient information, the optimal path to achieve the global minimum on the loss hypersurface is determined.

**Network Training**

Since the developed neural network is a convolutional network with many layers, the launch of 100 epochs on an "Intel" processor with 4 GB RAM and 2 GB video card lasted from several minutes to half an hour (depending from model to model). In order to optimize the process, have been decided to train CNN in remote access mode inside the Google Drive environment. Has been used Python 3 server accelerator based on Google Compute Engine. The time of passing 100 epochs was reduced to 5–10 seconds.

**Displacement results in slabs with center hole**

In the next step, the data were fed into the de-encoder and unwrapped. The CNN thus matched the data on geometric parameters (node coordinates, distances from the center, slab shape features, hole locations), with the data on displacements of the slab grid nodes used for training. The displacement information was translated into colors of a particular spectrum and displayed as an output image. In the center of figures 6a-d, 7a-d the color spectrum of displacements is displayed (the color corresponds to the magnitude of the displacements).

In order to show that the prediction accuracy does not change significantly after 50 epochs of training (even when the training duration is doubled, i.e., up to 100 epochs), here presented plots of prediction of displacements in full-body slabs (fig. 6g-j, 7g-j). A comparative modeling analyze of the displacements (in full-body slabs on the base) has been carried out in the figures below (fig. 6e-g, 7e-g). The relative and absolute errors in determining the displacements of the slabs are showed (fig. 6h-i, 7h-i).

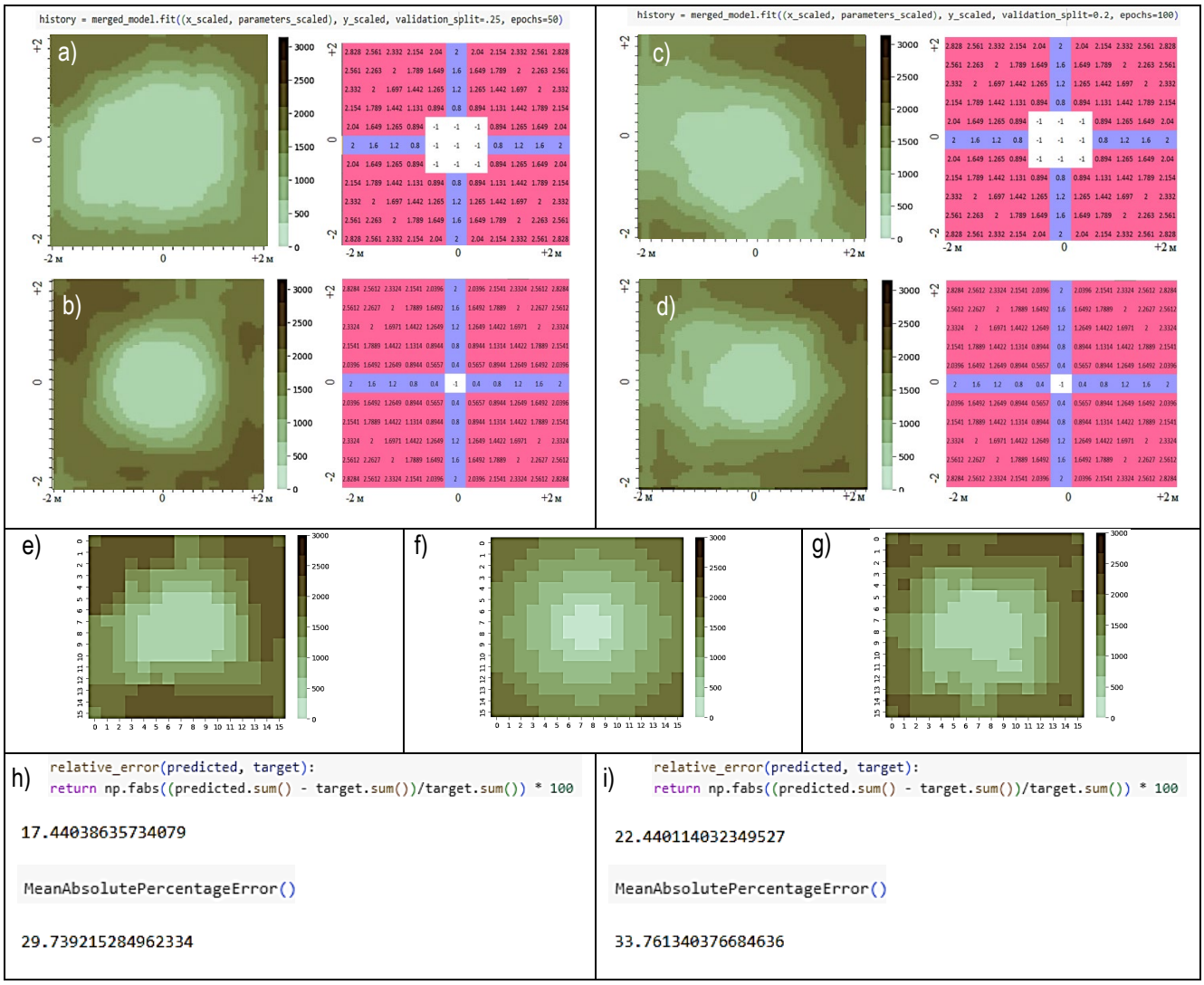


**Figure 6** – Displacements in slabs with a central holes, holes coded through "0":
a) model #1–1, central hole 1.2x1.2 m, training-validation split 75/25 %, number of epoch – 50,
b) model #1–2, central hole 0.4x0.4 m, training-validation split 75/25 %, number of epoch – 50,
c) model #1–1, central hole 1.2x1.2 m, training-validation split 80/20 %, number of epoch – 100,
d) model #1–2, central hole 0.4x0.4 m, training-validation split 80/20 %, number of epoch – 100,
i) model #1–1, full-body slab, training-validation split 75/25 %, number of epoch – 50,
f) actual full-body slab 2x2x0.1 m,
g) model #1–2, full-body slab, training-validation split 80/20 %, number of epoch – 100,
h) model #1–1, relative and absolute errors, i) model #1–2, relative and absolute errors


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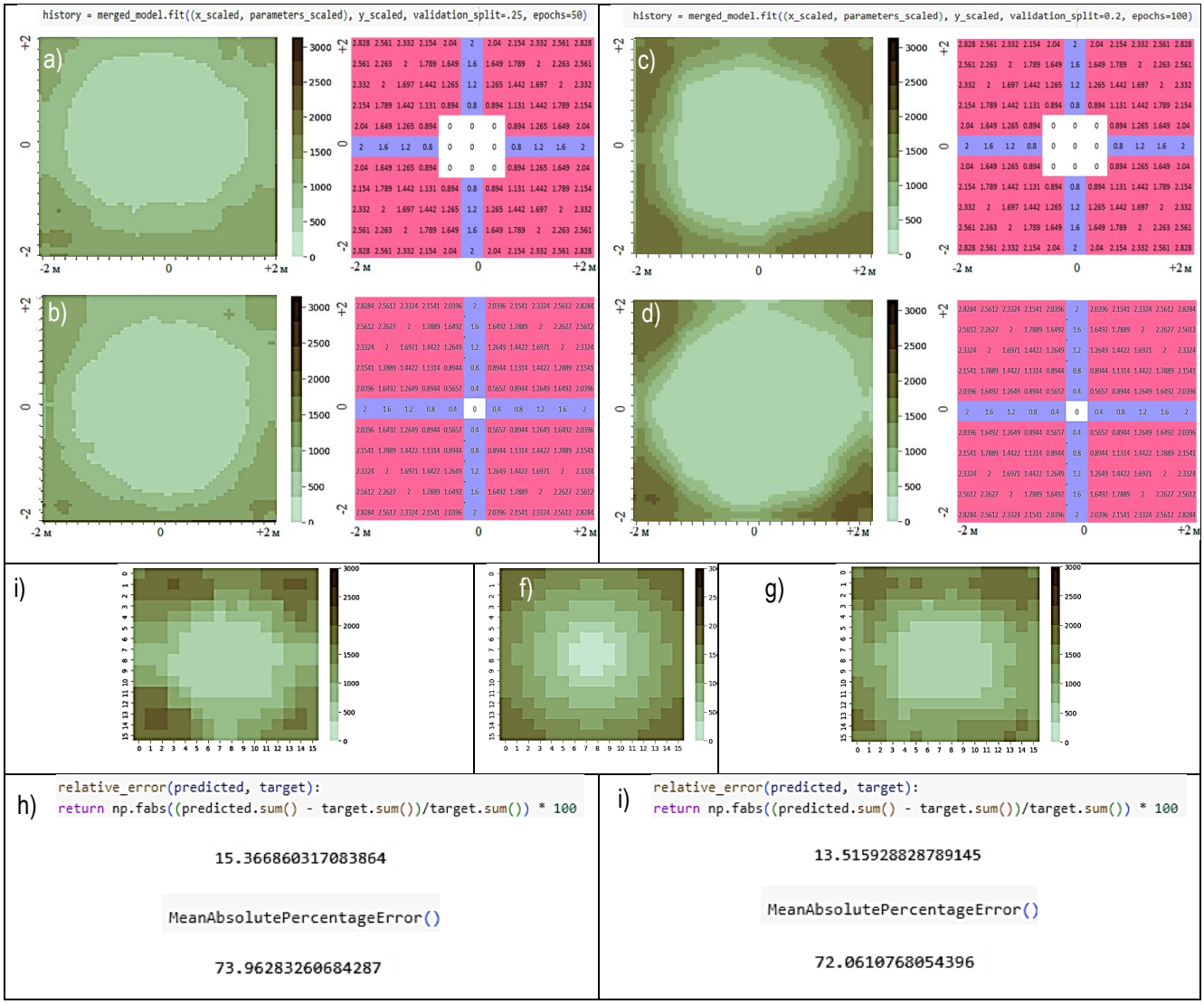


**Figure 7** – Displacements in slabs with a central holes, holes coded through "–1":
a) model #2–1, central hole 1.2x1.2 m, training-validation split 75/25 %, number of epoch – 50,
b) model #2–2, central hole 0.4x0.4 m, training-validation split 75/25 %, number of epoch – 50,
c) model #2–1, central hole 1.2x1.2 m, training-validation split 80/20 %, number of epoch – 100,
d) model #2–2, central hole 0.4x0.4 m, training-validation split 80/20 %, number of epoch – 100,
i) model #2–1, full-body slab, training-validation split 75/25 %, number of epoch – 50,
f) actual full-body slab 2x2x0.1 m,
g) model #2–2, full-body slab, training-validation split 80/20 %, number of epoch – 100,
h) model #2–1, relative and absolute errors,
i) model #2–2, relative and absolute errors

**Conclusions:**

1. Several options for coding data describing holes in slabs (via "0" and via "–1") are investigated. Two models were created to test the quality of prediction of slab displacements. The relative error for a full-body slab (taken over 256 points, i.e., the entire 16x16 grid), when used model #1–1 was 17.44 %; for model #1–2 – 22.44 %; for model #2–1 – 15.37%; and to model #2–2 – 13.52 %.

2. We assume that model #1 has smaller absolute errors due to the coding of holes with the number "0". It was easier for the model to establish the absolute difference between the displacements of full-body slabs (which have no hole in the center, where the value is strictly "0") and the displacements of the central region of the test slabs (the central region of the slab – the light pixels in the plots have zero displacements). In model #2, where coding was performed through "–1" relative errors in determining the displacements are somewhat smaller, at the same time we observe large absolute errors. This is primarily due to the peculiarity of "holes" coding. At the same time, such coding, apparently, complicates the training of the convolutional network, which is evident from the comparison of loss diagrams in models #1 and #2.

3. The developed neural network, trained on the basis of 147 samples, is quite confident in predicting displacements in slabs with a central hole, using data only from peripheral cutouts. If the training sample is increased, the relative errors as well as losses in training of the SNN can be significantly reduced.

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## MECHANICAL ENGINEERING

UDC 546.62+542.93

# MICROSTRUCTURE AND MICROHARDNESS OF Al-7 ALLOY WT% BI

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**Abstract**

The microstructure and microhardness of the Al–7 wt % Bi alloy crystallized at an average melt cooling rate of ~10 K/s has been studied. Bismuth and iron precipitates are mainly localized at the boundaries of aluminum grains, the average size of which is 40 μm. Bismuth particles have a spherical shape. The average value of the diameters of their cross sections is 1.5 μm. The specific surface of grain boundaries is 0.12 $\mu m^{-1}$. The specific surface area of the aluminum-bismuth interface is 0.062 $\mu m^{-1}$. The microhardness of the alloy is (323 ± 13) MPa and decreases monotonically during isothermal annealing at 150 °C.

**Keywords:** aluminum, bismuth, iron, silicon, grain, microstructure**,** microhardness.

**МИКРОСТРУКТУРА И МИКРОТВЕРДОСТЬ СПЛАВА Al-7 МАСС.% BI**

**В. И. Гладковский, Т. Л. Кушнер, А. И. Пинчук, В. Г. Шепелевич, В. М. Шилько**

**Реферат**

Исследована микроструктура и микротвердость сплава Al–7 масс.% Bi, закристаллизовавшегося при средней скорости охлаждения расплава ~10 K/c. Для изготовления сплава использовался алюминиевый лом, содержащий до 0,3 масс.% кремния и железа. Выделения висмута и железа преимущественно локализованы на границах зерен алюминия, средний размер которых равен 40 мкм. Частицы висмута имеют шарообразную форму. Среднее значение диаметров их сечений равно 1,5 мкм. Удельная поверхность границ зерен составляет 0,12 $мкм^{-1}$. Удельная поверхность межфазной границы алюминий-висмут равна 0,062 $мкм^{-1}$. Микротвердость сплава равняется (323±13) МПа и монотонно уменьшается в процессе изотермического отжига при 150 °C.

**Ключевые слова:** алюминий, висмут, железо, кремний, зерно, микроструктура**,** микротвердость.

**Introduction**

As known, the rapid melt-quenching method is to cool a jet of liquid metal on the outer (disc quenching) or inner (centrifugal quenching) surfaces of rotating drums, or rolling the melt between cold rolls made of materials with high thermal conductivity. In this method, a nanocrystalline structure is created in an amorphous alloy by crystallizing it. Spinning, i.e. obtaining thin foils of amorphous metal alloys by means of rapid (at a speed of at least $10^6$ K/s) cooling of the melt on the surface of a rotating disk or drum is well developed. The most typical methods of obtaining amorphous tapes and wires by rapid cooling are: a) quenching on a rotating drum, b) extraction of the melt by a rotating drum, c) cooling of a thin jet of melt with liquid. The amorphous tapes and wires are then annealed at a controlled temperature to crystallize. To create a nanocrystalline structure, annealing is carried out in such a way that a large number of crystallization centers arise, and the crystal growth rate is low.

Aluminum alloys containing indium, lead, and bismuth (Al–In, Al–Pb, and Al–Bi) have not been sufficiently studied, due to their limited use in industry. But in the last two decades, scientific and practical interest in them has manifested itself [1-4]. For example, alloys of the Al–Pb system are used as antifriction and damping materials. At the same time, their mechanical and operational characteristics are determined by both the chemical composition and size, morphology and phase distribution, as well as operating conditions. Structural defects (dislocations, grain boundaries, stacking faults, etc.) also affect their mechanical and electrochemical properties. It has been established that aluminum and bismuth alloys can be used as anode materials in the protection of metals, such as iron and steel, from corrosion, which is of great practical importance in various industries, construction and transport. It has been experimentally revealed that alloys of the aluminum-bismuth system interact with water under certain conditions, causing the release of heat and hydrogen, which is of great practical importance for the development of hydrogen energy. At the same time, the possibilities of using hydrogen in various fields of human activity, for example, in medicine, motor transport, etc., are expanding. It has also been established that such an interaction depends on temperature and pressure, as well as on the chemical composition of the alloy and its microstructure formed during crystallization and heat treatment [5–9]. When water and aluminum interact, various compounds are formed, including aluminum oxides, which can also be used in industry. To reduce the cost of hydrogen production, it is planned to use aluminum scrap (for example, aluminum tubes from end-of-life refrigeration units, aluminum wire from exhausted power lines, disused aluminum cookware, end-of-life structural aluminum products, etc.) instead of aluminum obtained using expensive electrolysis. The concentration of silicon and iron in the aluminum tube is ≈ 0.3 wt.%. In this regard, a study of the microstructure and microhardness of the Al–7 wt.% Bi alloy, made on the basis of aluminum tubes containing ≈ 0.3 wt.% of silicon and iron, and bismuth with a purity of 99.999%, was carried out, and its thermal stability was investigated by measuring the microhardness of the alloy during isochronous and isothermal annealing.

**Experimental methods**

Al–7 wt.% Bi alloy is obtained by fusion of aluminum tubes and bismuth with a purity of 99.999 % at a temperature of 750 °C. Then the melt was poured at room temperature into a graphite mold, where it crystallized in the form of an ingot with a cross section of 6×6 mm$^2$ and a length of 7 cm. The average melt cooling rate was ~10 K/s. Samples were cut from the middle part of the ingots to study the microstructure. The microstructure of the alloy was studied using a scanning electron microscope LEO-1455 VP. The microscope has an attachment for X-ray spectral microanalysis. The operating voltage of the electron microscope is 20 kV. The surface of the section was polished with a special paste containing dispersed solid particles of the abrasive substance. The microstructure parameters (mean chord of aluminum grains and bismuth precipitates, specific surface area of aluminum grain boundaries and aluminum–bismuth interphase boundary) were determined using a stereometric analysis of measurements obtained by the method of random secants [9]. The relative error in measuring the parameters of the microstructure was 8–15 %. Microhardness measurements were performed on a microhardness tester (marking in Russian language ПМТ-3) using a load of 20 g. The load time for measuring microhardness is 80 s. The microhardness value was calculated by measuring the diagonals of ten indenter imprints on the polished surface of the alloy under study. The relative error of its determination was 4 %. The thermal stability of the resulting alloy was investigated by microhardness using isochronous annealing carried out from 20 to 160 °C through 20 °C and holding at each temperature for 30 minutes, and isothermal annealing carried out at a temperature of 150 °C for 16 hours.

**Results and discussion**

Images of the section of the studied alloy Al–7 wt.% Bi at various magnifications are shown in Fig. 1 (a, b). At high magnifications (Fig. 1 (b)) there is a dark background, white and gray precipitates. The distribution of components along the electron beam scanning line over the surface of the alloy under study is shown in Fig. 2. The dark background matches the aluminum. White precipitates, as shown by X-ray spectral microanalysis, correspond to bismuth. The boundaries of aluminum grains are decorated with bright precipitates of other phases. The average chord of the sections of aluminum grains is $d_A$ = 25 μm, the calculated average size of aluminum grains is $D$ = 40 μm. The specific surface area of aluminum grain boundaries is $S_A$ = 0.12 μm$^{-1}$. Most bismuth particles are spherical in shape. The average value of the diameters of their cross sections is $d_B$ = 1.5 μm. The specific surface area of the aluminum-bismuth interface is $S_{A\text{-}B}$ = 0.062 μm$^{-1}$, which is two times less than $S_A$.

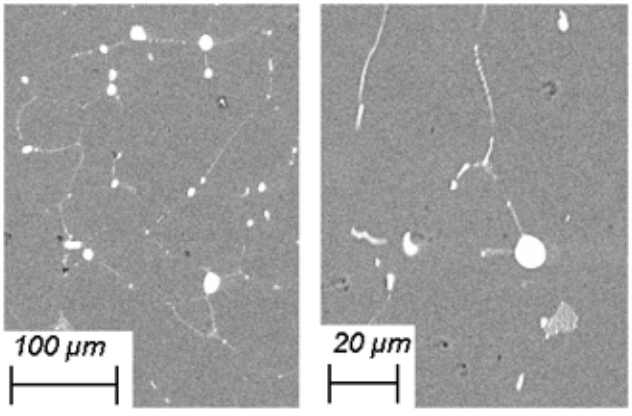


**Figure 1** – Precipitates of bismuth and iron phases at the grain boundaries of aluminum (a) and (b) alloy Al–7 wt.% Bi at different magnifications

Precipitates with a gray tint and a striped structure in the area of their accumulation contain iron. In these areas, as follows from the distribution (Fig. 2), the average concentration of iron reaches 10 wt.%. The silicon distribution is characterized by insignificant peaks (up to 2 wt.%) located at a distance of ~1 μm from each other, which indicates a more uniform distribution of silicon precipitates than the distributions of bismuth and iron precipitates in the Al–7 wt.% Bi alloy under study after crystallization at a cooling rate of 10 K/s.

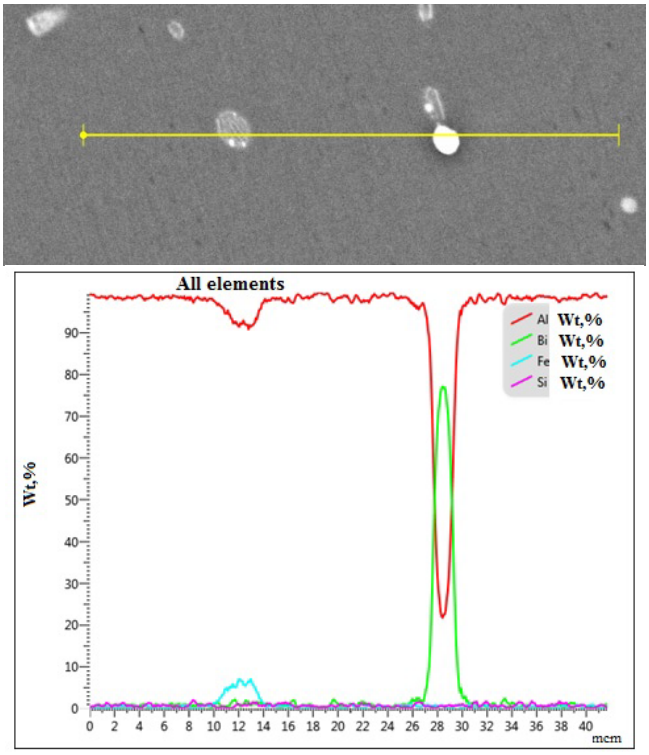


**Figure 2** – Distribution of components along the electron beam scanning line on the surface of the Al–7 wt.% Bi alloy

The distribution of chord lengths of random secants on bismuth precipitates by size groups is shown in Fig. 3. 3. The total number of images of bismuth precipitates used in the construction of the histogram was at least 150. The largest proportion (0.27) of chords falls on the group with a minimum size of 0.5 μm. With an increase in the length of chords in bismuth sections, their fraction decreases. The proportion of group chords with their maximum length (4 μm) is 0.05. The distances between bismuth precipitates reach 2 μm or more.

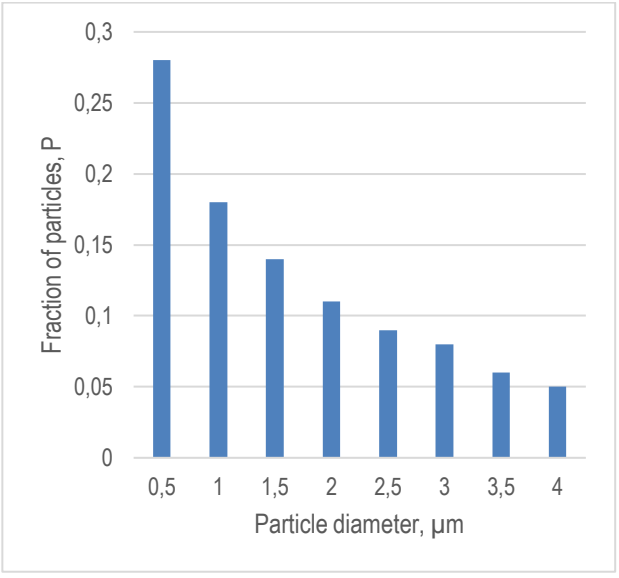


**Figure 3** – Distribution of chord lengths of sections of bismuth particles of Al–7 wt.% Bi alloy by size groups


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The concentrations of the components in different parts of the section of the Al–7 wt.% Bi alloy under study were determined (Fig. 4). Their values are presented in Table 1. In dark areas (spectra 3 and 4), the concentration of aluminum reaches 99.5 wt.%, and the concentrations of silicon and iron are equal to 0.5 wt.% and less than 0.03 wt.%, respectively, which is associated with a slight equilibrium solubility of these elements in aluminum and cooling of the alloy at a rate of 10 K/s. In the white area (spectrum 5), the concentration of bismuth is 98.0 wt.%, the concentration of aluminum is 1.7 wt.%, the concentrations of silicon and iron reach 0.5 and 0.03 wt. %, respectively. The value of the aluminum concentration in bismuth is overestimated, which is due to the excitation of the aluminum surrounding this bismuth precipitate by an electron beam.

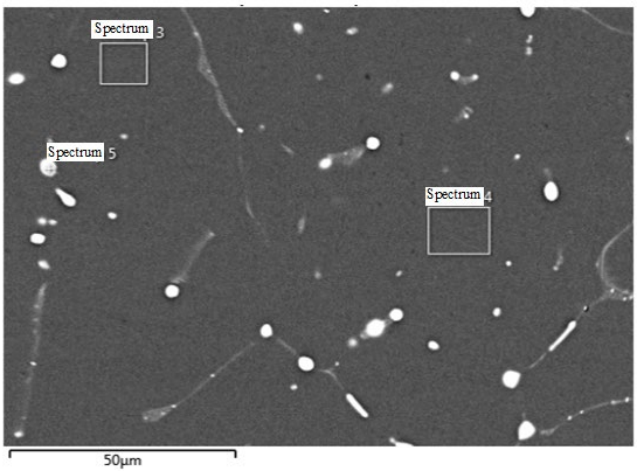


**Figure 4** – Image of the surface of the section of the alloy Al–7 wt.% Bi

**Table 1 –** Concentration of components in various areas of the section of the Al–7 wt.% Bi alloy

| Area | Concentration of components, wt.% | | | |
|---|---|---|---|---|
| | Al | Bi | Si | Fe |
| Spectrum 3 | 99,40 | 0,09 | 0,51 | 0,00 |
| Spectrum 4 | 99,46 | 0,02 | 0,49 | 0,03 |
| Spectrum 5 | 1,69 | 97,96 | 0,15 | 0,19 |

The formation of an inhomogeneous structure in a bulk Al(Fe, Si)–7 wt % Bi alloy is due to the peculiarities of the phase diagram of the Al–Bi system [11]. The mutual solubility of the components in the solid state is less than 1 mass%. In the alloys of the system, there is a stratification of the liquid phase $L$ into two liquids $L_1$ and $L_2$, differing in composition, when heated above 657°C. The volume fraction of liquid $L_1$ is much larger than the volume fraction of liquid $L_2$. When the melt is cooled below 657°C, the monotectic transformation of the $L_1$ liquid first occurs. In this case, aluminum is first released, and the bismuth and iron atoms are pushed to the boundaries of aluminum grains. The bismuth-rich $L_2$ liquid undergoes a eutectic transformation when further cooled below 270°C, in which bismuth and aluminum are released. Bismuth precipitates are larger, preferably located in areas located at the junctions of three grains. The released aluminum is attached to the grains of aluminum, which were formed earlier during monotectic transformation. Iron precipitates, as well as their accumulations, are predominantly located at the boundaries of aluminum grains. There are accumulations of dispersed precipitates of bismuth and iron located at the grain boundaries.

The microhardness of the Al–7 wt.% Bi alloy under study is equal to (323±13) MPa. When carrying out isochronous annealing in the temperature range of 100–160°C, a monotonic decrease in the microhardness of the alloy is observed.

Isothermal annealing of the alloy under study, carried out at a temperature of 150 °C, also causes a monotonous decrease in microhardness (Fig. 5). The change in microhardness at the initial stage of isothermal annealing is described by the ratio

$$(H_0 - H_t) = (H_0 - H_k)\, exp(-at),$$

where $H_0$, $H_k$ и $N_t$ are the microhardness values at initial, final and current time $t$ of isothermal annealing. The calculation showed that the value of the coefficient $a$ = 0.3.

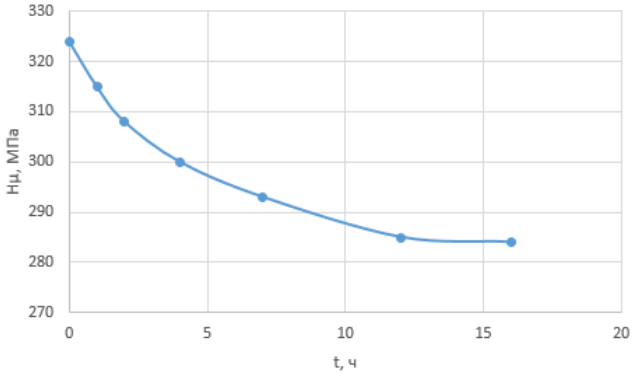


**Figure 5** – Dependence of the microhardness of the Al–7 wt.% Bi alloy on the holding time during isothermal annealing

The ratio of the temperatures of isothermal annealing and the beginning of melting of the alloy under study on the Kelvin scale is ≈ 0.45, i.e. at a temperature of 150°C, diffusion processes actively occur in the volume of grains and their boundaries of the alloy, causing the dissolution of small particles of the second phase (bismuth) and the growth of its larger particles [12]. This reduces the total number of bismuth particles and increases their average size and distances between them. Therefore, this process is energetically advantageous and leads to a decrease in the contribution of the dispersion mechanism to the hardening of the alloy, thereby causing a decrease in microhardness during isochronous and isothermal annealing [12, 13].

**Conclusions**

Crystallization of Al–7 wt. % Bi, made on the basis of aluminum scrap, in which the concentration of iron and silicon is ≈ 0.3 wt. %, at an average cooling rate of ~10 K/s leads to the formation of a microcrystalline structure. The average chord of the sections of aluminum grains is $d_{Al}$ = 25 μm, the average size of aluminum grains is 40 μm. The specific surface of aluminum grain boundaries is $S_{Al}$ = 0.12 μm$^{-1}$. Predominantly dispersed precipitates of bismuth and iron are localized at the grain boundaries. The distribution of silicon in the alloy is more uniform compared to the distribution of iron and bismuth precipitates. The average value of bismuth particle diameters is $d_{Bi}$ = 1.5 μm. The specific surface area of the aluminum-bismuth interface is $S_{Al\text{-}Bi}$ = 0.062 μm$^{-1}$. During ichohronous annealing in the temperature range of 100–150°C and during isothermal annealing at a temperature of 150°C, a decrease in microhardness occurs due to the coarsening of bismuth particles and a decrease in their dispersion contribution to the hardening of the alloy.

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# STRUCTURE AND PROPERTIES OF POLYAMIDE COATINGS FORMED USING INDUCTION HEATING

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**Abstract**

The article studies the physical and mechanical characteristics of coatings formed from powders of polyamides PA 11, PA 6 obtained by cryogenic grinding of semi-finished products cooled to liquid nitrogen temperature. Polyamide coatings were created by two different technological methods from a fluidized state. The morphology of polyamide particles was studied using optical and scanning microscopy. The structure of polymer composite materials has been studied by IR spectroscopy, optical and atomic force microscopy, and X-ray diffraction analysis. The conducted studies have shown that induction heating of steel substrates makes it possible to provide higher adhesive characteristics of polyamide coatings. Structural changes in coatings have a significant impact on the tribotechnical characteristics of coatings. It has been established that an increase in the degree of crystallinity and molecular order in the amorphous phases of the polymer leads to an increase in the hardness and wear resistance of polyamide coatings.

**Keywords:** polyamide, coating, morphology, wear, spectrum, powder, adhesion, heating.

## СТРУКТУРА И СВОЙСТВА ПОЛИАМИДНЫХ ПОКРЫТИЙ, ПОЛУЧЕННЫХ МЕТОДОМ ИНДУКЦИОННОГО НАГРЕВА

**Г. А. Костюкович, В. М. Хвисевич, Е. В. Овчинников, А. В. Попрукайло, А. И. Веремейчик**

**Реферат**

В статье проведено исследование физико-механических характеристик покрытий, сформированных из порошков полиамидов ПА 11, ПА 6, полученных криогенным измельчением полуфабрикатов, охлажденных до температуры жидкого азота. Полиамидные покрытия создавались двумя различными технологическими способами из псевдоожиженного состояния. С помощью оптической и сканирующей микроскопии изучена морфология частиц полиамида. Методами ИК-спектроскопии, оптической и атомно-силовой микроскопии, рентгеноструктурного анализа исследована структура полимерных композиционных материалов. Проведенные исследования показали, что индукционный нагрев стальных подложек позволяет обеспечить более высокие адгезионные характеристики полиамидных покрытий. Структурные изменения в покрытиях оказывают значительное влияние на триботехнические характеристики покрытий. Установлено, что повышение степени кристалличности и молекулярной упорядоченности в аморфных фазах полимера приводит к повышению твердости и износостойкости полиамидных покрытий.

**Ключевые слова:** полиамид, покрытие, морфология, износ, спектр, порошок, адгезия, нагрев.

**Introduction**

In mechanical engineering, over the past decade, there has been a trend to reduce weight in various designs used for the manufacture of components and assemblies, including the manufacture of components for automotive and tractor equipment [1]. In particular, in passenger cars, steel products are being replaced by products made of aluminum and magnesium alloys. This achieves the cost-effectiveness of the operation of manufactured structures for mechanisms and apparatus. However, in recent years, areas of application of so-called hybrid composite materials have been developing, which combine the high strength of the metal and the antifriction characteristics of polymers [2]. At the same time, hybrid components and composite materials are becoming increasingly important. Hybrid components and composite materials provide a performance advantage by highlighting the favorable properties of materials used in various designs and reducing their disadvantages. In this way, materials can be combined, which has not previously been given sufficient attention. Polymers are an example of this fact. Light weight and ease of forming products from them are only two aspects that make polymers interesting for large-scale production. The disadvantages of polymers are low resistance to abrasive wear and UV radiation, which is unacceptable for most technical applications. To improve the physical and mechanical characteristics, polymers are combined with various solid materials in order to improve the performance properties of polymers [2, 3]. At present, polymer coatings are widely used in various technical fields. The most common are partially crystalline thermoplastics with high wear resistance values. In particular, polyamides belong to this class of materials. The use of PA11 as a protective, anti-friction coating has been known for a long time. However, the disadvantage of this material is that this substance is an imported product, has a high wear compared to polyamides 6 and 66, as well as its cost. The possibility of solving problems associated with the use of polyamide 11 is determined by four directions. The first direction is the replacement of polyamide 11 with domestic analogues. In this regard, studies were

carried out on the creation of composite coatings [4–6] based on polyamide 6 and 66 to replace PA11. In a number of cases, high tribological and operational characteristics of these coatings were achieved [4–6], but a lower adhesion strength to metal substrates was observed compared to PA11. In a number of cases, additional technological processing of polyamide coatings was necessary, associated with obtaining coatings exactly in size and removing the surface layers of the polymer. Polyamide 11 also showed its best deformation and strength characteristics compared to PA6 and PA66 during the process, for example, of pulling splined bushings of cardan gears with a polymer coating. There was less rejection associated with the peeling of the polymer coating when using PA11. The second direction is the creation of own production for the production of polyamide 11. Currently, there are small specialized production facilities that allow the production of small batches of domestic production of polyamide 11. However, at the moment, these capacities are not enough to provide all consumers with this polymer. The third direction is the modification of polyamide 11 with domestic modifiers, in particular, nanometer dimensions to give the required performance characteristics, as well as the development of new technological approaches in the formation of polyamide coatings [7–9].

The fourth direction for reducing the cost and improving the performance of polyamide coatings is the optimization of existing technologies for the formation of these macromolecular compounds on metal substrates.

The purpose of this work is to study the physical and mechanical characteristics of polyamide coatings formed by different technological approaches from a fluidized state.

**Experimental technique**

To prepare powder materials, we used powders of polyamides PA 11, PA 6 obtained by cryogenic grinding of semi-finished products cooled to liquid nitrogen temperature. Fractionation of powders was carried out using a set of sieves. For the manufacture of composite materials for coatings, fractions with a cross-sectional size of $100 \leq d \leq 200$ μm were used. The morphology of the polyamide particles was studied using optical (MMV 2200) and scanning microscopy (Mira Tescan). The sizes of polymer particles were estimated using an NT-206 atomic force microscope. The structure of polymer composite materials (PCM) was studied by IR spectroscopy (Tensor-27), optical (MMV 2200) and atomic force (NT 206) microscopy, X-ray diffraction analysis (DRON-3.0). The physical and mechanical characteristics of the coatings were evaluated according to generally accepted methods. Adhesion strength was evaluated by peeling at an angle of 180°. The coatings were applied according to two technological approaches. The first one is a standard coating formation technology currently used at OAO Belcard for the formation of polyamide coatings on splined bushings of cardan gears of various nomenclature. The essence of the technology (technology I) is the formation of an adhesive sublayer of the Rilprim primer on the surface of the sleeve and heating a batch of sleeves with a primer in a chamber furnace to 400–420 °C, followed by exposure to air until the polyamide components are completely melted. In some cases, to create an adhesive-active layer, phosphating a metal surface is used. The surface of the metal sample was cleaned from oxides and contaminants by treatment with abrasive powder and degreased with gasoline. Another technological approach for the formation of polyamide coatings is heating the splined bushing or sample to 400–420 °C by using induction heating using the original inductor design (technology 2).

**Research results**

Figure 1 shows pictures of PA11 (Rilsan), PA6 powders obtained by solution and cryogenic technology for the formation of dispersed polyamide particles. The morphology of polyamide particles (PA 11) obtained by solution technology has a smoothed appearance close to a sphere. PA6 particles have a developed comminuted body appearance and hence higher specific surface area. The calculation of the shape factor, which is a generalizing parameter for assessing the shape of an object, showed values for polyamide 11 – 0.8, for PA6 – 0.4. This parameter is a dimensionless coefficient independent of orientational effects in the object structure. The maximum value of this coefficient is equal to one in the case of a circle and is determined based on the ratio of the area of the object to the square of its perimeter, multiplied by 4 π.

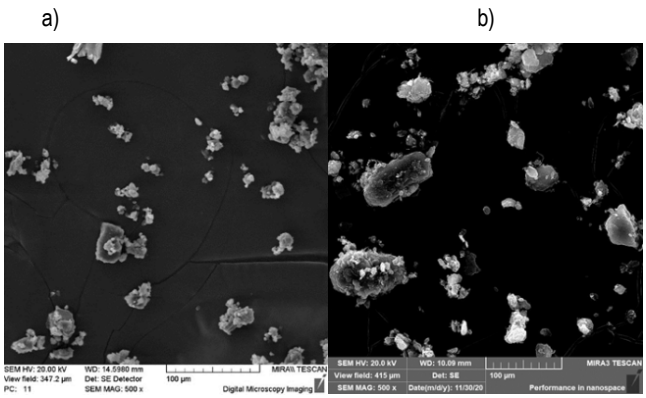
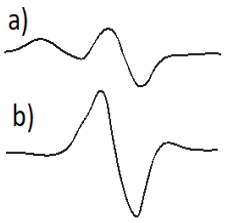


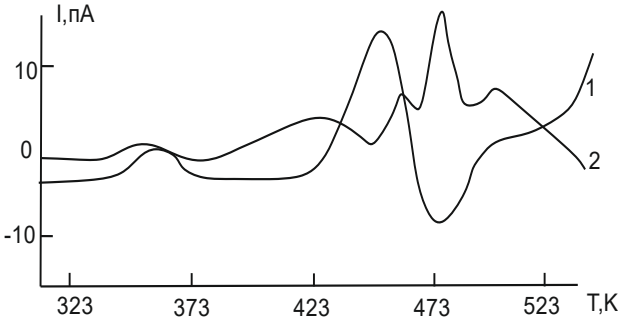

**Figure 1** – Morphology of PA11 (a), PA6 (b) particles
Dispersion of particles from 60 to 100 microns

The developed habit of the particles of polyamide powders and high values of the specific surface indicate the activity of these particles, which may be due to the presence of an uncompensated charge formed during mechanical dispersion at low temperatures. This assumption is confirmed by the results of studies carried out by the methods of EPR and thermally stimulated currents (Figures 2, 3).




a – characteristic view of the EPR spectra of dispersed particles of polyamide 11, obtained by polymerization; b – characteristic view of the EPR spectra of dispersed particles of polyamide 6 obtained by cryogenic technology

**Figure 2** – EPR spectra of powders of polymeric materials




1 – characteristic view of the TCT spectrum of dispersed particles of polyamide 11 obtained by polymerization; 2 – characteristic view of the TST spectrum of dispersed particles of polyamide 6 obtained by cryogenic technology

**Figure 3** – TCT spectra of powders of polymeric materials

The X-ray diffraction studies of coatings formed according to two technological approaches showed that the use of induction heating makes it possible to obtain protective coatings with higher values of the degree of crystallinity, both for coatings based on polyamide 11 and polyamide 6 (Figures 4, 5).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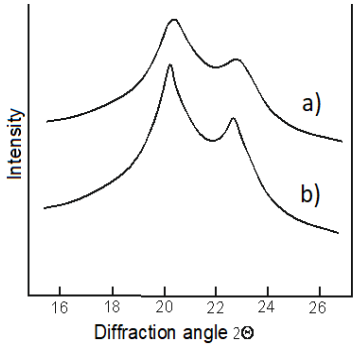
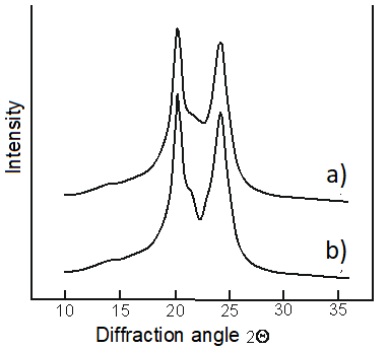



a – heating was carried out in a chamber furnace; b – induction heating

**Figure 4** – X-ray patterns of polyamide 11 coatings obtained on steel 40X using various technological approaches for heating the steel substrate




a – heating was carried out in a chamber furnace; b – induction heatin

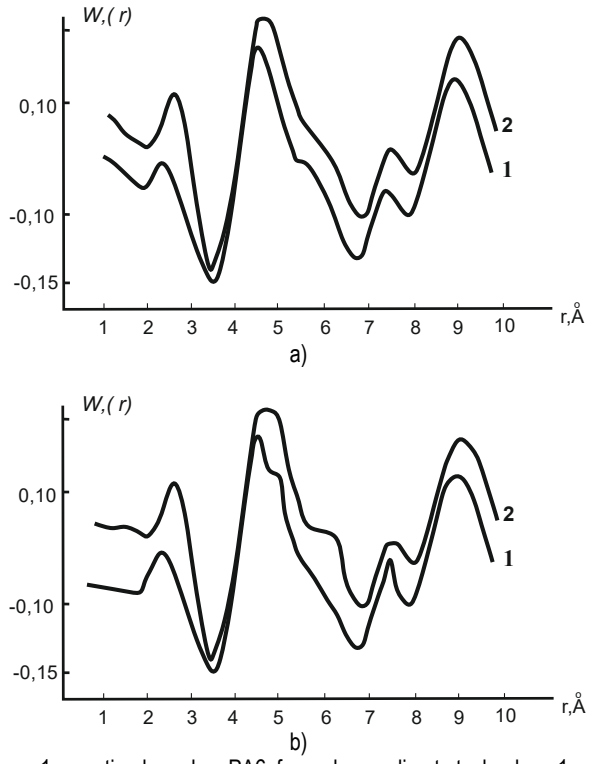
**Figure 5** – X-ray patterns of polyamide 6 coatings obtained on steel 40X using various technological approaches for heating the steel substrate

The deposition of polyamide coatings from polyamide 11 on splined bushings made of steel 40X leads to the formation of α-crystals in the polymer structure, as evidenced by the appearance of diffraction maxima in the region 2θ ~ 20o25' and 22o45'. This process occurs as a result of natural cooling of the samples to normal temperature. The technology of forming tribological coatings from polyamide 11 has a significant impact on the degree of crystallinity of the obtained protective coatings (table 1). The method proposed in [10] was used to calculate the degree of crystallinity. This approach does not give absolute values of the degree of crystallinity, but allows one to estimate with high reliability the changes in molecular order (degree of crystallinity) in polyamide matrices when external or internal factors change during the formation of coatings or products from a given polymer material.

**Table 1** – Dependence of the degree of crystallinity of polyamide coatings on the type of deposition technology

| Formation technology, polymer-grade | PA 6, option 1 | PA 6, option 2 | PA 11, option 1 | PA 11, option 2 |
|---|---|---|---|---|
| Degree of crystallinety (ε), % | 1.51 | 1.63 | 2.1 | 2.14 |

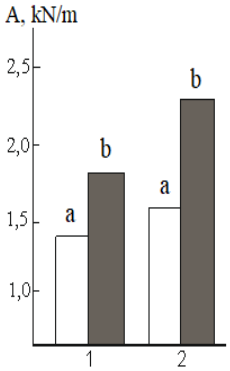
According to the data obtained for polyamide 6, two intense reflections are observed in the 2θ region from 15o to 30o. The calculation performed showed that this corresponds to interplanar distances d1=3.76 Å and d2 = 4.38 Å. Similarly, as for polyamide 11, option 2 of the technology for forming polyamide coatings increases the degree of crystallinity of polyamide coatings for the crystalline phase of the polymer material. It is possible to assume that molecular ordering will also be observed in the amorphous phase of polyamide coatings. The construction of the atomic density radial distribution function (RDDF) for the studied polymers [2] made it possible to establish that molecular ordering increases in the amorphous phase of the polymer matrix when using the second variant of the formation of polyamide coatings (Figure 6).




a,1 – coating based on PA6, formed according to technology 1; a,2 – coating formed according to technology 2; b, 1 – coating based on PA11, formed according to technology 1; b, 2 – coating formed according to technology 2

**Figure 6** – FRRAP of polyamide coatings

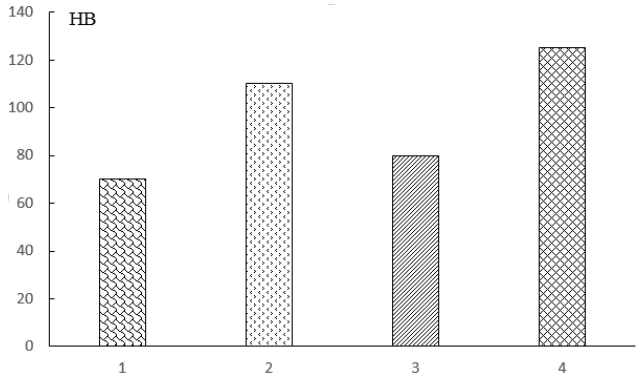
Based on the data obtained by X-ray diffraction analysis, it is possible to assume that as a result of the use of automated induction heating of splined bushings, the physical and mechanical characteristics of polyamide coatings will change. One of the main parameters determining the adhesive characteristics of polyamide coatings is adhesive strength. Conducted studies to determine the adhesive characteristics of polyamide coatings formed according to different technological approaches showed that induction heating of steel substrates makes it possible to provide higher adhesive characteristics compared to heating slotted bushings in chamber furnaces (Figure 7).




1 – option 1; 2 – option 2

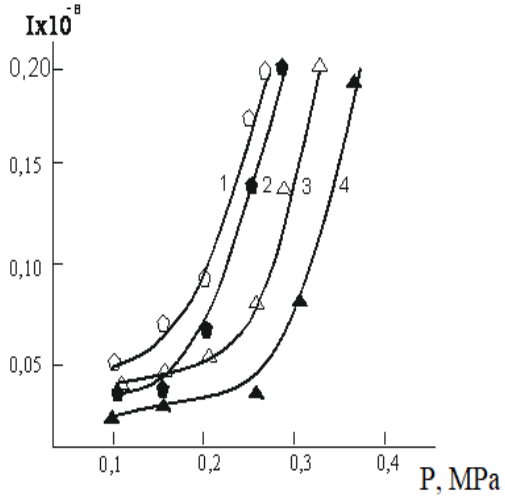
**Figure 7** – Adhesion strength of a coating based on PA6 (a) and P11 (b) with different coating formation technologies

Structural changes observed in coatings have a significant impact on the tribotechnical characteristics of polyamide coatings formed using various technological approaches. An increase in the degree of crystallinity and molecular ordering in the amorphous phases of the polymer leads to an increase in the hardness of the coatings (Figure 8) and, as a consequence, an increase in wear resistance (Figure 9).




1.3 - option 1 of coating formation, 2.4 - option 2 of coating formation

**Figure 8** – Dependence of the hardness of coatings from PA 11 (1.3) and PA 6 (2.4) on steel 60 PP




1.3 – option 1 of coating formation, 2.4 – option 2 of coating formation

**Figure 9** – Dependence of wear intensity on load during friction of coatings made of PA 11 (1.3) and PA 6 (2.4) on steel 60 PP; sliding speed 0.6 m/s

Based on the data presented in Figure 9, the wear intensity is reduced by 30–70 % for coating option № 2 compared to option № 1. This effect is typical for all grades of the studied polyamides and in a given range of loads.

**Conclusions**

The use of induction heating of splined bushings made of 40X steel leads to uniform heating of the samples under study, which makes it possible to more accurately determine the temperature ranges for the formation of polyamide coatings. The developed technological approach makes it possible to increase the values of the degree of crystallinity and molecular ordering in the amorphous phase of the polymer, which leads to an increase in the hardness and wear resistance of polyamide coatings formed from polyamide powder materials of various chemical structures and formation technologies. This article will be useful to specialists in the field of condensed matter physics, design engineers and technologists specializing in the development of automotive and tractor equipment, as well as graduate students and undergraduates.

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# RESEARCH INTO THE INFLUENCE OF LASER SCANNING SPEED ON THE CHARACTERISTICS OF 10G2 STEEL

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**Abstract**

A study was carried out of the dependence of the characteristics of strength and ductility of structural steel 10G2 samples on the modes of laser surface hardening and alloying with a fiber laser. On the opposite planes of a sample with overall dimensions of 6×20×200mm, 5 tracks were applied. Samples were tested for static destruction. It was established that the destruction of the treated samples in all cases was of a viscous nature with a satisfactory level of destructive deformations at stresses above the strength limit of the original material. Tensile diagrams indicate an insignificant effect of laser treatment on the elastic modulus of the material. The results obtained can serve as a basis for studying the relationship between laser beam heating modes and the material properties of the strengthened zone.

**Keywords**: laser hardening, alloying, scanning speed, temporary resistance, relative elongation.

**ИССЛЕДОВАНИЕ ВЛИЯНИЯ СКОРОСТИ ЛАЗЕРНОГО СКАНИРОВАНИЯ НА ХАРАКТЕРИСТИКИ СТАЛИ 10Г2**

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**Реферат**

Проведено исследование зависимости характеристик прочности и пластичности образцов из конструкционной стали 10Г2 от режимов лазерной поверхностной закалки и легирования волоконным лазером. На противоположных плоскостях образца с габаритными размерами 6×20×200 мм наносились по 5 дорожек. Проведены испытания образцов на статическое разрушение. Установлено, что разрушение обработанных образцов во всех случаях имело вязкий характер с удовлетворительным уровнем разрушающих деформаций при напряжениях выше предела прочности исходного материала. Диаграммы растяжения указывают на незначительное влияние лазерной обработки на величину модуля упругости материала. Полученные результаты могут служить базой для исследования взаимосвязи между режимами нагрева лазерным лучом и свойствами материала упрочненной зоны.

**Ключевые слова:** лазерная закалка, легирование, скорость сканирования, временное сопротивление, относительное удлинение.

## Introduction

Laser surface treatment technologies in some cases replace traditional heat treatment methods. This is determined by the advantages of a focused laser radiation: non-contact and localized thermal impacts, minimal heat-affected zone, high heating and cooling rates, reduced residual stress levels, minimized hogging, and increased structure dispersion [1]. Laser hardening can be considered as an alternative to surface hardening by carburization and subsequent volumetric hardening, as well as ion plasma nitriding. The scanning beam laser hardening technology without melting eliminates the need for surface grinding after hardening.

The relevance of problems associated with the influence of laser hardening modes on the structure and properties of various materials is confirmed by numerous publications of domestic and foreign scientists [1–17]. The authors of [1] were involved in determining the optimal laser hardening conditions for high-speed tool steel R6M5. As a result of testing samples processed using a technological gas CO2 laser at various powers and speeds of movement of a focused laser beam, it was found that laser hardening at a power of 600 W, a processing speed of 6 mm/s and a spot diameter of 3 mm increases the durability of knurling rollers up to 28 % compared to traditional volumetric heat treatment. Studies of the influence of laser pulse hardening on the structure, phase composition of tungsten-cobalt hard alloys VK6 and VK8 and the performance characteristics of cutting tools made on their basis were carried out in [2]. As a result of the research, optimal laser hardening modes were established, under which the durability of the hardened tool increases by 1.5-2.0 times. Research [3] is devoted to the effect of laser surface hardening on changes in the microstructure and wear resistance of tool die steel AISI H11 (analogous to 4Х5МФС). Laser hardening was carried out using a TruFiber 400 fiber laser with a scanning optical head. As a result of comparing the wear trace profiles of AISI H11 tool steel, it was found that laser hardening of the surface is characterized by a minimum penetration depth and maximum roughness. When measuring microhardness in the direction perpendicular to the laser beam tracks, the authors noted local softening due to the overlap of adjacent laser tracks. Article [4] investigated the influence of laser radiation parameters on the structure, microhardness and surface quality of 4Kh5MFS steel during laser hardening. It has been shown that laser hardening of 4Kh5MFS steel makes it possible to obtain a surface hard-ness of the order of 675–750 HV and a roughness of the order of 0.6–1.2 microns. In article [5], the microstructure, wear resistance (dry sliding fric-tion) and microhardness of steels AISI 1018 (analogous to steel 15), AISI 4140 (analogous to 42HFA) and gray cast iron after hardening with a diode laser with a power of 4 kW at three scanning speeds of 1000, 1500 and 2000 were studied. mm/min. As a result of processing, the hardness of AISI 1018 and 4140 steels increased from an average base value of 230 to 349 and 639 HV, respectively, and the hardness of gray cast iron from 330 HV to 830 HV. In article [6], the authors compared the hardness, depth of the hardened layer and wear resistance of the piston head of a diesel engine after laser hardening with a $CO_2$ laser and during high-frequency hardening. An increase in the hardness and depth of the hardened layer was noted during laser hardening in comparison with high-frequency hardening.

As a result of wear tests, it was found that the wear resistance of laser-hardened samples is 1.3 times higher than that of samples subjected to high-frequency hardening. In article [9], the authors studied the influence of various laser processing modes on the structure and properties of 20Kh3N3MFBA steel after volumetric heat treatment and the possibility of replacing the carburizing process with laser hardening. It has been established that the depth of the hardened layer depends on the speed of movement of the laser beam: the lower the speed, the greater the depth of the hardened layer. An optimal hardening mode has been established (speed 7 mm/s), at which maximum micro-hardness on the surface is achieved. It was determined in [11] that for structural steel 30KhGSA, hardening by continuous radiation of a multichannel (48 beams) CO2 laser on a complex model TsLT-Yu-5 with surface melting to a depth of 0.5 mm is optimal laser hardening mode. In this laser hardening mode, the processing zone consists mainly of tempered martensite, which provides high micro-hardness and abrasive wear resistance of the steel. The authors of work [12] were engaged in optimizing the degree of overlap of the hardened zone, and the authors of work [13] determined the optimal gap (2 mm) between two successive passes of a laser beam for processing steels S-45 (steel 45) and S-30 (Steel 30). In article [17], studies were carried out on the dependence of the characteristics of strength and ductility, as well as the microhardness of samples made of corrosion-resistant steel 40Cr13 on the modes of laser surface hardening with a fiber laser. It was established that the destruction of the treated samples in all cases was of a brittle nature with a low level of destructive deformations at stresses below the tensile strength of the original material.

It should be noted that research mainly consists of determining the influence of laser hardening modes on wear resistance, and the problem of the influence of laser processing on the strength characteristics and plasticity characteristics of the material is paid insufficient attention. The analysis of reference sources showed that among numerous publications of domestic and foreign scientists, there is insufficient research on the relationship between laser beam heating modes and the material mechanical properties of the strengthened zone.

### 1. Equipment and methods of conducting testing

The samples were made of 10G2 structural steel. Sample dimensions: thickness – 6 mm, width – 20 mm and length – 200 mm (deviations from the specified dimensions are taken into account when processing the results).

The samples were subjected to laser surface treatment using the radiation of a 1 kW ytterbium fiber laser with a lens for focusing the laser radiation, a moving system, and a head scanning the laser beam [10] under various processing modes (Table 1). Three samples were used for each quenching and alloying mode. On the opposite planes of a sample with overall dimensions of 20x200 mm, 5 tracks were applied. The length of the laser tracks was 170 mm. Each track was processed from the same side (Figure 1). The laser spot size is 0.35 mm. The distance from the sample surface to the last deflector was 450 mm. For alloying, a mixture of amorphous boron with acetone and BF-4 glue was previously applied to the samples.

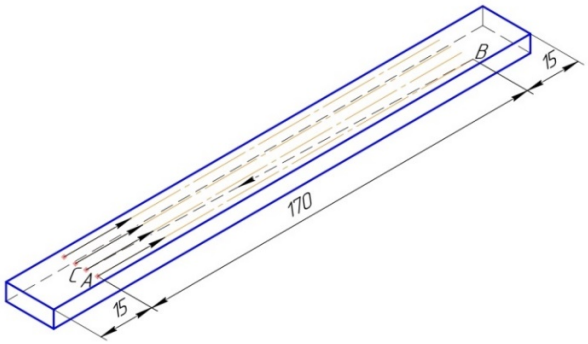



**Figure 1 –** Diagram of the movement of the laser scanning spot along the surface of the sample

To determine the strength characteristics, the samples were tested for static tension in accordance with GOST 1497-84 “Metals. Tensile test methods" on a Meitesi WDW-300 tensile testing machine (China). Tensile tests of the samples were carried out under load at a speed of 5 mm/min.

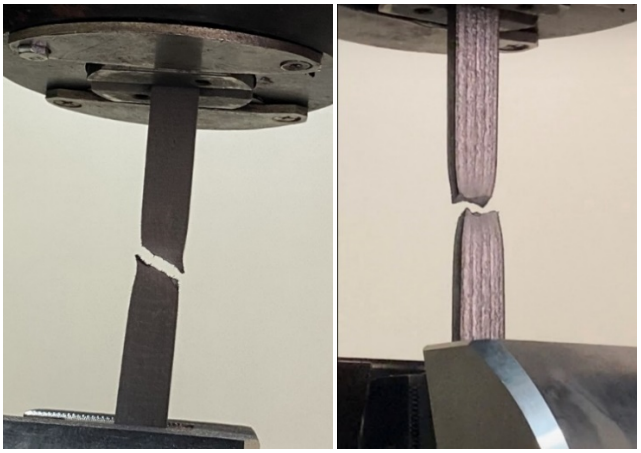
**Table 1 –** Laser processing modes

| Type of processing | Scanning spot, mm | Number of lines, pcs | Scanning frequency, Hz | Scanning speed *V*, mm/min | Sample number |
|---|---|---|---|---|---|
| Hardening | 4 × 2,25 | 7 | 220 | 300 | 1a, 1b, 1c |
| | | | | 500 | 2a, 2b, 2c |
| | | | | 700 | 3a, 3b, 3c |
| Alloying | | | | 300 | 4a, 4b, 4c |
| | | | | 500 | 5a, 5b, 5c |
| | | | | 700 | 6a, 6b, 6c |

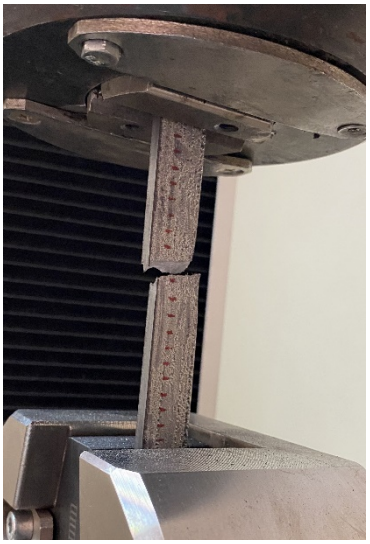
***Note**: in the column “Sample number” 1, 2, 3, 4, 5, 6 – batch number; a, b, c – sample number in the batch.*

**2. Some results and their consideration.** The destruction of untreated (UT) and treated samples occurred within the calculated length with the formation of a “neck”, a decrease in the cross-sectional area in the fracture zone and an increase in the length of the sample. All hardened and alloyed samples destroyed along sections perpendicular to the direction of the tensile load, and the samples, not subject to laser treatment, destroyed along sections located at an angle to the direction of the tensile force (Figure 2).

Examples of the destroyed samples and fracture sections are shown in Figure 3. All samples exhibit significant cold-hardening of the surface layers.



*a* – untreated sample *b* – laser-hardened sample



*c* – laser-alloyed sample

**Figure 2 –** Tensile testing of material samples

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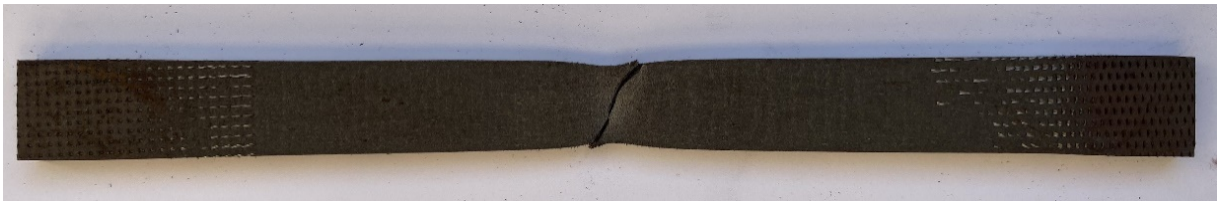
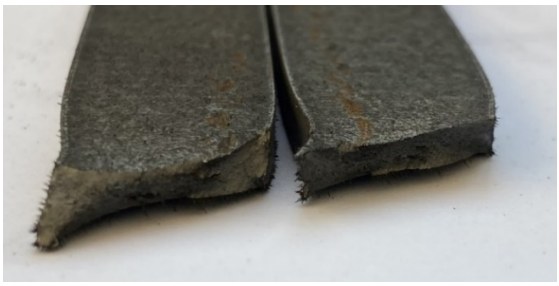


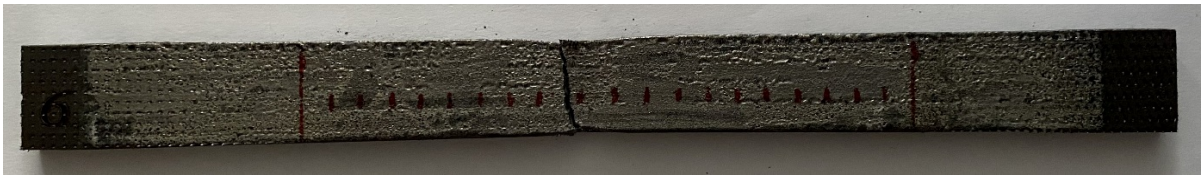
*a* – destroyed samples (sample HO2)



*b* – destruction cross-section (sample HO2)

*c* – destroyed samples (sample 1b)

*d* – destruction cross-section (sample 1b)



*e* – destroyed samples (sample 6a)

*f* – destruction cross-section (sample 6a)

**Figure 3 –** Destroyed samples (*a, c, e*) and destruction cross-section (*b, d, f*)

Based on the test results, the temporal resistance and relative elongation of all samples were determined. The data is summarized in table 2.

**Table 2** – Some characteristics when testing flat samples

| Scanning spot, speed of longitudinal movement | Type of processing | Batch number | Marking | Temporal strength , $\sigma_в$,, MPa | Relative elongation, $\delta$, % |
|---|---|---|---|---|---|
| | Untreated samples | HO | 1 | 567 | 26 |
| | | | 2 | 567 | 31 |
| | | | 3 | 565 | 31 |
| 4 × 2,25 mm (7 lines) 300 mm/min | Hardening | 1 | a | 648 | 17 |
| | | | b | 625 | 19 |
| | | | c | 666 | 19 |
| 4 × 2,25 mm (7 lines) 500 mm/min | Hardening | 2 | a | 622 | 22 |
| | | | b | 628 | 23 |
| | | | c | 628 | 18 |
| 4 × 2,25 mm (7 lines) 700 mm/min | Hardening | 3 | a | 626 | 21 |
| | | | b | 628 | 20 |
| | | | c | 622 | 23 |
| 4 × 2,25 mm (7 lines) 300 mm/min | Alloying | 4 | a | 622 | 14 |
| | | | b | 624 | 12 |
| | | | c | 625 | 14 |
| 4 × 2,25 mm (7 lines) 500 mm/min | Alloying | 5 | a | 635 | 13 |
| | | | b | 667 | 15 |
| | | | c | 626 | 9 |
| 4 × 2,25 mm (7 lines) 700 mm/min | Alloying | 6 | a | 651 | 15 |
| | | | b | 644 | 14 |
| | | | c | 643 | 15 |

Based on the results of the tests, the dependences of the σ stresses which arise in the samples on the ε deformations were plotted (Figure 4). For ease of comparison, the graphs were superimposed on the graphs of the samples that were not subjected to laser treatment.

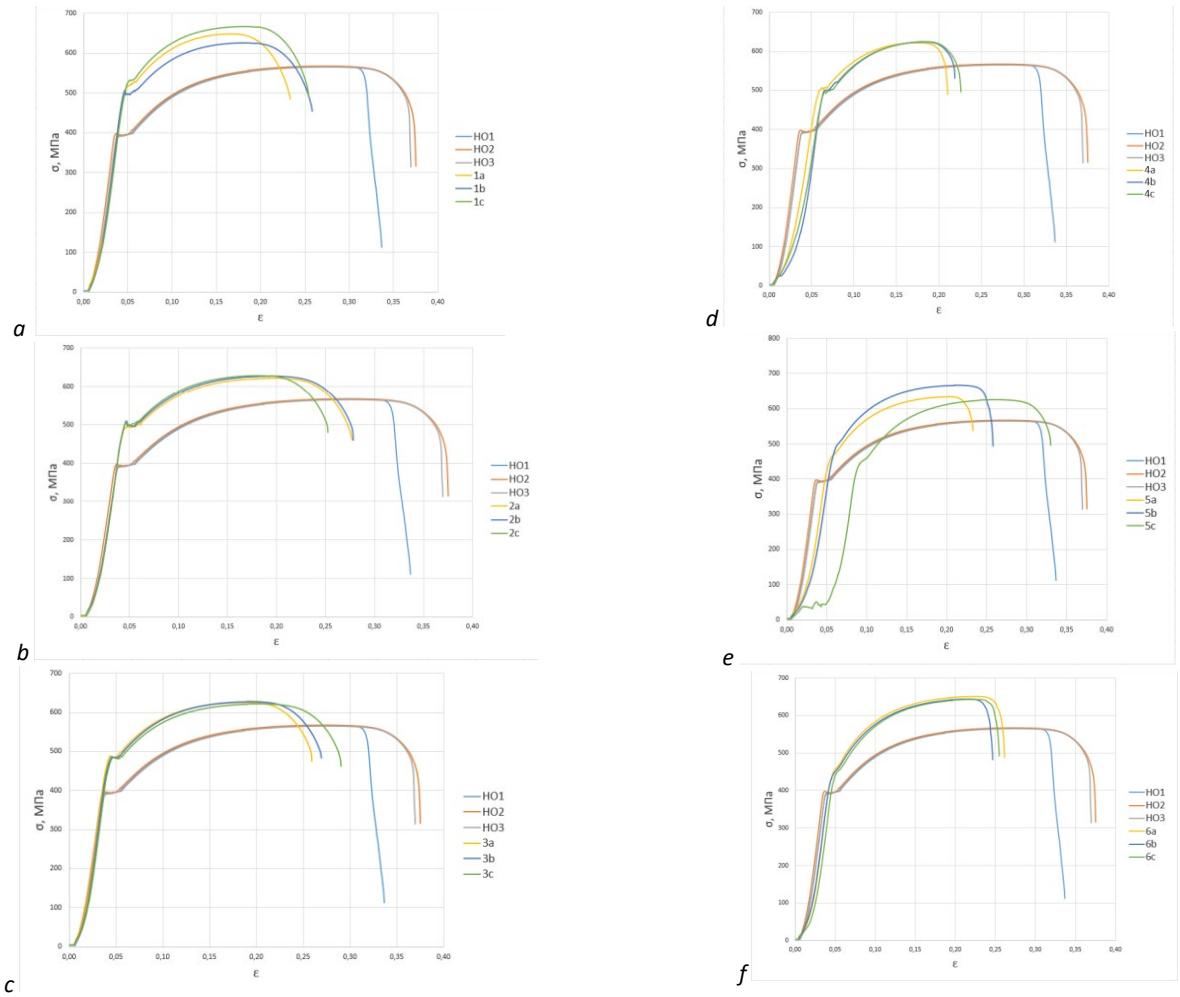



**Figure 4 –** Dependence of stresses (σ) arising in samples of 10G2 steel on deformations (ε): *a* – batch No. 1, *b* – batch No. 2, *c* – batch No. 3; *d* – batch No. 4; *e* – batch No. 5, *f* – batch No. 6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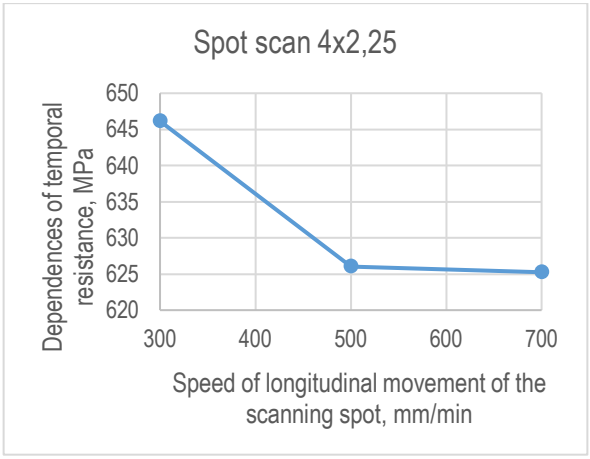
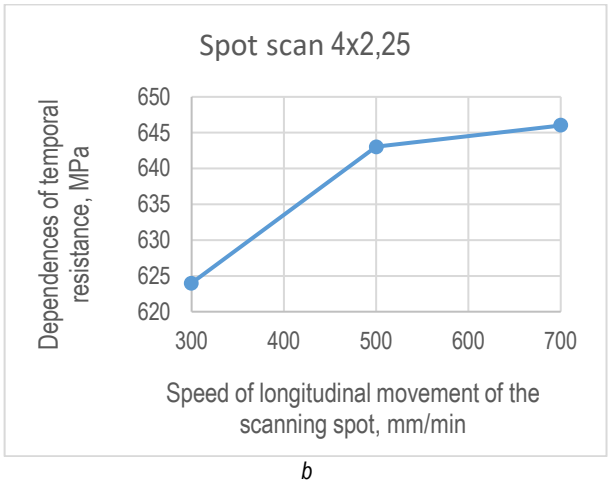
The analysis of the tensile diagrams indicates an insignificant influence of scanning speed parameters on the elastic modulus of the material in the studied range of parameters. While with laser alloying, the strain diagrams indicate a more significant influence of the laser scanning speed on the elastic modulus of the material. The destruction of hardened and alloyed samples occurred with a slight decrease in the level of destructive deformations. The test results show a high degree of repeatability of the obtained σ (ε) dependences.

The results show that the maximum stress for all the samples subjected to hardening and alloying increased in comparison with the untreated samples: by 14 % for batches No. 1, No. 6; by 13 % for batch No. 5; by 10 %; for batches No. 2, No. 3, No. 4. It should be noted that there is a slight decrease in the plasticity characteristics of 10G2 steel during laser hardening: a relative elongation of the hardened samples does not exceed 17–23 %, with a similar parameter of 31 % for the original samples. Whereas with laser alloying, the ductility characteristics decreased by more than half: relative elongation of the alloyed samples constituted 6–15 %. The decrease in plasticity characteristics is connected with a significant increase in the hardness of the quenched and alloyed zone and presence of microcracks on its surface.

Based on the test results, the dependences of the batch-average temporary resistance (Figure *5 a, b*) and relative elongation (Figure *6 a, b*) of hardened samples on the speed of the scanning spot longitudinal movement were determined.

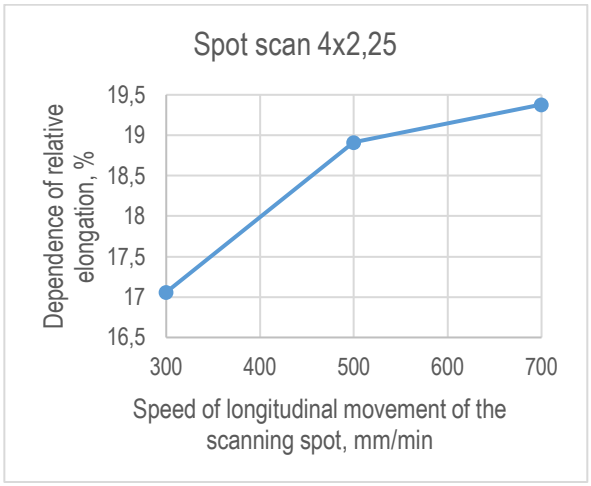



*a*

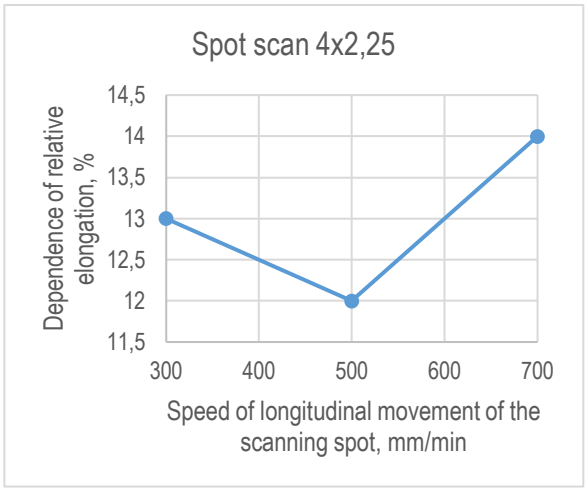



*b*

**Figure 5 –** Dependences of temporal resistance $\sigma_в$ on the speed of longitudinal movement of the scanning spot: *a* – hardened samples; *b* – alloyed samples




*a*




*b*

**Figure 6 –** Dependence of relative elongation δ on the speed of longitudinal movement of the scanning spot: *a* – hardened samples; *b* – alloyed samples

It has been determined that during laser hardening, the maximum value of temporal resistance corresponds to the lowest scanning speed (300 mm/min). With laser alloying, the highest value of temporal resistance corresponds to the maximum scanning speed (700 mm/min).

**Conclusion.** The research into the influence of laser scanning speed during laser hardening by radiation from a 1 kW ytterbium fiber laser on the mechanical characteristics of the 10G2 steel samples has been carried out. The studies were conducted at speeds of 300, 500, 700 mm/min. The results of static tensile tests point to a ductile nature of destruction of the treated samples. The destruction stresses of the hardened samples increased by 10–14 % with a proportional decrease in ductility characteristics. The destruction stresses of the alloyed samples also increased by 10–14 % with a decrease in plasticity characteristics by more than two times. The tensile diagrams showed an insignificant change in the elasticity modulus of the sample material after laser hardening and a more significant one during laser alloying compared to the original material.

The research results can be used to establish a relationship between a laser hardening modes and properties of the hardened zone material.

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## GEOECOLOGY

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# USING OF ORGANIC SLUDGE TO IMPROVE THE EFFICIENCY OF BIOGAS TECHNOLOGIES

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**Abstract**

Production volumes of organic sludge (digestate) increase as the amount of biogas plants in operation increases and biogas technologies are developed intensively. The rational use of organic sludge is a significant area for improving the efficiency of biogas technologies, since biohumus is an additional valuable product that can be used as organic fertilizer and, accordingly, reduce the cost of biogas production. The more organic material available for decomposition, the higher the biogas yield from the system and the more available organic sludge for plant nutrition. The resulting digestate requires appropriate refinement and quality improvement, primarily its dewatering and removal of harmful substances (including heavy metals). It makes possible to obtain and use an environmentally friendly biohumus as fertilizer for agricultural plants.

**Keywords:** biogas technologies, organic sludge, digestate, refinement system, dewatering, biohumus.

## ИСПОЛЬЗОВАНИЕ ОРГАНИЧЕСКОГО ОСАДКА ДЛЯ ПОВЫШЕНИЯ ЭФФЕКТИВНОСТИ БИОГАЗОВЫХ ТЕХНОЛОГИЙ

**Ю. В. Кляусова, А. А. Цыганова, Г. В. Бельская**

**Реферат**

По мере увеличения количества функционирующих биогазовых установок и интенсивного развития биогазовых технологий увеличиваются объемы производства органического осадка (дигестата). Рациональное использование органического осадка является значимым направлением повышения эффективности биогазовых технологий, так как биогумус является дополнительным ценным продуктом, который можно использовать в качестве органического удобрения и, соответственно, удешевлять производство биогаза. Чем более доступный для разложения органический материал, тем выше выход биогаза из системы и тем более доступен органический осадок для питания растений. Полученный дигестат требует соответствующей доработки и улучшения качества, прежде всего обезвоживания и удаления вредных веществ (включая тяжелые металлы). Это позволяет получать и использовать экологически чистый биогумус в качестве удобрения для сельскохозяйственных растений.

**Ключевые слова:** биогазовые технологии, органический осадок, дигестат, система доработки, обезвоживание, биогумус.

**Introduction**

The National Strategy for Sustainable Socio-Economic Development of the Republic of Belarus for the period up to 2030 defines the further innovative development for the country's fuel and energy complex [1]. This aim will be ensured by involving nuclear fuel and renewable energy sources in the energy balance. One of the main directions for the development of renewable energy is the production of biogas by creating biogas complexes on livestock farms, food industry enterprises, municipal waste landfills in large cities, as well as its effective technological application [2]. Some progress has been made in this regard. Thus, in 2021, the target for the share of renewable energy sources in the total consumption of fuel and energy resources amounted to 7.4 %, while the installed capacity (MW) of biogas complexes in running increased by 13 %. Electricity generation from biogas increased by 173 %.

According to the Register of Certificates of Origin Energy (Ministry of Natural Resources & Environmental Protection, Republic of Belarus) from 01.11.2021 [3, 4], 29 biogas plants with a total installed capacity by 38.127 MW are operating in the country. Among this quantity, 14 plants operate on the waste of livestock farms, their installed capacity is 18, 772 MW. Accordingly, 15 biogas plants operate using organic waste from municipal and communal services. They are located at municipal solid waste (MSW) landfills near large and medium-sized cities. These plants (using special gas-piston equipment) produce so-called landfill gas. Their total installed capacity is 19.355 MW [5].

An important condition for the effective biogas production is the appropriate structure of biogas plants, including the following technological zones:

1. Substrate management.
2. Composition of the raw material, its pre-processing and loading into the reactor.
3. Anaerobic fermentation process.
4. Storage, refine (cleaning from impurities) and use of biogas.
5. Storage (placement) and refine of organic sludge formed after fermentation.

All zones of biogas plants should be combined into one technological process and have appropriate equipment for successful operation. [6]. First four zones of biogas complexes in running are well studied. However, the fifth zone – the storage (placement) and refinement of organic sludge formed after fermentation – is not payed enough attention in literary sources. Often, there is no information at all. Due to our opinion, this can be explained by the small installed capacity of biogas complexes operated in foreign countries, primarily EU countries, and, as a result, by small volumes of organic sludge production.

The Republic of Belarus has developed specific conditions for the formation of a raw material base using in biogas technologies. First of all, it is the presence of large volumes, the dynamics of formation and the structure of organic raw materials suitable for using in bioreactors. The main source of organic raw materials is livestock, which is characterized by a high level of concentration and specialization. Currently, there are about 100 large cattle fattening farms, 120 large pig farms and about 60 poultry farms, which produce up to 300 thousand tons of liquid organic waste per day [7], or in terms of 30 million $m^3$ of wastewater per year. The main raw materials for the production of biogas currently are: 1) manure of agricultural animals (secondary biomass), with the addition of other components (green biomass) and 2) solid household waste - this is landfill waste containing an organic fraction - for the production of landfill gas using special equipment [8]. The biogas potential produced from organic livestock waste is 4 billion $m^3$ of biogas per year, which corresponds to 800 MW of electric capacity. Using this resource would provide savings about 3.87 million tons of equivalent fuel per year [9].

Organic sludge production is increasing as the amount of biogas plants in running increases and biogas technologies are developed all over the world. Thus, effective management of organic sludge and turning it to biohumus is a significant reserve for improving the efficiency of biogas technologies.

**Refinery System for Turning Organic Sludge to Biohumus**

An organic sludge or digestate (from digestate – fermented deposition) is a stabilized material containing undissolved organic residues of biomass fermentation (cellulose chains most of all), a liquid fraction and necrotic microorganisms. After fermentation processes, which occur at a temperature of about 60 °C, this material is free of weed seeds and pathogenic microorganisms. It does not have an odor.

The composition and properties of the resulting sludge directly depend on the composition and properties of the raw material used for fermentation processes. This is the main determinant of methane yield, as well as the rate of formation and quality of digestate. The more organic material available for decomposition (assimilation), the higher the biogas yield from the system and the more organic sludge available for plant nutrition. In addition, the quality of the resulting sludge can be affected by additional components (including toxic, for example, heavy metal compounds, antibiotics, etc.) contained in initial raw materials. Raw materials used for fermentation may contain mineral components consisting of sand, earth, stones. These components are called raw ash. Such constituents are undesirable for the process of biogas production and organic sludge formation. They can reduce the quality of the resulting digestate and lead to technical problems, namely settling to the bottom of the bioreactor and possible equipment breakdowns.

Anaerobic processes in the bioreactor occur in two ways, which are determined by the content of solid substance part and moisture part in the original biomass. These processes are called dry and wet fermentation. Dry fermentation requires less energy and material costs (for transporting the organic mass and heating the liquid fraction), however, the microbiological process under these conditions is unstable, which leads to uneven formation of biogas, and often to stop the microbiological process. Wet fermentation (with the addition of water to the brooding biomass) requires additional costs for transporting and heating water, which is accompanied by inevitable heat losses and quite high electricity consumption. Despite the fact that the dry fermentation method is cheaper, the wet fermentation process is used more often, since the production of biogas in this case is more stable and guaranteed. With regard to the properties of the digestate obtained by wet fermentation, high water content can be noted as the serious disadvantage. Some authors indicate that up to 92 % moisture and only 8 % dry (useful) fraction may be contained in the organic sludge. Since the main use of digestate is to bring it into soils as an organic fertilizer, it is necessary to improve the applied technologies and carry out the target work to optimize conditions for methane fermentation processes.

Different substrates containing organic compounds and a wet fraction are used in biogas plants. Most organic compounds are decomposed by microorganisms during anaerobic fermentation. Biogas or methane ($CH_4$) and carbon dioxide ($CO_2$) are the most important degradation products in terms of their amount. In addition, initially biogas may contain small amounts of hydrogen sulfide ($H_2S$) and ammonia ($NH_3$). Decomposition processes convert a liquid or solid initial substrate into a liquid or semi-liquid digestate with high water content.

The organic sludge after fermentation of the biomass contains a significant amount of nitrogen, which is easily available for plant nutrition, as well as phosphorus, potassium, sulfur and some micro-elements. Thus, digestate not contaminated with toxic substances can be considered as a high-quality organic fertilizer [10]. The nutritional composition of digestate may vary slightly depending on the substrates used for fermentation. The approximate composition of digestate is given in (Table 1).

**Table 1** – Composition of organic sludge

| Indicators | After fermentation of primary biomass | After fermentation of secondary biomass |
|---|---|---|
| Dry matter, % | 7.0 | 6.1 |
| PH | 8.3 | 8.5 |
| Organic substance, kg/t | 51.0 | 42.0 |
| Total nitrogen, kg/t | 4.7 | 4.8 |
| Ammonium, kg/t | 2.7 | 2.9 |
| Phosphorus | 1.8 | 1.8 |
| Potassium | 5.0 | 3.9 |

The above data on nutrient content in digestate are given for the two main types of feedstocks used in bioreactors - primary biomass, i.e. plant material of various origins (including green mass), and secondary biomass, or organic biological waste, mainly manure of agricultural animals. As can be seen from the table, digestate obtained from different types of raw materials has fairly similar indicators in terms of the content of dry matter and organic fraction, acidity indicator, as well as nitrogen (including ammonium), phosphorus and potassium contains.

Since only a small amount of ammonia leaves the substrate, most of the nitrogen remains in digestate. Decomposition processes reduce the amount of bound nitrogen in the organic substance, while the amount of ammonia increases from 45 % to 76 %, which is present in the ammonium nitrate digestate. This indicates the maximum conservation and accumulation of digestible nitrogen. When brought into the soil, digestate improves the conditions for the functioning of soil microorganisms and increases efficiency of nitrogen fixation. It leads to increased soil fertility in near period of time.

However, it should be noted that when digestate is stored and used, there is a high risk of ammonia releasing into the atmosphere. It is a negative process because ammonia has a high greenhouse effect. It is known that in ammonium form, nitrogen quickly becomes available for assimilation by plants. However, if the needs of cultivated plants are low, then the brought nitrogen can be used inefficiently and lead to denitrification of soils and include greenhouse effect.

The nutritional content of phosphorus in digestate is from 1.8 to 3.5 kg/t, with its content being approximately at the same level for the two main types of feedstock. Other macro- and micro elements added with the initial substrate, such as potassium, magnesium, calcium, also remain in digestate in the same amounts. The dynamics of the biogenic micro element of sulfur in anaerobic decomposition processes is of particular note. Sulfur, in the form of hydrogen sulfide ($H_2S$), partially goes into biogas. Depending on the method used to remove traces of hydrogen sulfide from the biogas (desulfurization process), most of the sulfur can also be returned to digestate [10, 11]. In addition, it is known that undigested cellulose residues contained in the organic sludge reduce the washing-out process of nutrient (including mineral) elements from the soil, and form its optimal water-air regime. All above mentioned qualities of organic sludge are of the high nutritional value for using it as plant fertilizer.

However, the potential use of digestate in our country is limited due to its rather specific physico-chemical properties. The first and main task of digestate quality management is to regulate its moisture content. (Fig. 1) shows theoretically possible uses of digestate [12].

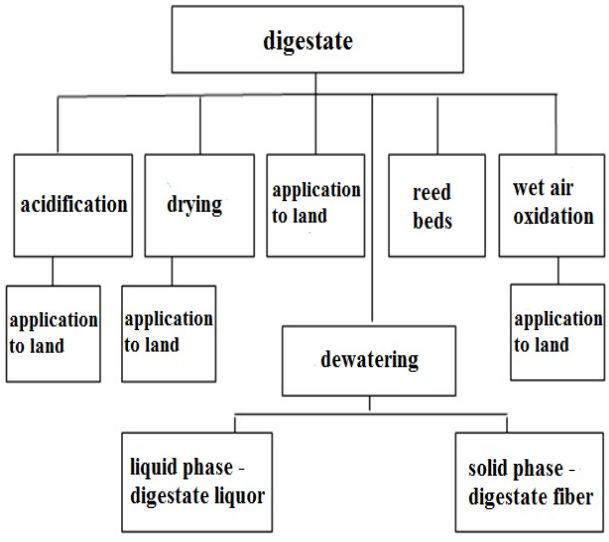


**Figure 1** – Methods of digestate management




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Methods of digestate management are:

1. Digestate after fermentation of organic raw materials can be introduced directly into soils, which is a fairly common technique. To reduce ammonium emissions, there are recommendations to add acid salts to it. However, this technique can lead to acidification of soils, so it is used very limited and in compliance with strict regulations.

2. Drying of digestate under natural conditions. For natural drying, the organic residue is pumped into special settling ponds that occupy sufficiently large territories. Here, moisture evaporates naturally under the influence of solar radiation and air temperature, and organic sedimentation also occurs. Sediment is directed for additional heat drying or introduced into soils.

3. Artificial drying of sediment. Artificial drying of formed organic sediment is carried out using heat energy generated by cogeneration plant of biogas complex. This makes it possible to obtain practically ready organic fertilizer without additional energy costs. The relatively low moisture content makes it suitable for transportation.

4. Target dewatering of digestate is carried out by special technological methods, including physical and chemical methods – coagulation, flocculation, etc., using chemical reagents and physical impacts. This leads to separation of the sludge into a semiliquid fraction containing complete nutrient elements of nitrogen, phosphorus and potassium (NPK), and a fibrous solid fraction consisting of undeposited cellulose fibers, as well as large volumes of water.

5. Oxidation of digestate with wet air. This is the oxidation process of the viscous organic fraction under conditions of increased pressure (4–6 MPa) and temperature (200–300 °C). The efficiency of this method can increase the organic matter content of the sludge to 90 %. The organic substance in this case is represented by a mixture of short chain fatty acids and methanol.

6. Creation of artificial wetlands. This technique is used with small volumes of digestate formation, which is pumped to areas located in low-lying areas. To accelerate mineralization processes, reeds and other swamp plants are planted in these areas. Water flowing from such a system can be used for irrigation. Periodically, sediment is extracted from the bottom of artificial wetlands and used as organic fertilizer [12].

All of the above digestate management techniques have advantages and disadvantages. Heat drying methods are highly efficient, however, they are quite energy intensive, which makes their using limited. Most often, in biogas plants, the generated heat energy is used for other needs, in particular, for the production of electric energy, drying of woody biomass, heating of production buildings and greenhouses. Where the volumes of digestate produced are large enough, heat drying is limited. Drying in settling ponds based on natural evaporation processes is more economically viable and environmentally efficient. This technique can reduce the liquid fraction of digestate from 90 % to 20 %. Significant disadvantages of this technology are the need for large areas, the risk of contamination of adjacent areas, and significant time needed. The process of oxidation of organic sludge with wet air requires economic costs to create high atmospheric pressure and temperature, as well as refinement of the obtained material. The creation of artificial wetlands requires large areas, processes are quite inert and require a long period of time.

**Conclusion**

One of the main directions of the development of renewable energy in the Republic of Belarus is the production of biogas by function biogas plants on livestock farms and landfills of solid municipal waste. As the amount of biogas plants in operation and the intensive development of biogas technologies increase, the volume of organic sludge production increases too. Biohumus can be obtained from any organic sludge formed by fermentation of biomass.

Digestate is an additional product of biogas production. The more organic material available for decomposition (assimilation), the higher the biogas yield from the system and the more organic digestate available for plant nutrition. Its composition allows to use digestate as a fertilizer, since up to 50 % of organic nitrogen is released in the fermenter in the form of ammonium nitrate, which indicates maximum preservation and accumulation of nitrogen. When brought into the soil, digestate improves the conditions for the functioning of soil microorganisms, nitrogen fixation and other microbiological processes leading to increased soil fertility. Furthermore the nutritional content of phosphorus and potassium is at the same level for the two main types of feedstock which indicates its high value as a fertilizer for agricultural plants.

On the other hand, toxic substances (heavy metal ions, antibiotics, etc.) can be contained in digestate, entering the soil, they are not decomposed by soil microorganisms. Therefore, digestate requires appropriate refinement, improvement of quality to turn it into biohumus for further sustainable use. Effective management of organic sludge and its transformation into high-quality and environmentally friendly biohumus can significantly reduce the payback time of biogas plants and optimize the cost of the obtained biogas.

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# REGULARITIES OF VARIABILITY IN AVERAGE MONTHLY FLOW RATES DURING THE LOW-WATER PERIOD IN THE RIVERS OF BELARUS

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**Abstract**

The research is devoted to the study of long-term dynamics of fluctuations in average monthly flow rates during the summer-autumn and winter low-water periods in the rivers of Belarus. The assessment of extreme water flows of rare frequency in the summer-autumn period for the two time intervals (1961–1990, 1991–2020) demonstrates an increase in their frequency at most gauging stations over the last 30-year period. The minimum average monthly flow rates in the summer-autumn period are most often observed in August or September. The research shows that all months covering the winter low-water period are characterized by a tendency to increase runoff, more pronounced after 1988.

**Key words:** flow rates, average monthly runoff, summer-autumn low water, winter low water, frequency of hydrological phenomena, modular coefficient.

## ЗАКОНОМЕРНОСТИ ИЗМЕНЧИВОСТИ СРЕДНЕМЕСЯЧНЫХ РАСХОДОВ СТОКА В МЕЖЕННЫЙ ПЕРИОД НА РЕКАХ БЕЛАРУСИ

**С. В. Сидак, А. А. Волчек, С. И. Парфомук, В. А. Кофанов**

**Реферат**

Работа посвящена исследованию многолетней динамики колебаний среднемесячных расходов стока в период летне-осенней и зимней межени на реках Беларуси. Выполненная оценка экстремальных расходов воды редкой повторяемости в летне-осенний период для двух временных интервалов (1961–1990 гг., 1991–2020 гг.) демонстрирует увеличение их частоты по большинству гидрологических постов за последний 30-летний период. Минимальные средние месячные расходы в летне-осенний период чаще всего наблюдаются в августе или сентябре. В работе показано, что для всех месяцев, охватывающих период зимней межени, характерна тенденция к увеличению стока, более выраженная после 1988 г.

**Ключевые слова:** расход воды, среднемесячный сток, летне-осенняя межень, зимняя межень, повторяемость гидрологических явлений, модульный коэффициент.

### Introduction

Many scientists have studied the patterns of formation of river runoff in Belarus and its variability in the spatiotemporal aspect [1–3]. The analysis of hazardous hydrological phenomena on the territory of Belarus over the past 20 years carried out in [4] shows that the most frequent are hazardous phenomena accompanied by low water levels. Therefore, the study of runoff during low water periods is of particular relevance. Analysis of the dynamics of runoff elements during this period and the identification of the main patterns of its variability is of great practical interest due to their consideration in the justification and development of water management and water protection measures. Minimum flow acts as a limiting factor in the use of water resources, and identifying patterns in the frequency and intensity of droughts is critical to assessing the potential environmental and social impacts on processes associated with surface water resources.

Despite the large number of works devoted to the study of minimum runoff, today the issue of long-term dynamics of average monthly flow rates during low-water periods in the rivers of Belarus remains insufficiently studied.

The purpose of this work is to assess the variability of the long-term average monthly flow of rivers in Belarus during the summer-autumn and winter low-water periods.

To achieve this goal, the following tasks were solved:

– Analysis of the dynamics of average monthly water flows during the low-flow period.
– Assessment of the frequency of extreme values of minimum summer-autumn runoff for the period 1961–2020.
– Identification of trends in the month during which the lowest river flow discharges of the year were observed.

### Materials and methods

As a rule, on the rivers of Belarus, the summer-autumn low-water period begins in early June and ends in late November – mid-December [5]. Winter low water usually begins at the end of November – mid-December, and on the rivers of the southern part of Belarus – at the end of December and lasts until the start of the flood, which usually begins in the first ten days of March in the south-west of Belarus, in the second or third ten days of March on the rivers of the northern and northeastern parts of the country. In view of this, the object of the study is the average monthly water flow (from June to March) at the gauging stations with long series of observations (the Pripyat River at Mozyr station, the Neman River at Grodno station, the Western Dvina River at Vitebsk station, the Berezina River at Bobruisk station, the Dnieper River at Orsha station, the Sozh River at Gomel station, and the Viliya River at Mikhalishki station).

To solve the above problems, the study used observation materials from the State Institution "Republican Center for Hydrometeorology, Radioactive Pollution Control and Environmental Monitoring" of the Ministry of


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Natural Resources and Environmental Protection of the Republic of Belarus for the studied hydrological gauging stations for the period of instrumental observations, published in the materials of state cadasters. The period of systematization and analysis covers a 60-year period (1961–2020). The restoration of gaps in data series was carried out using the "Hydrolog" computer software package [6].

In this study, moving 10-year averaging was used to identify larger changes in the course of monthly runoff curves, as well as to compare series of long-term runoff fluctuations at different gauging stations.

The assessment of changes in the probability of the formation of extreme water flows of rare frequency under conditions of modern climate warming was carried out using the following criterion: to analyze changes in the frequency of dangerous minimum summer-autumn water flows, the number of years with a water flow less than the 90 % probability flow was selected. This threshold value was chosen based on an analysis of data on the most significant droughts on the rivers of Belarus [5, 7].

**Results and discussion**

Figure 1 shows the long-term variation of modular runoff coefficients for the summer months over moving average 10-year periods for the period 1961–2020.

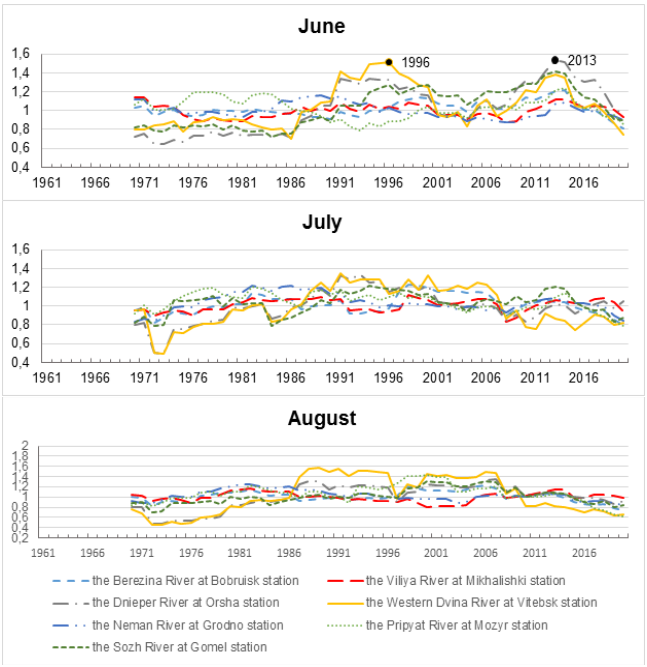


**Figure 1** – Change in modular runoff coefficients for the summer months by moving average 10-year periods, 1961–2020

The graph of moving 10-year average modular coefficients of river runoff for the summer months clearly shows that the long-term variability of river flow in June for most of the study observation points remained stable until 1986. From 1986 to 1997, June runoff was close to or above normal. From 1986 to 2020, there are two waves in runoff variability with peaks in 1996 and 2014. Runoff in August at the Western Dvina River at Vitebsk gauging station from 1973 to 1986 is characterized by indicators below normal, however its growth is observed; from 1986 to 2010, the flow in August at this gauging station was higher than normal; from 2007 to 2020 there is a steady downward trend in runoff. A similar situation arises for the Dnieper River at Orsha gauging station. For the Pripyat River at Mozyr station the deviation of runoff from the long-term average in August until 1996 did not exceed 20 %; until 2000 there was an increase in runoff; from 2000 to 2020 there was a trend towards a decrease in runoff. For the remaining gauging stations for the period 1961–2020 the runoff in August is characterized by high correlation between the series of 10-year moving averages; almost over the entire time interval, the deviation of the runoff for August from the long-term average value for these gauging stations does not exceed 20 %.

Figure 2 shows the multi-year variation of modular runoff coefficients for the autumn months over moving average 10-year periods for the period 1961–2020.

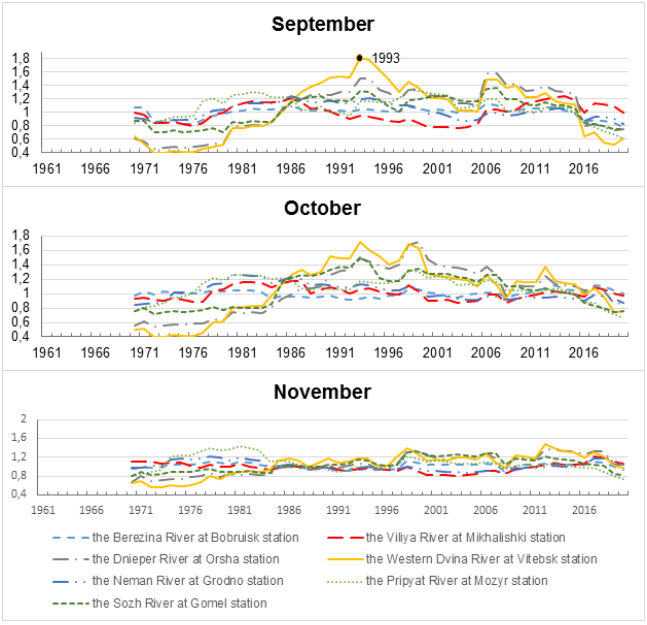


**Figure 2** – Change in modular runoff coefficients for the autumn months by moving average 10-year periods, 1961–2020

Graphs of moving 10-year average modular coefficients of river flow for the autumn months at the gauging stations Western Dvina River at Vitebsk, the Dnieper River at Orsha, and the Sozh River at Gomel clearly demonstrate a fairly stable trend towards an increase in flow until 1993, and then a decrease in flow until 2020, which is changeable. In November, for these gauging stations until 2015, there is a trend towards an increase in runoff in the long-term course. For the Berezina River at Bobruisk station, runoff deviations in October over the entire studied time interval from the norm do not exceed 10 %. For the Neman River at Grodno station, the runoff from 1974 to 2000 is higher than normal and has a wave-like character with a peak in 1982; after 2000, the flow is below the long-term average flow rate for October, the deviation from which does not exceed 10 %. The course of the curve of modular runoff coefficients for October according to sliding 10-year periods for the river is similar for the Viliya River at Mikhalishki station. For the Pripyat River at Mozyr gauging station for the 40-year period 1975–2015 the runoff in October is higher than the long-term average flow rate for October, and the change in runoff has a wave-like character. Statistically insignificant negative trends in moving 10-year average modular coefficients of river flow for November are characteristic of gauging stations Berezina River at Bobruisk, the Viliya River at Mikhalishki, the Neman River at Grodno, and the Pripyat River at Mozyr. The greatest variability of runoff in September was noted at the Western Dvina River at Vitebsk gauging station. It is characterized by a stable tendency to increase runoff until 1993, runoff values above the long-term average for September during the period 1985–2015.

From Table 1 it can be seen that for all the studied stations there was an increase in runoff during the months covering the winter low-water period. The exception is the flow in December at the Viliya River at Mikhalishki station and the Pripyat River at Mozyr station (reduction of runoff by 2 % and 7.6 %, respectively). The greatest change in runoff is typical for February. For the months covering the period of summer-autumn low water, the situation is ambiguous: at the Dnieper River at Orsha station and the Sozh River at Gomel gauging station, an increase in runoff is observed in these months; for the remaining gauging stations, multidirectional changes in runoff are characteristic.

An assessment of the frequency of dangerous minimum summer-autumn water flows was carried out for two periods: 1) from 1961 to 1990 (base period), 2) from 1991 to 2020 (modern period). The assessment results for the studied gauging stations are shown in Table 2.

**Table 1** – Average runoff values by month for three time intervals and changes in runoff values for the period 1961–1990 in relation to the period 1991–2020 (Δ, %).

| Period | Months | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | December | January | February | March | June | July | August | September | October | November |
| | *the Berezina River at Bobruisk station* | | | | | | | | | |
| 1961–1990 | 97.9 | 94.0 | 87.5 | 133.6 | 100.3 | 87.8 | 84.6 | 83.8 | 97.9 | 100.8 |
| 1991–2020 | 99.2 | 103.3 | 114.2 | 156.0 | 105.0 | 89.3 | 80.5 | 77.2 | 99.2 | 102.4 |
| 1961–2020 | 98.5 | 98.6 | 100.9 | 144.8 | 102.6 | 88.6 | 82.5 | 80.5 | 98.5 | 101.6 |
| Δ, % | **1.3** | **9.9** | **30.5** | **16.8** | **4.7** | **1.7** | –4.8 | –7.9 | **1.3** | **1.6** |
| | *the Western Dvina River at Vitebsk station* | | | | | | | | | |
| 1961–1990 | 138.6 | 113.1 | 100.8 | 183.2 | 152.5 | 125.1 | 108.8 | 111.4 | 139.1 | 163.2 |
| 1991–2020 | 171.2 | 166.0 | 131.8 | 298.8 | 174.8 | 118.6 | 104.4 | 116.6 | 158.3 | 204.5 |
| 1961–2020 | 154.9 | 139.5 | 116.3 | 241.0 | 163.6 | 121.8 | 106.6 | 114.0 | 148.7 | 183.8 |
| Δ, % | **23.5** | **46.8** | **30.8** | **63.1** | **14.6** | –5.2 | –4.0 | **4.7** | **13.8** | **25.3** |
| | *the Viliya River at Mikhalishki station* | | | | | | | | | |
| 1961–1990 | 55.2 | 52.2 | 48.6 | 78.9 | 52.8 | 48.0 | 48.0 | 47.3 | 52.4 | 58.5 |
| 1991–2020 | 54.1 | 60.9 | 63.8 | 86.2 | 51.6 | 46.9 | 42.6 | 44.8 | 47.3 | 54.1 |
| 1961–2020 | 54.6 | 56.5 | 56.2 | 82.6 | 52.2 | 47.5 | 45.3 | 46.0 | 49.9 | 56.3 |
| Δ, % | –2.0 | **16.7** | **31.3** | **9.3** | –2.3 | –2.3 | –11.3 | –5.3 | –9.7 | –7.5 |
| | *the Dnieper River at Orsha station* | | | | | | | | | |
| 1961–1990 | 77.1 | 60.3 | 53.6 | 114.3 | 81.8 | 77.9 | 65.5 | 61.1 | 65.1 | 79.1 |
| 1991–2020 | 89.1 | 87.8 | 82.1 | 166.3 | 111.2 | 83.6 | 73.8 | 76.7 | 88.0 | 107.9 |
| 1961–2020 | 83.1 | 74.1 | 67.8 | 140.3 | 96.5 | 80.7 | 69.7 | 68.9 | 76.5 | 93.5 |
| Δ, % | **15.6** | **45.6** | **53.2** | **45.5** | **35.9** | **7.3** | **12.7** | **25.5** | **35.2** | **36.4** |
| | *the Neman River at Grodno station* | | | | | | | | | |
| 1961–1990 | 161.5 | 161.0 | 155.3 | 257.7 | 164.1 | 138.5 | 125.7 | 129.2 | 153.7 | 173.9 |
| 1991–2020 | 163.6 | 186.5 | 210.1 | 290.2 | 144.9 | 128.2 | 110.6 | 113.9 | 133.9 | 165.3 |
| 1961–2020 | 162.6 | 173.8 | 182.7 | 274.0 | 154.5 | 133.4 | 118.1 | 121.5 | 143.8 | 169.6 |
| Δ, % | **1.3** | **15.8** | **35.3** | **12.6** | –11.7 | –7.4 | –12.0 | –11.8 | –12.9 | –4.9 |
| | *the Pripyat River at Mozyr station* | | | | | | | | | |
| 1961–1990 | 322.5 | 333.7 | 310.6 | 487.5 | 408.1 | 320.1 | 260.4 | 236.7 | 254.2 | 300.0 |
| 1991–2020 | 298.0 | 334.1 | 407.1 | 666.9 | 401.0 | 292.9 | 270.6 | 223.0 | 240.9 | 279.7 |
| 1961–2020 | 310.3 | 333.9 | 358.9 | 577.2 | 404.6 | 306.5 | 265.5 | 229.9 | 247.5 | 289.9 |
| Δ, % | –7.6 | **0.1** | **31.1** | **36.8** | –1.7 | –8.5 | **3.9** | –5.8 | –5.2 | –6.8 |
| | *the Sozh River at Gomel station* | | | | | | | | | |
| 1961–1990 | 124.5 | 119.1 | 105.1 | 201.8 | 121.4 | 115.3 | 96.6 | 92.6 | 108.9 | 123.9 |
| 1991–2020 | 145.9 | 149.5 | 160.4 | 273.5 | 164.5 | 119.6 | 106.9 | 99.0 | 115.3 | 147.7 |
| 1961–2020 | 135.2 | 134.3 | 132.8 | 237.6 | 142.9 | 117.5 | 101.7 | 95.8 | 112.1 | 135.8 |
| Δ, % | **17.2** | **25.5** | **52.6** | **35.5** | **35.5** | **3.7** | **10.7** | **6.9** | **5.9** | **19.2** |

*Note:* the highlighted values correspond to the gauging stations and months that are characterized by an increase in runoff values for the period 1991–2020 in relation to the period 1961–1990.

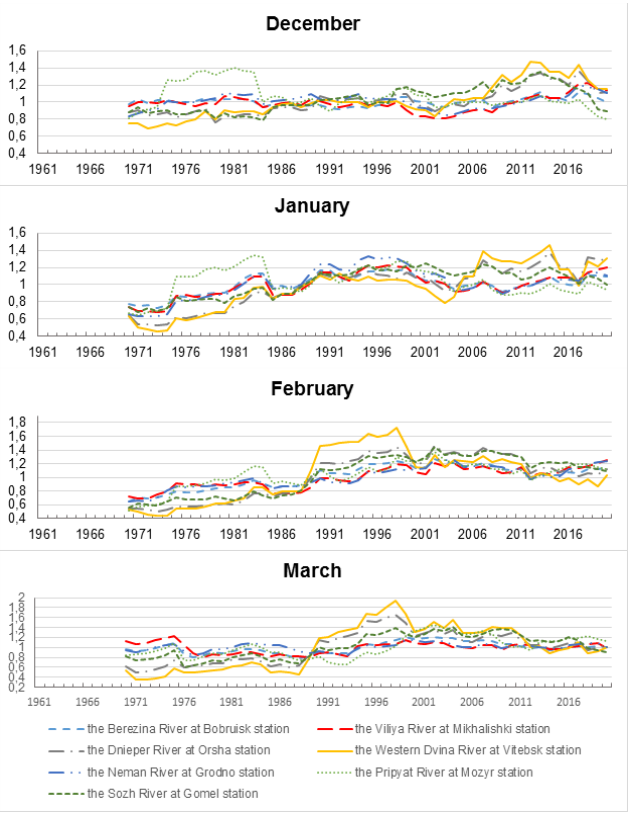


**Figure 3** – Change in modular runoff coefficients for the winter low-water period by moving average 10-year periods, 1961–2020

**Table 2** – Assessment of the formation of extreme water flows of rare frequency in the summer-autumn period

| River – gauging station | Amount of cases | |
|---|---|---|
| | 1961–1990 | 1991–2020 |
| the Pripyat River at Mozyr station | **2** | **3** |
| the Neman River at Grodno station | **2** | **4** |
| the Western Dvina River at Vitebsk station | **1** | **4** |
| the Berezina River at Bobruisk station | 4 | 3 |
| the Dnieper River at Orsha station | 2 | 2 |
| the Sozh River at Gomel station | 5 | 1 |
| the Viliya River at Mikhalishki station | **3** | **4** |

*Note:* the highlighted values correspond to the gauging stations where there was an increase in the amount of extreme water flows of rare frequency

The assessment results allow us to conclude that for most gauging stations over the last 30-year period, there has been an increase in the number of extreme values of the minimum summer-autumn runoff of rare frequency. Moreover, this increase occurs “against the background” of a statistically insignificant decrease in the average value of the minimum summer-autumn runoff for the second period for the Neman River at Grodno station, an increase in the minimum summer-autumn flow (by 4–28 %) for the remaining sections under study [9].


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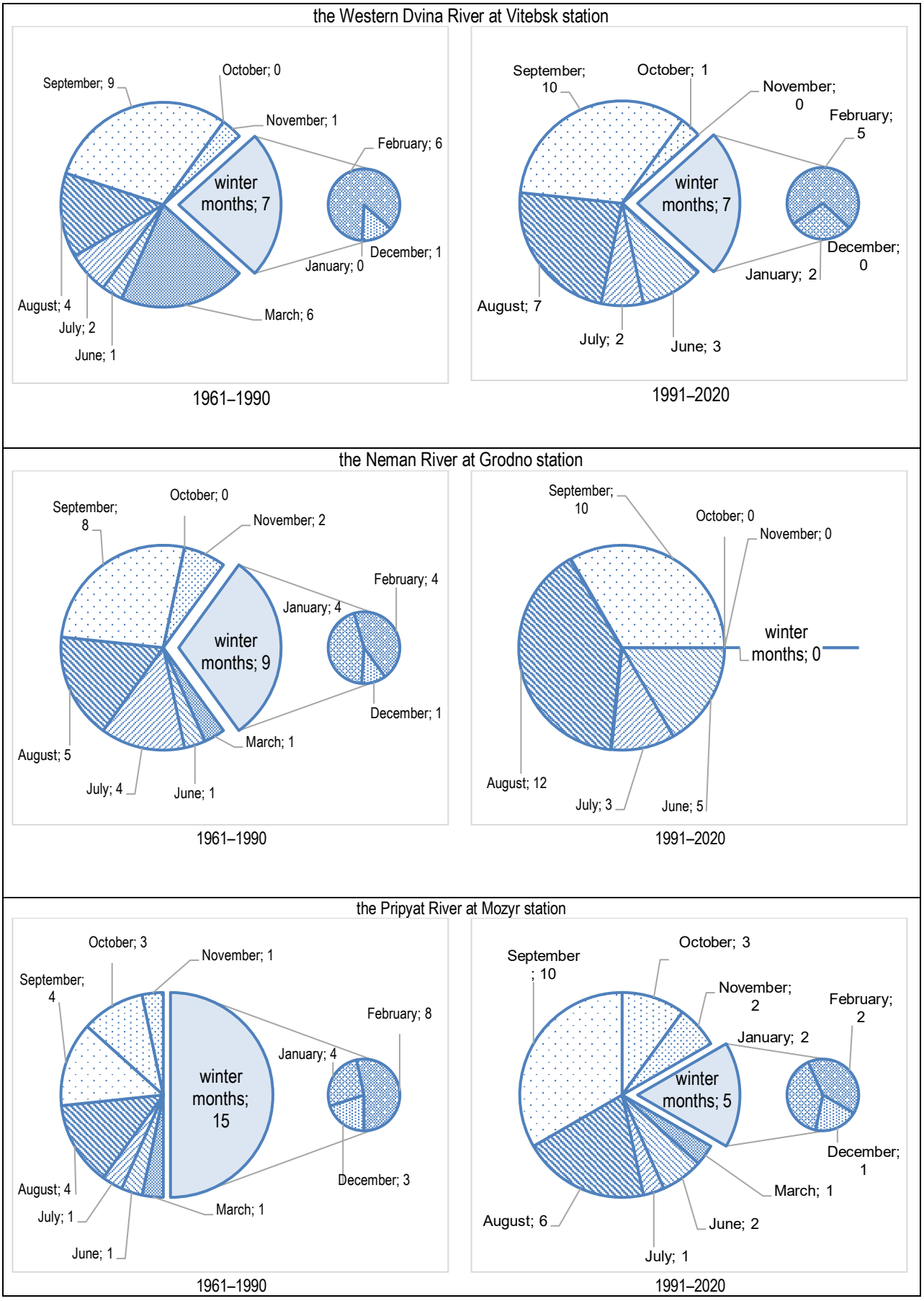


**Figure 4** – Amount of cases of observation of the minimum annual average monthly flow for the periods 1961–1990 and 1991–2020

Figure 4 clearly demonstrates the change in months in which minimal river flows were observed. The minimum average monthly runoff in the summer-autumn period is most often observed in August or September. For the period 1961–1990 for some stations the minimum values of water flow in 50 % of cases occurred in the winter months, then for the period 1991–2020 the minimum expenses of the year occur in the summer and autumn months.

**Conclusion**

An analysis of the long-term dynamics of river runoff for individual months of summer-autumn and winter low water showed that the water regime of the rivers in Belarus is characterized by certain transformations, primarily manifested in an increase in the runoff of winter months, most pronounced after 1988 and the relative constancy of the flow in February and March in the period from 2000 to 2020. The assessment of extreme water flows of rare frequency in the summer-autumn period for two time intervals (1961–1990, 1991–2020) demonstrates an increase in their frequency at most gauging stations over the last 30 year period. The minimum average monthly flow rates in the summer-autumn period are most often observed in August or September. All months covering the winter low-water period are characterized by a tendency to increase run-off, more pronounced after 1988.

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## ECONOMICS

UDC 338.24.021.8

# LOW-CARBON ECONOMY: WORLD TRENDS AND COUNTRY ANALYSIS

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**Abstract**
This article outlines the current understanding and specific policies of different countries on the concept of "low-carbon economy", and is committed to studying the low-carbon economic policies implemented by various countries, with a view to further promoting the "green economy" transformation plan of the Republic of Belarus. This article introduces the energy policies of different countries by collecting and observing and comparing data and materials, and summarizes the current development trend of the world's low-carbon economy.

**Keywords:** low-carbon economy, green energy policy, energy transition, low-carbon society.

## НИЗКОУГЛЕРОДНАЯ ЭКОНОМИКА: МИРОВЫЕ ТРЕНДЫ И СТРАНОВОЙ АНАЛИЗ

**Т. Г. Зорина, Ян Чжуси**

**Реферат**
В этой статье описывается текущее состояние и конкретная политика разных стран в отношении концепции «низкоуглеродной экономики», а также она посвящена изучению низкоуглеродной экономической политики, проводимой различными странами, с целью дальнейшего продвижения «зеленой экономики» для трансформации Республики Беларусь. В этой статье представлена энергетическая политика разных стран путем сбора, наблюдения и сравнения данных и материалов, а также обобщены текущие тенденции развития низкоуглеродной экономики в мире.

**Ключевые слова:** низкоуглеродная экономика, политика «зеленой» энергетики, энергетический переход, низкоуглеродное общество.

### Introduction

"Low carbon economy" first appeared in government documents in the 2003 the United Kingdom energy white paper "Our Energy Future: Creating a Low Carbon Economy" [1]. In the context of global warming, the "low carbon economy" based on low energy consumption and low pollution has become a global hotspot.

Low-carbon economy means that under the guidance of the concept of sustainable development, through technological innovation, institutional innovation, industrial transformation, new energy development and other means, the consumption of high-carbon energy such as coal and oil can be reduced as much as possible, and greenhouse gas emissions can be reduced [2].

The global background proposed by the low-carbon economic policy is a severe challenge to human survival and development caused by global warming [3]. A comparative analysis of the energy policies implemented by different countries will help us understand the decisions made by countries with different historical and natural environments to deal with the ecological energy crisis, thus providing recommendations for accelerating the transition to a green economy in the Republic of Belarus.

### Material and method

We have collected and tabulated the low-carbon policies currently being implemented mainly by different countries (Table 1). A "+" in the table indicates that the policy is being implemented, and a "–" indicates that the policy has not been implemented or its implementation has been hindered. We will take the low-carbon policies in the table 1 as an example, look for the differences and similarities of low-carbon policies in different countries, and obtain conclusions by quantitative comparative analysis.

When collecting data and making a table of low-carbon economic policies in various countries, we can clearly see that due to the different natural environments and historical cultures between countries, the low-carbon policies adopted by countries are also different. We will elaborate and analyze these policies in detail.

### RES (Renewable energy resources)

From table 1, we can see that all countries choose to use new clean energy.

**Table 1** – Low carbon policies in different countries [1–12]

| | China | Belarus | the United States | the United Kingdom | Japan | Denmark | Russian Federatio | India | Germany | Turkey | Canada | France | Brazil | South Korea | European Union |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RES | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| Eco-industry | + | + | + | – | + | + | + | – | + | + | + | + | – | – | + |
| Climate change tax | – | – | – | + | – | – | – | – | – | – | – | + | – | – | – |
| Financial subsidy | + | – | + | + | + | + | + | – | + | – | – | + | + | – | + |
| Tax incentives | + | – | – | + | + | + | – | – | + | – | + | + | + | – | + |
| Enact laws | + | + | + | + | + | + | + | – | + | + | + | + | + | – | + |
| Improve the carbon trading market | + | – | – | + | + | + | – | + | – | – | + | + | – | – | + |
| Eco-plan | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| Reform the industrial structure | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |

After investigation, the focus of new energy developed by different countries is also different. For example, China focuses on the development of wind, hydro, nuclear and geothermal energy. In April 2021, the National Energy Administration of China issued an announcement to solicit public comments on the "Notice on Matters Related to the Development and Construction of Wind Power and Photovoltaic Power Generation in 2021" [1]. The opinion stated that it is necessary to implement the goals of carbon peaking and carbon neutrality, and by 2030, the proportion of non-fossil energy in primary energy consumption will reach about 25 %, and the total installed capacity of wind power and solar power will reach more than 1.2 billion kilowatts; the European Commission passed in 2007. The EU strategic energy technology plan, the purpose of which is to promote the research and development of new low-carbon technologies [2]; the British government is currently not considering the construction of new nuclear power plants, and the important measures for carbon reduction are the development of wind energy and biomass energy [4]; the German government vigorously develops wind energy and promotes Existing wind equipment is replaced, and the development of biogas energy is encouraged. The German government has also formulated the "Renewable Energy Heating Law" to promote the use of renewable energy for heating. The EU emphasizes the increase in the proportion of renewable energy; Japan emphasizes the role of nuclear power and solar energy in terms of clean energy. To this end, Japan further implements incentive policies including subsidies to strengthen the world's first position in the use of solar energy. The United States has restarted nuclear energy development, including encouraging the construction of advanced nuclear power plants, funding research and development of advanced nuclear reactor technology, and establishing global nuclear energy partnerships [5].

In the first half of 2020, coal-fired power generation in Portugal, Spain, and Germany fell by 95 %, 58 %, and 39 %, respectively, and coal-fired power generation in the Netherlands, Austria, and France all fell by more than 50 % [6]. Germany, the United Kingdom, Austria and other countries have accelerated the shutdown of coal power facilities and made clear the timetable for the withdrawal of coal power. Germany passed the “Phase-out Coal Power Act” and the “Mining Area Structural Adjustment Act” in 2020, stipulating the phase-out of coal power by 2038 at the latest; the United Kingdom has pledged to completely stop using coal power by 2024. Australia plans to close coal-fired power stations by 2030 (Figure 1).

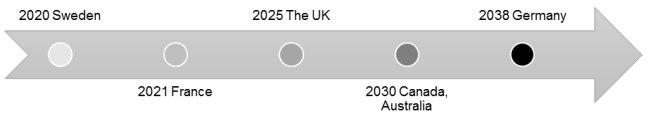


**Figure 1** –The withdrawal time of coal power in developed countries in the world [2, 4, 5]

**Eco-industry**

From table 1, with the exception of the UK, India, Brazil and South Korea, all countries have opted to develop eco-industries. These countries hope to plan the structure of the industrial system into an industrial ecological chain consisting of three parts: "resource production", "processing production" and "reduction production" through legal, administrative or economic means.

China proposes to vigorously develop eco-agriculture, eco-industry and eco-tourism, that is, let the industry take the road of pollution-free and clean [1]. The construction of Japan's eco-industrial parks is dominated by regional autonomous bodies, jointly assisted and managed by the state and local governments, and the active participation of enterprises and administrative departments [7]. Germany mainly controls air pollution, actively establishes nature reserves, and restores polluted water bodies and vegetation [5].

In order to cope with climate change and reduce greenhouse gas emissions, many countries have successively established carbon neutrality goals to guide the green and low-carbon development of the economy.

Carbon neutrality refers to the greenhouse gas directly or indirectly generated by the country, enterprises, or individuals within a certain period of time, through afforestation, energy saving and emission reduction, etc., to achieve positive and negative emissions offset, so as to achieve the goal of "zero emissions".

According to statistics from the British Energy & Climate Intelligence Unit, as of January 2021, the European Union and 27 countries have achieved or committed to carbon neutrality goals (Table 2).

**Table 2** – Timeline for countries and regions to commit to carbon neutrality [1, 2, 4, 5, 7, 9, 10]

| Countries | Target year | Current state |
|---|---|---|
| The UK, France, Denmark | 2050 | Legislation completed |
| EU | 2050 | Under legislation |
| Germany, Canada, Japan, Korea | 2050 | Policy statement |
| The US | 2050 | Policy statement |
| China, Brazil | 2060 | Policy statement |

From table 2, we can see that 2050 is the main time node for the world to achieve carbon neutrality, including the European Union, the United States, France, the United Kingdom, and nearly 20 countries and regions that plan to achieve carbon neutrality by 2050. A few countries plan to achieve carbon neutrality earlier. It is worth mentioning that Bhutan has achieved the goal of negative carbon emissions in 2018 [8]. But while these countries have set near-term goals, many are not moving fast enough, and ultimately achieving carbon neutrality will not be easy. Take the G20 countries whose total GDP accounts for 90 % of the world's total GDP as an example. According to statistics from IEA, in 2019, the G20 countries emitted a total of 78 % of the world's carbon dioxide, but so far only 9 member countries have proposed carbon neutrality goals at the legislative or policy level.

**Climate change tax**

The survey found that only the UK and France opted for a climate change tax [4]. The climate change tax is a national tax and is levied on fuels (electricity, natural gas, solid fuels or liquefied petroleum gas, etc.) used in the industrial, commercial and public sectors for heating, lighting or kinetic energy, is designed to encourage efficient use of energy and promote renewable energy, thereby helping the UK and France achieve their national and international targets for reducing greenhouse gas emissions. The household energy consumption does not fall within the scope of the collection, and small-scale business energy consumption is also not within the scope of collection.

**Financial subsidy and Tax incentives**

China provides subsidies to consumers who purchase new energy vehicles. The specific standard is that the government will give subsidies of 3,000 yuan/kWh to new energy vehicles that meet the supporting conditions. The maximum subsidy for plug-in hybrid passenger vehicles is 50,000 yuan per vehicle; the maximum subsidy for pure electric passenger vehicles is 60,000 yuan per vehicle [1]. The sales volume of new energy vehicles in China increased from 507,000 in 2016 to 1.367 million in 2020, completing a leapfrog development in a short period of time.

Germany has established a low-carbon fiscal and tax policy from the perspective of improving energy efficiency and promoting energy conservation [9]. One is to levy an ecological tax on oil, gas and electricity since 1999; the other is to sign an agreement with the industry, stipulating that the tax incentives enjoyed by enterprises are linked to energy conservation.

EU fiscal policy focuses on developing new rules for the development of carbon capture and storage technologies and the application of market instruments such as environmental taxes [2].

In terms of encouraging enterprises to save energy and reduce emissions, the New Energy Law of the United States proposes that the government will provide 1 billion US dollars of financial support every year for sectors such as transportation and buildings with high energy consumption and encourage relevant research departments to develop energy-efficient operating systems. In encouraging families and individuals to use energy-saving products, the US government will provide tax relief for large-scale


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energy-consuming facilities such as heating and air-conditioning [5]. In addition, each state government has also formulated local preferential tax policies for energy-saving products, such as California energy-saving dishwashers, washing machines, etc., according to the actual local conditions, and the tax reduction amount is between 50 and 200 US dollars.

The Canadian government implements the "green procurement" policy and increases financial support and guidance in energy conservation and emission reduction. Canada will invest 1.48 billion Canadian dollars in the next four years to carry out the "ecological energy renewable development plan". In addition, the government will invest $ 35 million in the Eco-Energy Renewable Heating Program to support industry in developing environmentally friendly heating technologies for hot water supply and space heating [5].

Japan has established a relatively complete vehicle fuel tax policy. Implement high tax policies for energy products [7]. For example, the tax included in the price of oil is more than six times that of the United States. The government encourages people to use energy-saving products, and provides tax incentives and subsidies for energy-saving products. It is understood that the Japanese government implements special depreciation and tax relief for the use of 111 types of energy-saving equipment listed in the catalog, and the tax relief accounts for about 7 % of the equipment purchase cost. The Japanese government has also formulated a series of preferential measures to encourage the research and development and application of electric vehicles. Overprice subsidies, low-interest loans and a 7 % tax cut are offered to EV buyers. At the same time, the value-added tax, purchase tax and annual tax on electric vehicles will be lowered.

The UK uses fiscal and taxation policies to guide and support household energy conservation and emission reduction [4]. The first is to levy garbage tax and environmental protection tax. Garbage tax is calculated and levied according to the principle of "pay as much tax as you throw away"; environmental protection tax, also known as "green tax", requires house renters to hire an energy inspector to assess the energy consumption of the house before leasing, and then Obtain a rental license and pay environmental tax for the rated rental property.

The French government encourages the use of energy-saving equipment in industries, services, housing construction, transportation and other fields through preferential policies of tax reduction and exemption [10]. In addition, the French government also encourages enterprises and individuals to develop and use clean vehicles using solar energy or electricity, and through preferential depreciation ratios, new energy vehicles and related equipment are encouraged to enter the market. At the same time, the French government encourages the production and consumption of products listed in the catalogue published by the government through financial subsidies, and provides subsidies of 15 % to 20 % of the price for the purchase and use of related equipment. The establishment of an energy conservation guarantee fund is also an important part of the policy. The fund was jointly established by the French Environment and Energy Control Agency and the Small and Medium Enterprise Development Bank to provide loan guarantees for small and medium-sized enterprises to invest in energy efficiency, so as to ensure that small and medium-sized enterprises can apply for loans for energy efficiency investments.

**Enact laws**

In addition to India and South Korea, other countries have responded in terms of energy legislation. China has formulated the “Key Points of Energy Supervision in 2021” and “Key Task List of Energy Supervision in 2021”, and seriously investigated and dealt with a number of typical cases. The UK proposed in May 2022 that an energy bill would be introduced to enable the transition to cheaper, cleaner and safer energy. From the National Energy Act of 1978 issued in November 1978 to the Energy Independence and Security Act of 2007 in December 2007, the United States has gradually established development strategies, development goals and technology research and development plans for new energy-related industries. In March 2010, Japan proposed the “Basic Act on Global Warming Countermeasures” and passed the “Renewable Energy Special Measures Act” in August 2011. In 2009, the European Union passed the “EU Third Energy Reform Plan”, which proposed that by 2025, energy efficiency should be increased by 20 %, and new energy should account for 20 % of the total energy.

Through the above data, we found that the laws of energy conservation and emission reduction in western developed countries are structured from the two dimensions of energy legislation and environmental resources legislation. First of all, in the energy legislative framework, there are not only comprehensive energy basic laws, but also a separate law to adjust coal, electricity, oil and natural gas, and there are legal norms that harmonize the environment and resources. For example, under the leadership of its basic energy law, the Energy Act (enacted in 1935, revised in 1998), Germany has established special energy laws including the Coal Economy Act (1919) and the Energy Supply Security Act (1974) legislative system.

Secondly, developed countries will choose to establish a special energy conservation legal system. For example, in order to promote the legislative process of energy conservation and emission reduction in its member states, the EU has promulgated and implemented three mandatory minimum energy efficiency standards, one framework directive on mandatory energy efficiency labeling for household appliances, and eight implementing directives in terms of product energy efficiency.

It is worth noting that in the legislation of many countries, greenhouse gas emission reduction is considered to be the most important content of energy conservation and emission reduction laws and policies.

First, the government will set statutory greenhouse gas emission reduction targets. For example, on November 26, 2008, the UK enacted the Climate Change Act, which made the UK the first country to legally reduce greenhouse gas emissions by 80 % by 2050 compared to 1990 levels. On June 26, 2009, the U.S. House of Representatives passed the Clean Energy and Security Act, which stipulates that by 2020 the U.S. will reduce greenhouse gas emissions by 17 % from 2005 levels and by 83 % by 2050.

Second, support the advancement of clean energy through legislation to make clean energy an important alternative source for addressing climate change. For example, Japan's legislation to promote nuclear energy is the "Basic Law of Atomic Energy" (1955); in 1997, Japan enacted the "Law on Special Measures for Promoting the Utilization of New Energy" and its supporting regulations, "Law on Special Measures for Promoting the Utilization of New Energy", which vigorously promotes the development of wind and solar energy, geothermal, waste-to-energy and fuel cell power generation and other new and renewable energy sources.

Thirdly, countries actively promote the extensive participation of the international community in greenhouse gas reduction actions. The "Kyoto Protocol" established three mechanisms, one is emissions trading (ET) between developed countries, which is a mechanism for cooperation between developed countries that undertake quantitative emission reduction obligations; the other is developing countries and developed countries. The Clean Progress Mechanism (CPM), which allows developed countries to invest in GHG reduction projects in developing countries, and the resulting Certified Emission Reductions (CERs) can be credited against their own emission reduction obligations The third is the Joint Implementation (JI) between transition countries and developed countries, which is a project-based cooperation mechanism between transition countries and developed countries in the Soviet Union and Eastern Europe. It is similar to CDPM, but has its own independent management agency, registration procedures, methodologies, etc.

**Improve the carbon trading market**

Regarding the improvement of the market-oriented mechanism of carbon neutrality, countries have also adopted different approaches, and the carbon tax system is one of them.

A carbon tax is a tax levied on fossil fuels based on their carbon content or carbon emissions for the purpose of reducing carbon dioxide emissions. From 2019 to 2020, countries such as the Northwest Territories of Canada, Singapore, and South Africa began to implement carbon taxes [11]. As of May 2020, there were 24 countries that implemented carbon taxes (fees).

In comparison, Europe is the most mature region for carbon taxation in the world. Carbon tax has played a positive role in reducing carbon emissions, reducing energy consumption and changing energy consumption structure in European countries, especially in Nordic countries [2]. In March

2021, the European Parliament passed a motion to establish a Carbon Border Adjustment Mechanism (CBAM), and decided that from 2023, if countries that have trade with the EU do not comply with the relevant regulations on carbon emissions, their exports will face to the carbon tariff.

Countries have common but differentiated responsibilities for climate change according to their national strengths and historical responsibilities. This principle has long been an important part of international climate cooperation. Developing countries generally believe that if developed countries unilaterally implement carbon border price adjustment strategies on commodities imported by developing countries, it violates the long-established principles of international climate agreements. At the same time, some countries call on developed countries to be responsible for the carbon footprint of their consumption.

Take the European Union as an example. In the EU carbon border price adjustment mechanism, some people propose that the mechanism should exempt exports from least developed countries, but some people think that such a proposal will reduce the effectiveness of the mechanism [5]. The compromise proposal is to take part of the revenue from the carbon border price adjustment mechanism and use it to compensate developing countries for losses in the process of carbon reduction.

**Eco-plan**

All countries have the same choice in ecological planning, whether developed or developing countries have their own ecological plans.

In 2016, China set a time limit of five years, and proposed to adjust and optimize the energy structure before 2022, and build a safe and stable modern energy industry system [12]. In April 2020, the French government released a new multi-year energy plan (PPE), which aims to achieve 20.1 GW of renewable power generation capacity by 2023 and 44 GW of renewable power generation capacity by 2028. In December 2020, Germany adopted a draft amendment to the Renewable Energy Act (EEG), officially setting the target for German offshore wind power: 20 GW by 2030 and 40 GW by 2040. In the same month, the Japanese government announced that by 2050, Japan's renewable energy supply will nearly triple from the current basis, accounting for 50 % to 60 % of the country's electricity. In March 2021, the UK announced plans to switch 20 terawatt-hours of energy from fossil fuels to low-carbon energy by 2030, equivalent to 17 % of all renewable energy in the UK in 2019. The United States established ARPA-C, an inter-agency advanced research organization focused on climate, to help the United States achieve the goal of a 100 % clean energy economy. In 2021, the Biden administration pursues a "green energy revolution", vigorously promoting solar power, onshore and offshore wind power, and deploying nuclear power and hydropower.

**Table 3** – Green policies and Eco-plans introduced by some countries/regions [1, 2, 4, 5, 7, 9, 10]

| **Countries/Regions** | **Policies** |
|---|---|
| Germany | Invest 9 billion euros as an investment in the field of hydrogen energy; the German people will give financial subsidies when purchasing electric vehicles |
| Japan | Launch a green growth strategy involving energy, transportation and other fields; strengthen international cooperation; the government actively provides financial support and subsidies |
| China | Incorporate emission reduction targets into the "12th Five-Year Plan"; Shenzhen has become the first national low-carbon ecological demonstration city; set up special institutions to guide "low-carbon economy"; do a good job in publicity and education |
| India | Set up a special fund (about 1.3 billion US dollars) to support the development of renewable energy and related manufacturing industries, adjust taxes and fees for imported renewable energy, and set up a basic tariff of 15 %. |
| Turkey | Renewable energy power generation companies that have won the tender quota before June 30, 2021 will receive a 10-year fixed-price power purchase guarantee |
| Korea | By 2025, the cumulative installed capacity of clean energy will reach 42.7 million kilowatts; about 20.3 billion US dollars will be invested to build a smart grid. |
| France | Proposes a 100 billion euro stimulus package, plans to spend 30 billion euros on greener energy policies |
| EU | A quarter of the "Next Generation EU" economic stimulus package of up to 750 billion euros has been passed, and a quarter of the funds have been clearly used for the EU's green recovery plan and fair transition fund. |

**Findings**

As the birthplace of the industrial revolution and the founder of the existing high-carbon economic model, the United Kingdom deeply recognizes its historical responsibility in the process of climate change. The most active advocate and practitioner of low-carbon economy.

As a developed industrialized country, the German government is at the forefront of the world in energy development and environmental protection technology. The German government has implemented a high-tech strategy for climate protection, including climate protection and reduction of greenhouse gas emissions into its sustainable development strategy, and has formulated specific goals and objectives for climate protection in energy conservation and emission reduction through legislation and a highly binding executive mechanism.

Since 2009, France has attached great importance to and committed to reducing the emission of carbon dioxide and other greenhouse gases, and vigorously developed renewable and clean energy with the theme of nuclear energy. France has achieved remarkable results in saving energy and reducing carbon emissions in the fields of industry, construction and transportation.

Denmark has created a unique economy in terms of renewable energy and clean and efficient energy technologies such as wind power and straw power generation. Denmark has become one of the best countries in the world to reduce carbon dioxide and solve the energy problem, embarking on a path of sustainable energy development.

In 2008, the Canadian government refined the specific categories of the four major scientific and technological development areas of the national science and technology development strategy of "making science and technology an advantage of Canada", especially in the fields of environmental science and technology and energy.

Although the United States has not joined the "Kyoto Agreement", in the past 20 years, the United States has attached great importance to energy conservation and carbon reduction. The United States implemented the Clean Air Act in 1990, passed the Energy Policy Act in 2005, and in July 2007 the US Senate proposed the Low-Carbon Economy Act.

Japan is a resource-poor country, and it is also a country that is wreaking havoc on the world's environment and global climate change. In 1997, as the initiator and sponsor of the Kyoto Protocol, Japan invested heavily in the development and utilization of alternative and renewable energy sources such as solar energy, wind energy, light energy, hydrogen energy, and fuel cells, and actively developed research on tidal energy and geothermal energy.

Table 4 shows the proportion of renewable energy in final energy consumption in each country from 2010 to 2019.


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**Table 4** – Renewable share in final energy consumption of different countries [6]

| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|---|---|---|---|
| **China** | 5 | 5 | 5.9 | 6.5 | 7.3 | 7.7 | 8.4 | 9.1 | 9.8 | 10.6 |
| **Belarus** | 7.3 | 7.5 | 7.2 | 7 | 6.7 | 6.8 | 6.7 | 7.3 | 7.2 | 7.8 |
| **the United States** | 7.4 | 8.4 | 8.7 | 9.1 | 9.2 | 9 | 9.5 | 9.9 | 10.1 | 10.4 |
| **the United Kingdom** | 3.7 | 4.4 | 4.8 | 6 | 7.4 | 8.6 | 8.6 | 9.7 | 11 | 12.2 |
| **Japan** | 4.7 | 4.8 | 4.7 | 5.1 | 5.6 | 6.2 | 6.4 | 6.9 | 7.2 | 7.7 |
| **Denmark** | 21.2 | 23.8 | 26.9 | 27.1 | 30.2 | 32.9 | 32.2 | 35.2 | 34.7 | 37.5 |
| **Russian Federation** | 3.3 | 3.2 | 3.2 | 3.6 | 3.3 | 3.2 | 3.4 | 3.2 | 3.1 | 3.2 |
| **India** | 12.0 | 11.7 | 12.0 | 13 | 13.1 | 13.5 | 13.9 | 14.4 | 15.4 | 15.9 |
| **Germany** | 11.6 | 12.5 | 13.6 | 13.6 | 14.0 | 14.6 | 14.2 | 15.2 | 16.1 | 17.2 |
| **Turkey** | 14.2 | 12.7 | 13.0 | 13.8 | 11.5 | 13.3 | 13.2 | 11.4 | 11.8 | 14.1 |
| **Canada** | 21.9 | 21.8 | 22.2 | 22.4 | 22.5 | 22.7 | 22.1 | 22.5 | 22.0 | 22.1 |
| **France** | 12.0 | 10.7 | 12.3 | 13.4 | 13.2 | 13.3 | 14.2 | 14.1 | 15.2 | 15.5 |
| **Brazil** | 42.8 | 41.8 | 40.2 | 39.4 | 38.7 | 40.4 | 42.4 | 42.1 | 43.3 | 44.1 |
| **South Korea** | 1.3 | 1.3 | 1.6 | 1.9 | 2.9 | 2.7 | 2.5 | 2.8 | 3.2 | 3.4 |
| **European Union** | 13.4 | 13.5 | 14.7 | 15.4 | 15.9 | 16.4 | 16.5 | 16.6 | 17.3 | 18.1 |

From Table 4, we can see that, except for Russia and Canada, where the data are relatively flat, the proportion of renewable energy in final energy consumption in other countries has fluctuated somewhat over the past 20 years, but the overall trend is rising. This shows that the energy conservation and emission reduction policies of various countries have achieved very good results, and it also shows that the energy conservation and emission reduction policies of various countries are being seriously implemented.

**Conclusions**

The purpose of the research is achieved – we understand how different countries formulate low-carbon economic strategies according to national conditions and social conditions. Countries are actively developing a low-carbon economy and issuing policies. On the one hand, they are actively taking responsibility for environmental protection and fulfilling the requirements of the national energy conservation and consumption reduction targets. On the other hand, they are adjusting the economic structure, improving the efficiency of energy utilization, developing new industries, and building an ecological civilization.

Due to different national conditions, the methods of choice are also different: countries with land resources or natural resources will choose to vigorously develop emerging industries, countries with relatively scarce resources will encourage people to adjust their consumption structure through financial subsidies and financial support; developed countries will directly Industrial development is promoted through financial investment (such as the establishment of special funds), while developing countries are more likely to adjust taxes and fees.

Therefore, we can try to make some suggestions for the energy transition of the Republic of Belarus: First, actively develop renewable energy technologies: such as researching more reliable battery energy storage technologies, and actively developing clean energy such as solar energy and wind energy. Second, the government should create a level playing field for renewable energy technologies: even though Belarus currently has certain technologies, production capacity and funds for clean energy transformation, it still needs policies to reduce market risks. That is, the government should provide financial support for energy technology training, research and innovation, and pass legislation to protect the energy ecosystem. Third, it is necessary to stimulate investment in energy by public and private financial institutions. With sufficient funds in the energy industry, the government needs to have a clear system of accountability and commitment, including but not limited to adjustments to loan portfolios, bonuses for investment companies, and strict punishment standards.

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# EVALUATION OF EFFECTIVENESS OF INTERNATIONAL REGULATION OF FOREIGN TRADE IN DAIRY PRODUCTS

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**Abstract**

In this article, as one of the main criteria for the effectiveness of regulating foreign trade in dairy products at the international level, the dynamics of changes in the average values of customs duties on dairy products as a result of WTO accession is considered in relation to the largest players in the world dairy market, member countries of the European Union and Eurasian Economic Union.

The conducted analysis made it possible to conclude that as a result of joining the WTO there is both a decrease and increase in the level of tariff protection of imported dairy products.

**Keywords:** customs duty, tariff protection, World Trade Organization, foreign trade, dairy production.

## ОЦЕНКА РЕЗУЛЬТАТИВНОСТИ МЕЖДУНАРОДНОГО РЕГУЛИРОВАНИЯ ВНЕШНЕЙ ТОРГОВЛИ МОЛОЧНОЙ ПРОДУКЦИЕЙ

**С. В. Соркин**

**Реферат**

В настоящей статье в качестве одного из основных критериев результативности регулирования внешней торговли молочной продукцией на международном уровне рассмотрена динамика изменения средних значений ставок таможенных пошлин на молочную продукцию в результате вступления в ВТО в отношении крупнейших игроков мирового рынка молочной продукции, стран-членов Европейского союза и Евразийского экономического союза.

Проведенный анализ позволил обосновать вывод о том, что в результате вступления в ВТО наблюдается как снижение, так и повышение уровня тарифной защиты импортируемых молочных продуктов.

**Ключевые слова:** таможенная пошлина, тарифная защита, Всемирная торговая организация, внешняя торговля, молочная продукция.

**Introduction**

At the moment international regulation of foreign trade in dairy products is carried out within the framework of the World Trade Organization on the basis of the Agreement on Agriculture (hereinafter the Agreement), which entered into force on January 1, 1995 following the results of the Uruguay Round of negotiations. Some aspects of regulation are also addressed in other WTO regulatory documents, in particular in the Agreement on sanitary and phytosanitary measures; Agreement on technical barriers to trade; Agreement on subsidies and countervailing measures; Agreement on trade facilitation, etc.

The analysis of the peculiarities and evaluation of the effectiveness of international regulation of foreign trade in agricultural (including dairy) products based on the WTO Agreement on Agriculture has scientific and practical interest for the Republic of Belarus, which is at the stage of the negotiation process on accession to the WTO. The issues of market access for agricultural products are of key importance for Belarus. State support for agriculture is one of the key aspects of our country's WTO accession negotiations. Negotiations should fix a maximum allowable level of support for agriculture, with all instruments and measures broken down into existing "baskets" according to the WTO classification. In these circumstances, it is important to establish a truly effective system of protection for domestic producers that meets international standards and WTO principles.

**Main part. Effectiveness of international regulation of foreign trade in dairy products**

The provisions of the WTO Agreement on Agriculture apply to a wide range of agricultural products, including all types of dairy products, the specificity of which is that, in agriculture, dairy products are the most distorted and supported sector in the world. Import restrictions due to high tariffs, combined with surplus production as a result of domestic support, contributed to the provision of huge amounts of export subsidies, which in turn led to lower prices on the world market. At the start of multilateral trade negotiations, trade liberalisation was expected to reduce policy-induced distortions in the global dairy market. In practice, however, developed countries have found ways to circumvent WTO rules, thereby influencing international market prices [1; p. 66].

The WTO Agreement on Agriculture provides the following measures for a reduction in the level of state support [2]:

- increasing access to the domestic markets of WTO members by tariffing non-tariff measures (replacing all non-tariff restrictions with tariff equivalents) and progressively reducing the level of customs and tariff protection;
- reducing domestic support to agriculture by WTO members;
- increasing of export competition and reduction of export subsidies by WTO members.

As one of the main criteria for the effectiveness of international regulation of foreign trade in dairy products within the WTO framework, it seems appropriate to consider the dynamics of changes in the average values of customs duty rates on dairy products before and after WTO accession. Table 1 shows the results for the major players in the global dairy market.

Analysis of the data in Table 1 suggests that, as a result of WTO accession and compliance with the terms of the Agreement on Agriculture, there has been a reduction in the level of tariff protection for the dairy industry for all major players (except for the US, where the increase in the average customs duty rate for dairy products is mainly due to the tarification of non-tariff regulatory measures as required by the WTO). The largest decrease is typical for the world's leading importers of dairy products – China and India (rates have decreased by almost 3 times or more than 27 %). The level of tariff protection of Australia and New Zealand has not changed and remains one of the lowest in the world. In Brazil, the average customs duty rate for dairy products has also remained almost unchanged over the last 25 years, at around 20 %.

The effectiveness of international regulation of foreign trade in dairy products in relation to the countries of the European Union and United Kingdom is presented in Table 2.



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**Table 1** – Dynamics of changes in average rates of customs duties on dairy products as a result of WTO accession

| Country / Commodity item / HS Code of the EAEU | Year of accession to the WTO | Average customs duty rate in the last year before joining the WTO | Average customs duty rate in 2021 |
|---|---|---|---|
| **Brazil** | 1995 | | |
| Milk and cream, not condensed (0401) | | 30 | 12,83 |
| Milk and cream, condensed (0402) | | 27,80 | 23,60 |
| Buttermilk, yogurt, kefir (0403) | | 20 | 16 |
| Milk whey (0404) | | 20 | 21 |
| Butter (0405) | | 20 | 16 |
| Cheeses and cottage cheese (0406) | | 11,68 | 18,40 |
| **All dairy products (codes 0401-0406)** | | **21,58** | **17,97** |
| **Australia** | 1995 | | |
| Milk and cream, not condensed (0401) | | 0 | 0 |
| Milk and cream, condensed (0402) | | 0 | 0 |
| Buttermilk, yogurt, kefir (0403) | | 0 | 0 |
| Milk whey (0404) | | 0 | 0 |
| Butter (0405) | | 1,33 | 1,33 |
| Cheeses and cottage cheese (0406) | | 16,65 | 15,72 |
| **All dairy products (codes 0401-0406)** | | **3,0** | **2,84** |
| **New Zealand** | | | |
| Milk and cream, not condensed (0401) | | 0 | 0 |
| Milk and cream, condensed (0402) | | 3 | 3 |
| Buttermilk, yogurt, kefir (0403) | | 2,5 | 3,33 |
| Milk whey (0404) | | 3,33 | 3,33 |
| Butter (0405) | | 0,83 | 0 |
| Cheeses and cottage cheese (0406) | | 0 | 0 |
| **All dairy products (codes 0401-0406)** | | **1,61** | **1,61** |
| **China** | 2001 | | |
| Milk and cream, not condensed (0401) | | 25 | 15 |
| Milk and cream, condensed (0402) | | 35 | 10 |
| Buttermilk, yogurt, kefir (0403) | | 50 | 15 |
| Milk whey (0404) | | 28 | 13 |
| Butter (0405) | | 50 | 10 |
| Cheeses and cottage cheese (0406) | | 50 | 12,6 |
| **All dairy products (codes 0401-0406)** | | **39,67** | **12,6** |
| **India** | 1995 | | |
| Milk and cream, not condensed (0401) | | 60 | 30 |
| Milk and cream, condensed (0402) | | 60 | 42 |
| Buttermilk, yogurt, kefir (0403) | | 60 | 30 |
| Milk whey (0404) | | 60 | 40 |
| Butter (0405) | | 60 | 40 |
| Cheeses and cottage cheese (0406) | | 60 | 32 |
| **All dairy products (codes 0401-0406)** | | **60** | **35,67** |
| **USA** | 1995 | | |
| Milk and cream, not condensed (0401) | | 3,18 | 15,57 |
| Milk and cream, condensed (0402) | | 6,24 | 14,80 |
| Buttermilk, yogurt, kefir (0403) | | 14,01 | 31,18 |
| Milk whey (0404) | | 7,6 | 22,99 |
| Butter (0405) | | 7,68 | 15,81 |
| Cheeses and cottage cheese (0406) | | 12,48 | 19,44 |
| **All dairy products (codes 0401-0406)** | | **8,53** | **19,97** |
| **Israel** | 1995 | | |
| Milk and cream, not condensed (0401) | | 172 | 50 |
| Milk and cream, condensed (0402) | | 108,97 | 133,20 |
| Buttermilk, yogurt, kefir (0403) | | 129,13 | 60 |
| Milk whey (0404) | | 33,33 | 30 |
| Butter (0405) | | 101,33 | 118,33 |
| Cheeses and cottage cheese (0406) | | 114,65 | 50,54 |
| **All dairy products (codes 0401-0406)** | | **109,9** | **73,68** |

Source: Own development based on [3]

**Table 2** – Dynamics of changes in the average values of customs duties on dairy products in the UK and EU countries as a result of WTO accession

| Country / Commodity item / HS Code of the EAEU | Year of accession to the WTO | Average customs duty rate in the last year before joining the WTO | Average customs duty rate in 2021 |
|---|---|---|---|
| **Italy** | 1995 | | |
| Milk and cream, not condensed (0401) | | 62,81 | 56,31 |
| Milk and cream, condensed (0402) | | 83,03 | 67,89 |
| Buttermilk, yogurt, kefir (0403) | | 103,38 | 57,07 |
| Milk whey (0404) | | 185,39 | 100,58 |
| Butter (0405) | | 83,66 | 50,68 |
| Cheeses and cottage cheese (0406) | | 43,08 | 41,61 |
| **All dairy products (codes 0401-0406)** | | **93,56** | **62,36** |
| **France** | 1995 | | |
| Milk and cream, not condensed (0401) | | 62,81 | 56,31 |
| Milk and cream, condensed (0402) | | 83,03 | 67,89 |
| Buttermilk, yogurt, kefir (0403) | | 103,38 | 57,07 |
| Milk whey (0404) | | 185,39 | 100,58 |
| Butter (0405) | | 83,66 | 50,68 |
| Cheeses and cottage cheese (0406) | | 43,08 | 41,61 |
| **All dairy products (codes 0401-0406)** | | **93,56** | **62,36** |
| **United Kingdom** | 1995 | | |
| Milk and cream, not condensed (0401) | | 62,81 | 53,94 |
| Milk and cream, condensed (0402) | | 83,03 | 65,60 |
| Buttermilk, yogurt, kefir (0403) | | 103,38 | 54,09 |
| Milk whey (0404) | | 185,39 | 96,38 |
| Butter (0405) | | 83,66 | 38,58 |
| Cheeses and cottage cheese (0406) | | 43,08 | 40,33 |
| **All dairy products (codes 0401-0406)** | | **93,56** | **58,15** |
| **The Netherlands** | 1995 | | |
| Milk and cream, not condensed (0401) | | 62,81 | 56,31 |
| Milk and cream, condensed (0402) | | 83,03 | 67,89 |
| Buttermilk, yogurt, kefir (0403) | | 103,38 | 57,07 |
| Milk whey (0404) | | 185,39 | 100,58 |
| Butter (0405) | | 83,66 | 50,68 |
| Cheeses and cottage cheese (0406) | | 43,08 | 41,61 |
| **All dairy products (codes 0401-0406)** | | **93,56** | **62,36** |
| **Poland** | 1995 | | |
| Milk and cream, not condensed (0401) | | 18,33 | 56,31 |
| Milk and cream, condensed (0402) | | 20 | 67,89 |
| Buttermilk, yogurt, kefir (0403) | | 22,5 | 57,07 |
| Milk whey (0404) | | 22,5 | 100,58 |
| Butter (0405) | | 10 | 50,68 |
| Cheeses and cottage cheese (0406) | | 18 | 41,61 |
| **All dairy products (codes 0401-0406)** | | **18,55** | **62,36** |
| **Lithuania** | 2001 | | |
| Milk and cream, not condensed (0401) | | 20 | 56,31 |
| Milk and cream, condensed (0402) | | 19,2 | 67,89 |
| Buttermilk, yogurt, kefir (0403) | | 20 | 57,07 |
| Milk whey (0404) | | 20 | 100,58 |
| Butter (0405) | | 45 | 50,68 |
| Cheeses and cottage cheese (0406) | | 30 | 41,61 |
| **All dairy products (codes 0401-0406)** | | **25,7** | **62,36** |

Source: own development based on [3]

It follows from the data in Table 2 that as a result of joining the WTO and fulfilling the conditions of the Agreement on Agriculture, there is both a decrease (Italy, France, Great Britain and the Netherlands) and an increase (Poland, Lithuania) in the level of tariff protection of imported dairy products. The same average customs duty rates in 2021 can be explained by the Common Agricultural Policy of the European Union (CAP), which sets uniform import duties for all member states. Countries such as Italy, France, Great Britain, the Netherlands in the 1990s had even higher rates of customs duties on the import of dairy products, therefore, in relation to these countries, there was a decrease in the level of tariff protection. Poland and Lithuania had significantly lower customs duties, and as a result of unification and transfer of regulation after joining the EU from the national to the supranational level, there was an increase in the average level of tariff protection of dairy products.

In general, the European Union is characterized by one of the highest levels of agricultural protectionism in accordance with the CAP. Thus, in respect of imports of goods from third countries, the EU member states apply uniform tariff and non-tariff measures to protect the domestic food


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market. The arsenal of non-tariff methods of regulation (intervention prices, export subsidies, tariff quotas, technical barriers, etc.) is widely used, which, when converted into tariff equivalent, gives high values of ad valorem customs duties [4]. In connection with the above, the average level of tariff protection of dairy products in Lithuania has increased more than 2 times (from 25.7 % in 2000 to 62.36 % in 2021) and more than 3 times in Poland (from 18.55 % in 1994 to 62.36 % in 2021).

The dynamics of changes in the average rates of customs duties on dairy imports as a result of WTO accession in the countries of the Eurasian Economic Union and Ukraine is presented in Table 3.

**Table 3** – Dynamics of changes in average rates of customs duties on dairy products in the EAEU countries and Ukraine as a result of WTO accession

| Country / Commodity item / HS Code of the EAEU | Year of accession to the WTO | Average customs duty rate in the last year before joining the WTO | Average customs duty rate in 2021 |
|---|---|---|---|
| **Ukraine** | 2008 | | |
| Milk and cream, not condensed (0401) | | – | 10 |
| Milk and cream, condensed (0402) | | 4,74 | 10 |
| Buttermilk, yogurt, kefir (0403) | | 7 | 10 |
| Milk whey (0404) | | 2,95 | 10 |
| Butter (0405) | | 9,05 | 10 |
| Cheeses and cottage cheese (0406) | | 3,43 | 10 |
| **All dairy products (codes 0401-0406)** | | **5,43** | **10** |
| **Russia** | 2012 | | |
| Milk and cream, not condensed (0401) | | 13,89 | 14,17 |
| Milk and cream, condensed (0402) | | 24,2 | 14,6 |
| Buttermilk, yogurt, kefir (0403) | | 15 | 15 |
| Milk whey (0404) | | 15 | 14,62 |
| Butter (0405) | | 15 | 15 |
| Cheeses and cottage cheese (0406) | | 15 | 14,94 |
| **All dairy products (codes 0401-0406)** | | **16,35** | **14,72** |
| **Armenia** | 2001 | | |
| Milk and cream, not condensed (0401) | | 10 | 14,17 |
| Milk and cream, condensed (0402) | | 10 | 14,6 |
| Buttermilk, yogurt, kefir (0403) | | 10 | 15 |
| Milk whey (0404) | | 10 | 14,62 |
| Butter (0405) | | 10 | 15 |
| Cheeses and cottage cheese (0406) | | 10 | 14,94 |
| **All dairy products (codes 0401-0406)** | | **10** | **14,72** |
| **Kazahstan** | 2015 | | |
| Milk and cream, not condensed (0401) | | 14,17 | 14,17 |
| Milk and cream, condensed (0402) | | 18,64 | 14,6 |
| Buttermilk, yogurt, kefir (0403) | | 15 | 15 |
| Milk whey (0404) | | 14,74 | 10 |
| Butter (0405) | | 18,25 | 15 |
| Cheeses and cottage cheese (0406) | | 17,17 | 14,92 |
| **All dairy products (codes 0401-0406)** | | **16,33** | **13,95** |
| **Kyrgyzstan** | 1998 | | |
| Milk and cream, not condensed (0401) | | 10 | 14,17 |
| Milk and cream, condensed (0402) | | 10 | 14,6 |
| Buttermilk, yogurt, kefir (0403) | | 10 | 15 |
| Milk whey (0404) | | 10 | 14,62 |
| Butter (0405) | | 10 | 15 |
| Cheeses and cottage cheese (0406) | | 10 | 14,94 |
| **All dairy products (codes 0401-0406)** | | **10** | **14,72** |

Source: own development based on [3]

The experience of our partners in the EAEU has shown that as a result of joining the WTO, it is possible both to reduce (Russia, Kazakhstan) and increase (Armenia, Kyrgyzstan) the overall average level of tariff protection of dairy products. In Russia, the result of joining the WTO in 2012 was a decrease of 1.6 %, Kazakhstan's accession to the WTO in 2015 predetermined a decrease of 2.4 %. There was an increase of 4.7 % in Armenia and Kyrgyzstan.

Russia, the largest trading partner of Belarus, has opened its dairy market to a lesser extent after joining the WTO in 2012. The average import duty rate for dairy products is almost unchanged (16.35 % in 2011 and 14.72 % in 2021), although Russia has separately negotiated the possibility of applying tariff quotas to the import of certain dairy products. Thus, for whey (EAEU HS codes 0404 10 120 and 0404 10 160), a tariff quota of 15,000 tons was established, the intra-quota rate of customs duty was 10 %, the non–quota rate was 15 %. The most significant opening of the Russian food market as a result of WTO accession occurred in terms of imports of inexpensive foreign cheeses competing with domestic analogues (the price bar, after which no duty is charged, was almost halved on them), duties on milk powder were reduced from 25 % to 15 % [5].


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The average level of the bound tariff of Ukraine after joining the WTO decreased for food products and increased for non-food products. Moreover, the non-food sector in Ukraine is more protected by non-tariff barriers than the food sector. These facts indicate that Ukraine, after joining the WTO in 2008, has great opportunities to protect producers and exporters of non-food products, while agricultural products (including dairy) are subject to stronger competition from imported analogues [6]. The average level of tariff protection of agricultural products as a whole after joining the WTO decreased from 13.8 % to 9.1 %, despite its in-crease in relation to dairy products from 5 % in 2007 to 10 % in 2021.

**Conclusion**

In that way the assessment of the effectiveness of international regulation of foreign trade in dairy products by analyzing the dynamics of changes in the average level of tariff protection of dairy products after joining the WTO allowed to come to the following conclusions.

Firstly, as a result of WTO accession, a number of countries experienced a decrease in the average level of tariff protection for dairy products (China, India, Israel, France, Great Britain, Italy, the Netherlands, Russia, Kazakhstan), while some countries faced an increase in the average rates of customs duties on dairy imports products (USA, Poland, Lithuania, Armenia, Kyrgyzstan, Ukraine).

Secondly, taking into account the negative experience of Ukraine, in the process of negotiations on the accession of the Republic of Belarus to the WTO it is necessary to consider a higher level of tariff protection in relation to agricultural (including dairy) but not industrial products.

Thirdly, taking into account the experience of China, India, Russia and other countries, it seems quite reasonable to maintain the possibility of applying tariff quotas for certain types of dairy products (in particular, for some types of cheeses and fermented milk products) within the framework of the negotiation process on Belarus' accession to the WTO. This tool allows to perform a flexible customs and tariff policy, when within the established tariff quota there are some rates of import customs duties, and outside the quota there are other, higher values of import customs duty rates.

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# FORESIGHT: METHODOLOGICAL AND PRACTICAL ASPECTS

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**Abstract**

The article discusses methodological and practical aspects of foresight as a modern technology of strategic management, analyzes the terminological field of foresight, clarifies its classification, examines the features of the formation of for-site technologies in Belarus, systematizes the methodological tools of foresight research.

Based on expert methods, a field study was conducted to determine the attitude of practicing specialists of domestic companies to foresight issues, the possibility of highlighting the features of domestic practice and reflecting problematic factors in the organization of foresight sessions, an algorithm for conducting foresight sessions was developed as a practical tool to design the future of organizations and improve the efficiency of their functioning in long-term period.

**Keywords:** foresight, strategic management technologies, long-term forecasting, foresight methods and tools, foresight-session.

## ФОРСАЙТ: МЕТОДОЛОГИЧЕСКИЕ И ПРАКТИЧЕСКИЕ АСПЕКТЫ

**Е. В. Зацепина, Э. Г. Чурлей**

**Реферат**

В статье рассматриваются методологические и практические аспекты форсайта как современной технологии стратегического управления, проведен анализ терминологического поля форсайта, уточнена его классификация, исследованы особенности становления форсайт-технологий в Беларуси, систематизирован методический инструментарий форсайт-исследований.

На основе экспертных методов проведено полевое исследование с целью определения отношения практикующих специалистов отечественных компаний к вопросам форсайта, возможности выделения особенностей отечественной практики и отражения проблемных составляющих в организации форсайт-сессий, разработан алгоритм проведения форсайт-сессий как практического инструмента, позволяющего проектировать будущее организаций и повышать эффективность их функционирования в долгосрочном периоде.

**Ключевые слова:** форсайт, технологии стратегического управления, долгосрочное прогнозирование, методы и инструменты форсайта, форсайт-сессия.

**Introduction**

Increasingly, the heads of domestic enterprises note the complexity of managerial decision-making, which is caused by the transition from a world of relative predictability to a world with greater uncertainty, higher economic instability, geopolitical confrontation and frequent destructive natural disasters – a world in which any company is easier and more often off course.

Although these disruptions and crises require immediate response and action, they cannot be approached solely through the prism of crisis management. They are probably symptoms of deeper shifts and transformations.

In industry, almost 40 % of managers do not think that their enterprises will be economically viable in ten years if they continue on their current path and do not transform. Studies also show that 75 % of organizations are not ready for the pace of change in and around their industry [1; 2]. This should be a wake-up call, prompting scientists and practitioners to deeply rethink the approaches to strategic management.

In this context, it is necessary to encourage managers to develop future thinking based on the use of foresight or foresight technologies. The purpose of foresight is not to predict the future – to reveal it as if it were pre-determined – rather, it invites us to consider the future as something that we can create and/or form, and not as something already solved. At the same time, the diversity of the future generates a variety of approaches to its design, which determines the importance and relevance of research on both methodological and practical aspects of foresight in order to integrate it into the activities of domestic enterprises.

**Terminological field of foresight, peculiarities of development in Belarus**

In times of ever-faster changes, increasing complexity and critical uncertainty, responsible strategic management requires readiness for the unexpected in the context of the emerging future. Today, scientists distinguish a number of ways of thinking about the future: extrapolation, strategizing, futurology, science fiction, foresight [1].

All of these approaches exist, develop and are used in a complementary way. At the same time, from the perspective of the prospects of their application in the activities of domestic companies, foresight is of particular scientific and practical interest as a way to expand and rethink a variety of alternative options for the future.

Foresight is considered as modified (new) the type of thinking about the future. It should be noted that this is different from the existing, classical forecast, assuming at its core a vision of the future to design, and not to guess and not to foresee [3].

The in-depth analysis of the terminological field performed by scientists allows us to consider foresight in several planes: the future (or foresight), strategic management, organizational decisions. This is determined by the high level of complexity of the technological apparatus, including elements of technology, methodology, processes, tools, etc.

Thus, the classical definition of the concept of foresight can be considered the definition of B. Martin, which is presented in the UNIDO approaches: "Foresight is a systematic attempt to look into the long-term future of science, technology, economy and society in order to identify areas of strategic research and the creation of generic technologies that can bring the largest economic and social benefits [4].


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In the fundamental documents of European countries, foresight is interpreted as a process of active knowledge of the future and the creation of a vision of medium- and long-term prospects, aimed at making relevant decisions and mobilizing joint efforts. The for-site arises as a result of the interpenetration of development trends in the field of political analysis, strategic planning and the study of the future. It unites key participants of changes and various sources of knowledge to develop a strategic vision and develop the ability to predict the future [5].

In his research, P. Becker identifies two aspects of foresight. Firstly, it is a process, not a set of tools, which includes a consultative process that provides an exchange of views (including feedback) between participants. Secondly, the initial position of foresight is the recognition of the multiplicity of options for the development of the future. Which of these options will be implemented depends, in particular, on the decisions being taken today. Thus, foresight requires a conscious, "active" position in relation to the future and recognition that the choice made today can influence the formation of the picture of tomorrow or even create it [6].

In addition, P. Becker identified five main functions of foresight: innovation development (stimulation and support of innovation processes); prioritization (identification of the most important areas of research and development); the ability to foresee (providing basic information for early warning of risks); setting the direction of development (the basis for strategic planning); strategy formulation (the company's participation in the implementation of strategic initiatives) [6].

V.P. Tretyak, when considering foresight, focuses on the active participation of society in the realization of the future being formed and its study as a mechanism for coordinating the interests of individual groups of citizens: consumers and public organizations, scientists, politicians and business. Foresight, according to the scientist, is a technology for long-term forecasting of large-scale processes based on the processing of collective expert assessments received from various segments of society who are ready to actively contribute to the design of the future [7].

It can be noted that foresight is implemented on the basis of a participatory approach with the participation of researchers, practitioners and other stakeholders, knowledge about the future is created, evaluated and used. This is reflected in its understanding as a form of communication, a social technology that helps to form a coherent vision of the future on the scale of the project team, the state and even interstate organizations.

At the same time, N.V. Godes rightly notes that today there is no single definition of the category of foresight in the scientific and practical literature. Each organization, country, group of experts dealing with foresight, offers its own formulation that emphasizes one or another aspect [8].

The formation of theoretical elements of foresight is carried out by many scientists and, according to some of them, this process has not yet been completed. In this regard, it is advisable to reflect on existing approaches to the establishment of types of foresight as a technology of strategic management and development (Table 1).

**Table 1** – Types of foresight as strategic management and development technologies [1; 9–14]

| № | Classification Feature | Type |
|---|---|---|
| 1. | By the method of creating foresight projects (top and bottom) | *Foresight (top-down)* – the initiative to create foresight projects comes from above, and little attention is paid to interaction in this system.<br>*Foresight (bottom-up)* – the initiative to create projects comes from below and is based on the active interaction of science and civil society. |
| 2. | By the field of use | *Technological foresight* (development of productive forces); *socio-economic foresight* (development of human capital); *scientific foresight* (development of the scientific sphere); *foresight of management systems* (development of management systems). |
| 3. | By the degree of openness | *Open foresight* – is a formalized scientific and technological forecasting. *Closed foresight* – foresight, carried out by the forces of closed prognostic structures, directly focused on the immediate environment of the customer. |
| 4. | By the subject of consideration | *Thematic (sectoral, national) foresight*, or foresight, affecting certain sectors of the economy and having an impact on the overall process of economic development.<br>*Corporate foresight* – corporate foresight projects are aimed at choosing technological priorities, determining the main factors that can influence market changes, evaluating potential products that may be in demand in these markets, choosing measures necessary to develop existing and achieve new competitive advantages.<br>*Territorial foresight* is a mechanism of voluntary acceptance of commitments and responsibilities in relation to the general future of the territory, which is determined by society as a result of forecasting. |

Due to the fact that foresight is a developing scientific direction, the classification proposed by the authors is not comprehensive and can be specified by additional features and species. In addition, in practice, the considered types of for-site interact and overlap, forming mixed formats when implementing certain projects.

To reveal the meaningful potential of foresight, scientists and practitioners identify a number of its basic principles: engagement (commitment) in the discussion and development of development strategies based on a comprehensive vision of the future; communication (communication) of those participating; concentration on long-term time horizons (concentration on the long term); coordination (coordination) in the form of reflection of relations with the economy and society [4].

At the same time, the principle of concentration on the long-term period, which sets the boundaries of the time horizons of foresight, requires special study. The time horizon of forecasting is determined by the specifics of the foresight project, the degree of territorial coverage, state policy, economic cycles, the speed of technological changes, innovation life cycles, etc. For example, if a sufficiently large time horizon is chosen for international projects – up to 50 years, then in national foresights the horizon varies in the range from 5 to 20 years.

Regarding the corporate level, the use of foresight technologies is aimed at collecting information about the current state of changes in the areas under consideration for the development of strategic plans of companies in different time horizons: short-term foresight (up to 5 years), medium-term foresight (up to 10 years), long-term foresight (up to 25–30 years).

The significance of foresight is that this technology acts as a kind of bridge between the research of prospects and the development of political, socio-economic, technological, corporate plans and strategies.

Analyzing the current state of foresight in the Republic of Belarus, it should be noted that this technology is at the stage of its formation both in the theoretical and methodological and in the applied context. In the scientific environment, there are works of Russian scientists devoted to the study of various aspects of foresight research in the context of the world and national economy [8; 15–18], regional development [19], corporate governance [20], etc. However, a number of issues related to the practice of organizing and conducting foresight sessions and designing behavioral strategies based on them remain insufficiently disclosed.

Today, Belarusian foresight, taking into account progressive foreign experience, is being built as a modern technology of foresight, based on the fact that the future of the country is being created today. Thus, one of the types of foresight – rapid foresight ("high-speed foresight"), which involves building a "map of the future" based on objectively developing trends, identifying threats and opportunities for development and the formation of project initiatives, was used in the development of the draft National Strategy for Sustainable Socio-Economic Development of the Republic of Belarus for the period up to 2035 [21].


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The session of the Russian-Belarusian Expert Club in 2016 can be cited as an example of the use of foresight technology. Then the results of his work made it possible to determine the most important directions for the development of bilateral relations until 2020. The foresight session "Prospects of Economic Science in the Digital Age", held in 2021 at the Institute of Economics of the National Academy of Sciences of Belarus with representatives of the Belarusian government, leading scientists and academicians of the National Academy of Sciences of Belarus and the Russian Academy of Sciences are indicative [22].

Also, foresight elements were used in the development of a system of integrated forecasting of scientific and technological progress (CF STP) for 2021–2025 and until 2040. A group of more than 140 experts (representatives of academic and university science, heads of enterprises, etc.) was formed in 14 major sectors of the economy and areas of scientific and technological development of the country.

Different countries place different emphasis on the expected effects of the foresight approach: technological effects in the economy and public life, marketing, industry and telecommunications, ecology and sustainable development.

By participating in international and national foresight projects, as well as initiating corporate foresight sessions, domestic business can significantly influence the formation of a system of national priorities, taking into account the needs of the real sector, to orient the state scientific and technical policy in the creation of a system, the center of which will be innovative industrial enterprises that provide demand applied research and development for the subsequent production of innovative products in demand by society.

**Methodological tools of foresight and approaches to its application**

The set of foresight methods and tools used is constantly expanding. Now there are already several dozen positions in this list. Attempts to quantify existing trends and their consequences using specially developed models and computer tools are concentrated at one pole. Another rather large group of methods is based on the knowledge of experts, on the development of special procedures and techniques for working with experts. In the practice of developing foresight projects, a combination of methods is most often used.

As a demonstration element of the variety of methods of foresight research, the "Foresight Diamond" (in some publications – Foresight Diamond) has firmly taken root, which was finally edited in the works of I. Miles and R. Popper [13; 23]. This geometric figure reflects the mutual arrangement of various methods relative to each other in a space that is defined by two binary oppositions: creativity and evidence; expertise and interaction. In addition, it is assumed that the methods are divided according to formal logical signs: qualitative, quantitative, mixed.

Foresight operates with a certain methodology that allows to implement its principles and achieve the desired results, which, however, is not completely linear, strictly structured and formalized. In this regard, it seems to us expedient to systematize a variety of foresight methods from the standpoint of the applied approaches to its implementation, considered in the scientific literature: predictive, exploratory and normative.

The predictive approach assumes the availability of data on the basis of which the fundamentals (features, nuances, bases) can be determined that can influence the future. Predictive methods include bibliographic analysis, Delphi method, expert panels, source review, modeling and simulation, trend extrapolation, big data analysis, patent analysis, etc. [24; 25].

The exploratory approach implies the absence of a clear connection with the past, but forms proposals for future events. The exploratory methods include brainstorming, the method of essays, games, science fiction, staging, high-speed foresight, etc. [24; 26–28].

The normative approach basically contains consideration of dissatisfaction with the current situation, which is the basis for designing the future in accordance with the subject's vision to correct the state of affairs taking into account his ideas. The normative approach assumes a positive view of the future for its formation not on the basis of the current form of development of events, but on desire and vision. The category of normative foresight methods may include a goal tree, reverse staging, public panels, mutual impact analysis, technology mapping, SWOT and STEEPV analysis, etc. [24; 29–32].

As a general rule, predictive methods are less often used on more distant horizons and exploratory methods are more often used. Normative methods are mainly used at medium horizons.

Depending on the methods used, it is possible to obtain various results of foresight research: roadmaps, development scenarios, a list of ideas and priorities, databases, impact models, decision matrices, trend radars, maps of the future, etc. [33].

In the context of foresight research, the use of secondary sources of information, as sources widely distributed, relatively accessible and frequently updated, is of particular importance at the present stage. This significance is determined by the wide development and accessibility of Internet resources, including the widespread transition to digitization of collected and collected information.

Nevertheless, despite the abundance of Internet resources, significant difficulties are caused by the selection of reliable sources for monitoring. The conducted research made it possible to form a list of resources that can be used in the process of searching for the necessary information for foresight: mass media, print and online publications; materials of conferences, forums, festivals; search resources; resources of international research and consulting companies; resources of expert communities; resources of specialized trend research companies; resources for monitoring (databases, social networks), analytical services, etc. [34].

To develop the sequence of work in foresight technology, it is necessary not only to form a list of tools for information support and provision of secondary information, but also to develop a scheme for the selection of experts and the use of primary information. The procedure for selecting experts can be adopted in a format that determines the sequence of the following types of work:

- scanning (monitoring, search) of specialists on the topic under consideration, industry;
- collecting information about education (as well as academic degrees and titles);
- analysis of information about work experience, publications, knowledge of the studied field, search for experts (specialists) who are an example of the implementation of specific trends;
- information about the area of specialization and information about the work performed in the studied areas;
- formulation of questions requiring answers (in the field of searching for trend signals and the trends being studied), verification of compliance of questions (areas for study) with the specialization of experts;
- addition of the list of experts by representatives of various fields (economics, sociology, culture, politics, etc.) [34].

Among the requirements for experts, there is also a citation index in international databases, the presence of patents, fame in the professional field.

The experience accumulated to date, described by scientists and practitioners, allows us to formulate a number of important conclusions about the importance of foresight and the possibility of its practical application:

The foresight community, which forms the desired image of the future, is analyzed as a pre-met and a result, while foresight is an ongoing process.

The roadmap format can be considered as the basic result of foresight.

One of the problems of foresight is the abundance of fantasies that have no confirmation.

There is a shortage of real orders for the organization of foresight sessions due to concerns and distrust of companies.

There is a shortage of experts and a weakness of expert networks.

It should be noted that among the approaches developed to date by scientists and practitioners, reflected in the scientific literature, a step-by-step scheme-algorithm is being formed, consistently reflecting the necessary actions during the organization and conduct of the for-site session, including a number of stages:

1. Formation of the goals and objectives of the foresight session with a reflection of the sources of funding for research.
2. Development of criteria for the search and selection of experts.
3. Presentation of the collected data on the current situation at the meso- and macro-levels of experts.
4. Making predictions for the object under study.
5. Consolidation of prepared forecasts into road maps, development scenarios, windows of opportunity [35; 36].

The presented approach is logical and understandable, clearly shows the sequence of actions necessary to perform, but it seems to be quite general from the point of view of its practical application. In this regard, the need for a field study to collect information about the actual state of foresight development at domestic enterprises has been identified.

**Practical aspects of research and application of foresight technologies in Belarus**

Theoretical studies have revealed a significant number of developed approaches that determine the current state of foresight in different countries. However, the issues of understanding, necessity and application of foresight technologies remain insufficiently considered from the point of view of practical consideration, especially in Belarus. There are also questions of relevant approaches in the formation of the organization algorithm and the conduct of foresight sessions as a practical tool.

To implement the tasks set, it is advisable to conduct a field study based on expert methods. According to the theoretical studies carried out, experts with the following characteristics were selected for field work: education, work experience in the field under consideration, position.

The application of these criteria is conditioned by the need to invite experts with a combination of the described parameters to conduct interviews, which makes it possible not only to promptly collect the necessary information, but also to obtain reasonable answers to the questions posed based not only on experience, but also on accumulated statistical data.

The main purpose of this field study is the need to determine the attitude of practitioners to foresight issues, as well as the experience in conducting it to be able to highlight the features of domestic practice and reflect problematic components in the organization and implementation of foresight sessions. Also, the purpose of the conducted research was to determine the necessity and importance of foresight for domestic enterprises. In the course of the study, specialists who hold senior positions in domestic companies and have at least 5–7 years of managerial experience been involved as respondents.

The hypothesis formulated in the course of research is the assumption of insufficient information support for experts and practitioners (or the inability to find relevant sources of information, the lack of a convenient scheme (algorithm) for conducting foresight sessions in practice), which leads to the impossibility of using foresight in work.

According to the developed design of the study, in-depth interviews were conducted with experts selected according to the specified requirements. The interviews were conducted in August-October 2023 in Minsk. The main blocks of questions considered with respondents:

– assessment of the need for foresight for domestic enterprises;
– consideration of foresight from the point of view of terminology;
– defining the basics of foresight from the point of view of information support;
– exploring the importance of foresight;
– identification of areas of application of the results of foresight sessions.

The information obtained in the course of the conducted field research reflects the following important conclusions: the majority of respondents (more than 60 %) understand forecasting of the future by foresight, in turn, a little more than 30 % of respondents see the construction and modeling of the future by foresight (Figure 1). This proves the need for further research in the field of foresight, and also reflects the relevance of the construction and description of methodological aspects.

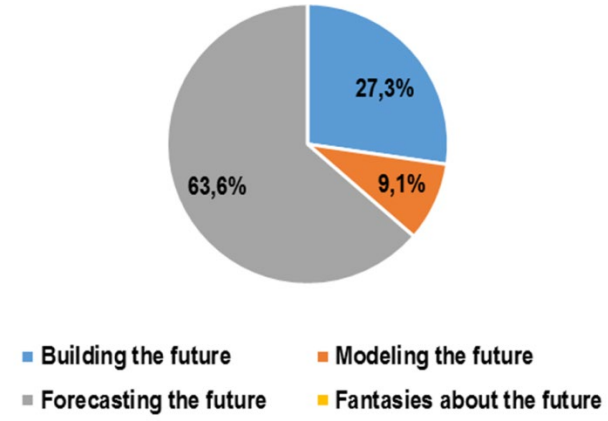


**Figure 1** – Distribution of respondents' responses on understanding the "foresight" category

Respondents rightly believe that foresight is based on large-scale research, organization and subsequent foresight sessions for the formation of action plans (more than 80 % of respondents). At the same time, the respondents chose the answers "about-judging the situation, forming a list of problems", etc. The smallest number of results refers to the option "the validity of foresight on benchmarking", probably due to the lack of awareness of the participants of the study of the methodology of benchmarking.

The respondents' assessments of the need for foresight showed that the average value is at the level of about 6,5 points (with a spread from 3 points to 10 points with a different number of responses).

It is also important to note that according to respondents, the results of foresight can be used in the long-term planning of the company's activities (100 %), in the formation of the company's vision (72 %), probably a number of respondents believe that foresight can "calm the owners a little" to indicate the directions of future development (18 %).

Nevertheless, respondents understand that the organization and holding of foresight sessions is not possible without difficulties and reflect that the main problem fields are the instability of the surrounding world (90 %), which has a serious impact on the future actions of companies, as well as affecting the complexity of the implementation formed during the sessions directions (Figure 2).

Also, more than 70 % of respondents identified a problem in the form of a shortage of specialists for the organization and conduct of work. It should also be noted that about 50 % of respondents pay attention to the lack of information necessary for organizing and conducting foresight sessions.

According to the conducted research, the average level of interest in conducting foresight sessions is currently low and amounts to 5 points. Of course, such values are due not only to the difficulties identified in the course of the study, but also to the insufficiency of the methodological apparatus, which has a serious impact on the concerns of managers and specialists.

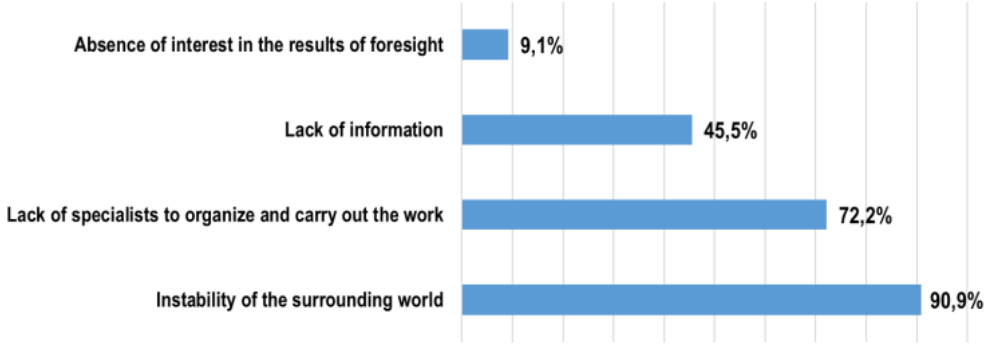


**Figure 2** – Distribution of respondents' responses about the problem fields of foresight


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The conducted research reflected the need for foresight at the present stage, and also revealed the insufficiency of tools for practical application. Currently, the foresight session is considered as a tool of an applied nature. A foresight session means a group work of pre-selected experts aimed at researching and constructing the components of the future, taking into account the collected information about trends and trend signals that are the basis for building promising development models. Foresight sessions should also become applied tools and are extremely important when developing roadmaps.

To implement the difficulties identified in the course of the study, it is advisable to talk about creating a sequence of works for the purpose of conducting foresight sessions. The work plan being developed implies the inclusion of seven stages, each of which, of course, having links with the previous one, determines the directions of further actions (Table 2).

**Table 2** – Sequence of organization and execution of work in the foresight session

| Name and number of the stage | Characteristics the stage of work | Justification of the need |
|---|---|---|
| 1. Start of work | Definition of the foresight subject area | Definition of sectoral, territorial and temporal aspects |
| 2. Goal setting | Formation of goals and objectives of the foresight session | Definition of the subject area, which makes it possible to clearly form the goals of the project, reduce the level of uncertainty, competent resource provision |
| 3. Budgeting | Formation of the budget and reflection of the source of funding | For planning and control, ensuring transparency, prioritization and subsequent successful implementation of the project |
| 4. Team building | Development of criteria for the search and selection of experts | Selection and definition of roles, competencies and responsibilities of experts |
| 5. Collecting information | Research design and data collection | Development of research design and collection of the necessary amount of information |
| 6. Shaping the vision of the future | Execution of planning for the object under study | Highlighting opportunities and threats, forming an action plan |
| 7. Summing up and visualization | Transformation of prepared forecasts into road maps, development scenarios, windows of opportunity | Concretization and operationalization of formed plans and forecasts, formation of strategic plans, identification and use of found opportunities |

Along with the qualitative implementation of the stages of organizing the foresight session discussed above, it is also worth mentioning the work on collecting initial data for performing subsequent actions related to the formation of a vision of the future and visualization of the results obtained. For this purpose, practitioners most often turn to the procedure of research or problem-oriented scanning of horizons in order to search for weak signals of potential changes.

Horizon scanning has two goals: the first goal is "warning", which is to identify dangerous trends as early as possible; the second goal is "creative", which allows you to reflect on new opportunities and take the first steps to implement them. At the same time, the experience of considering possible trends and multiple interpretations of weak signals by different experts can help the manager's thinking become more flexible and see several ways to solve one problem [31].

A number of foreign scientists note the growing interest in the methodology of horizon scanning, which is due to the progressive complexity and uncertainty of processes in modern society. It is emphasized that scanning due to empirical dependence is a more flexible approach to strategic forecasting [37].

From our point of view, it is the scanning of horizons that can help domestic organizations identify signals, identify trends and think more inventively (form more creative approaches and their expectations of the future) about what can wait, allowing them to use opportunities and mitigate threats.

In general, the use of foresight technologies is based on a deep understanding of the processes occurring in the external environment, which helps to see ahead and navigate in the future, influencing the emerging reality, rather than fighting it. The risk of losing sight of the forces causing the condition, which some experts call intermittent equilibrium, and others discontinuity, is significantly reduced.

In order for foresight to lead to useful results, it is necessary to apply it as a permanent and irreplaceable process that accompanies the company's movement into an uncertain and complex future. This information can warn strategic decision makers about the need for appropriate adjustments to plans, the implementation of arbitrary measures, if necessary. Foresight is aimed at the formation of an organizational culture of foresight and, ultimately, at the development of a more verified prospective trajectory for the development of the entire organization.

**Conclusion**

Thus, the use of foresight technologies allows you to explore, imagine and anticipate the future in a structured way. This order and structure are best achieved through professional methods of foresight. Working on the basis of a structured knowledge base formed through systematic forecasting, organizations can significantly increase the chances of successful results.

Today, foresight activities are established at large enterprises, consulting firms and public organizations around the world. However, it is still often difficult for managers of domestic enterprises to explain the "soft" and "hard" benefits that investments in organizational foresight capabilities bring, especially in conditions of tight budget constraints. But forethought is not just an extra bonus in good times, it's a matter of survival at all times.

Systematic activities for conducting foresight sessions in organizations can lead to the following results: increasing awareness of future trends and phenomena that are relevant to the success of the organization; holistic and contextual representation of key events of the future, understanding random topics and visualizing them into a logically structured picture; early warnings due to continuous scaling of horizons for notification about opportunities and threats; long-term plans and solutions that are developed taking into account immersion in specific topics to achieve compliance of investment decisions with future changes.

Today, foresight is a concrete and effective way to ensure readiness for the future for individual organizations and, more broadly, for our society as a whole. Through the conducted research of methodological and practical aspects of the use of foresight, it becomes possible to make this area of knowledge more tangible for the formation of interest in its development on the part of domestic enterprises.

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# UNEVEN DEVELOPMENT OF PRODUCTION INNOVATIONS AND CONSUMER INNOVATIONS AND ITS CONSEQUENCES FOR ECONOMIC GROWTH

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**Abstract**

The article describes the mechanism of influence of production innovations and consumer innovations on the structure of supply and demand for resources in the national economy. The reasons and possible options for the uneven development of production innovations and consumer innovations are considered. The mechanism of influence of uneven development of production innovations and consumer innovations on economic growth is revealed.

**Keywords:** innovation, production innovations, consumer innovations, uneven development, economic growth.

## НЕРАВНОМЕРНОСТЬ РАЗВИТИЯ ПРОИЗВОДСТВЕННЫХ И ПОТРЕБИТЕЛЬСКИХ ИННОВАЦИЙ И ЕЁ ПОСЛЕДСТВИЯ ДЛЯ ЭКОНОМИЧЕСКОГО РОСТА

**Н. Ф. Зеньчук**

**Реферат**

В статье описывается механизм воздействия производственных и потребительских инноваций на структуру предложения и спроса на ресурсы в национальной экономике. Рассмотрены причины и возможные варианты неравномерности развития производственных и потребительских инноваций. Раскрыт механизм влияния неравномерности развития производственных и потребительских инноваций на экономический рост.

**Ключевые слова:** инновации, производственные инновации, потребительские инновации, неравномерность развития, экономический рост.

**Introduction**

The mechanism and results of the impact on economic growth of innovations in the field of production goods (hereinafter referred to as production innovations) and innovations in the field of consumer goods (hereinafter referred to as consumer innovations) are fundamentally different. While production innovations aimed at developing technologies ensure growth in aggregate supply, consumer innovations aimed at improving and creating fundamentally new consumer goods ensure growth in aggregate demand.

Innovations develop unevenly. Joseph Schumpeter [1] substantiated the idea that the development of innovations is discrete in time. At the same time in the concept of techno-economic paradigms the emphasis is placed precisely on the development of technics and technology, that is, on production innovations, and the role of consumer innovations is not studied separately from production innovations. However, specific techno-economic paradigm and consumer innovations generated in it are not an inseparable whole and they may not coincide in time and territorially, across countries.

The purpose of this study is to examine how unevenness and imbalance in the development of production innovations and consumer innovations affect the functioning of the national economy and economic growth. It is expected to solve the following problems:

1. study the mechanism of impact of production innovations and consumer innovations on the structure of supply and demand for resources in the national economy;
2. analyze the reasons and possible options for the uneven development of production innovations and consumer innovations;
3. analyze the mechanism of influence of uneven development of production innovations and consumer innovations on economic growth.

**1 Impact of production innovations and consumer innovations on the structure of supply and demand for resources in the national economy**

Innovation processes in the economy take place in contradictory conditions of limited resources and unlimited needs [2]. Accordingly, efforts to create and implement innovations are realized in two main directions: saving resources and better meeting the needs and wants of people and society.

It is necessary to distinguish between innovations in the field of production goods (in other words, in the field of engineering and technology) and innovations in the field of consumer goods. Consumer goods are understood as goods and services intended to directly satisfy human needs and wants. Production goods are goods and services used in the production process (equipment and technology).

Production innovations are aimed at solving two problems:

1. saving resources used for production;
2. opening up opportunities for creating innovative consumer goods, the production of which was impossible at the previous level of technological development.

As a result of production innovations, savings on certain types of resources and the replacement of some types of resources with others are achieved. Therefore, the structure of resource consumption in the production sector is changing.

Consumer innovations are aimed at improving consumer goods, expanding their range and improving their quality, as well as creating fundamentally new consumer goods. The role of consumer innovations is that the emergence of innovative consumer goods creates new needs and wants among the population and stimulates the population to acquire these goods, even without waiting for the complete physical wear and tear of old, previously purchased things with similar functions.

The demand from the population for innovative consumer goods gives rise to a corresponding need in the production sector for various resources necessary for the production of these goods. Changes in the population's demand for consumer goods lead to changes in the structure of resources required for the production of these goods.

Thus, the structure of the supply of resources changes under the influence of production innovations aimed at improving production processes, and the structure of the need for resources changes under the influence of consumer innovations aimed at meeting the potential needs of the population (see Figure 1).

Therefore, these structures are not identical, they do not coincide. At the level of the national economy, the supply of certain types of resources does not always equal the need for them.

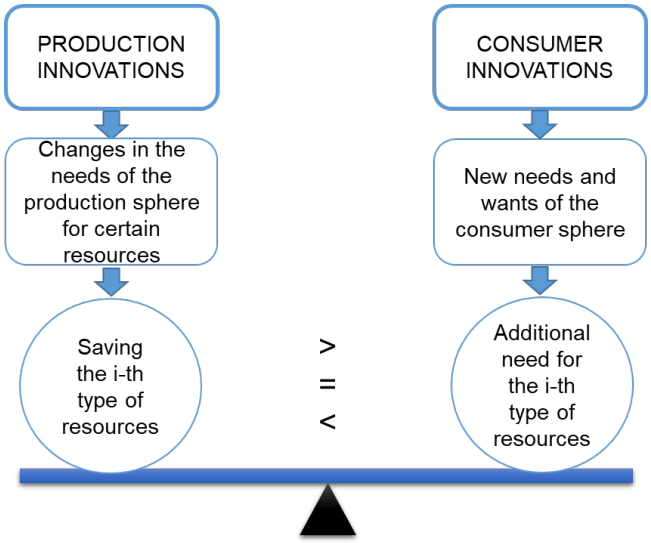


**Figure 1** – Changes in supply and need for various types of resources under the influence of production and consumer innovations [Note. Own development]

**2 Uneven development of production innovations and consumer innovations**

Joseph Schumpeter in his work "Economic Cycles" [1] substantiated the idea that the development of innovations is discrete in time, that the introduction of innovations occurs in "clusters". Over time, the terms "waves of innovation" and "techno-economic paradigms" began to be used more often. The concept of techno-economic paradigms occupies a significant place in the modern theory of innovative development.

At the same time, in published studies on this topic [3, 4, 5, 6, 7], the role of consumer innovations was not studied separately from production innovations. Innovative consumer goods, as a rule, are perceived in indissoluble connection with the corresponding techno-economic paradigms, as their inseparable part.

For example, according to the definition of S.Yu. Glazyev, the techno-economic paradigm is a holistic and sustainable formation, within which a closed cycle is carried out, starting with the extraction and receipt of primary resources and ending with the release of a set of final products corresponding to the type of public consumption. The complex of basic sets of technologically related industries forms the core of the techno-economic paradigm [5]. That is, this definition mentions "a set of final products corresponding to the type of public consumption" [5, p. 11], but it is not considered separately from the technological structure.

Yu.V. Yakovets, for example, suggests the following structure of the techno-economic paradigm:

– the core or basic innovations that form the qualitative characteristics of the paradigm;

– production technologies that form the basis for the restructuring of the sphere of material production;

– technologies of the non-productive area of the economy, used in the service sector, in personal consumption and in military affairs [6, P. 167–173].

In this definition, "technologies in the non-productive area of the economy, used in the service sector, in personal consumption" are taken into account, but are not considered separately from the techno-economic paradigm.

However, production innovations and consumer innovations play different roles in economic growth. In addition, consumer goods can be sold and consumed outside the corresponding techno-economic paradigm they belong to. In connection with the above, it is necessary to study the role of consumer innovations in economic development, considering them not as an inseparable part of the techno-economic paradigm, but as a separate influencing factor.

Further we will mean that the consumer-economic paradigm is a set of interrelated methods and processes of satisfying the personal needs and wants of the population, for which consumer goods are produced using equipment and technologies of the corresponding techno-economic paradigm. In consumer-economic paradigm consumer goods predominate, which cannot be produced using technologies of lower techno-economic paradigms [8].

In an economic system, at any given time, several techno-economic paradigms exist simultaneously. Among them the main, dominant paradigm can be distinguished, which characterizes the main directions of the economic system development at this moment [9, p. 801]. In the same way, at any given time, several consumer-economic paradigms exist simultaneously in the national economy.

The current techno-economic and consumer-economic paradigms may not coincide both in time and territorially, across countries. Almost any consumer goods of earlier paradigms can be produced using the equipment and technologies of later paradigms. For example, ordinary bread can be baked both in a village oven and in a bakery using various types of industrial equipment (II–IV paradigm), in a home electronic bread maker (V paradigm), and in the near future, perhaps with involving a home android robot or printed on a 3-D food printer (VI paradigm). Cleaning the floor in a home can be done with a broom and a damp cloth, an electric vacuum cleaner (IV paradigm), a robotic vacuum cleaner (VI paradigm), and using an android robot (VI paradigm).

And vice versa, almost any consumer goods of later consumer-economic paradigms can be imported into a country that does not have the appropriate techno-economic paradigm, is not capable of producing such goods, but is at earlier stages of technological development. For example, today the population of many countries that do not have the technology to produce computers and mobile phones (V paradigm) actively use these goods.

**3 Impact of changes in the structure of demand and supply of resources on economic growth**

Speaking about saving resources in the context of innovative development, it is necessary, first of all, to consider labor resources. The peculiarity of this analysis is that a person acts not only as a production resource, but also as a consumer of the final product, as the final goal of production, and thus ensures economic circulation.

The economic mechanism of changes in supply and demand for labor resources under the influence of production innovations and consumer innovations is presented in Figure 2. The result of production innovations is often an increase in labor productivity and savings in labor resources, which can be quantitatively presented as a fund of saved working time. This saved working time can potentially be used by society to produce additional volumes of production and consumer goods. However, the production of additional volumes of consumer goods is expedient and possible only if there is demand for them from the population. In turn, the demand for production goods depends on the demand for consumer goods created with their help.

In this case, three options for the development of innovation processes in the national economy are possible.

1. Production innovations develop faster than consumer innovations. If innovations occur mainly in the direction of improving production processes, which causes a sharp increase in labor productivity and an increase in the output of traditional consumer goods, and at the same time not enough attention is paid to improving the consumer goods themselves, then, sooner or later, there will be oversaturation of markets with traditional consumer goods. Even if traditional goods that the population already possesses are offered to them at reduced prices, people still do not want to purchase what they already have in excess quantities. Producers cannot sell the volumes of goods produced, which may be the beginning of a recession in the economy [10].


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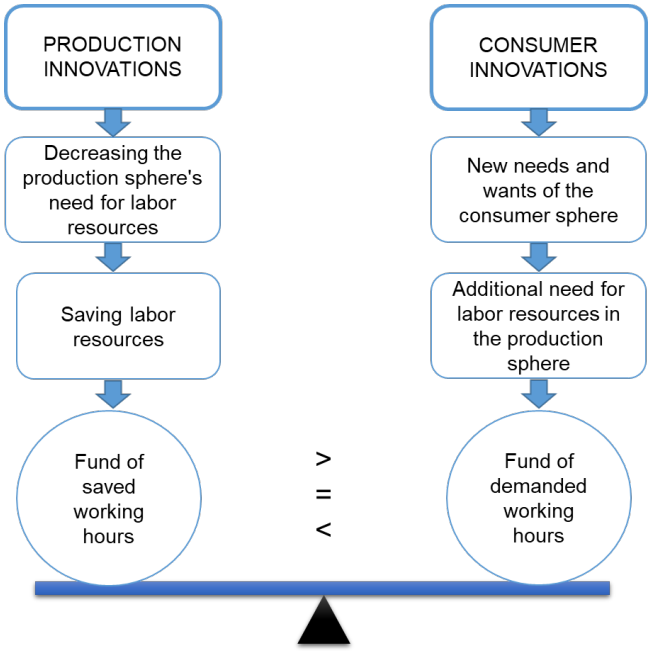


**Figure 2** – Changes in supply and demand for labor resources under the influence of production innovations and consumer innovations [Note. Own development]

In such a situation, the fund of saved working time is greater than the fund of additionally demanded working time. The lag of consumer innovations from production innovations limits economic growth from the side of aggregate demand. Without consumer innovation, the volume of consumption and production of goods per capita can be reproduced from year to year only on the same scale, but not on an expanded scale (simple reproduction).

2. Production and consumer innovations develop equally. The working time saved as a result of increased labor productivity is used entirely to create in-demand innovative consumer goods. The fund of saved working time is equal to the fund of additionally demanded working time.

A simultaneous increase in aggregate demand under the influence of consumer innovations and aggregate supply under the influence of production innovations transfers the national economy to a state in which a greater volume of national production and consumption is achieved, that is, economic growth occurs.

3. Production innovations develop slower than consumer innovation. Innovative development is uneven, there are leading countries and catching up countries. The needs of the population of catching up countries can be formed by innovative consumer goods that are already produced in countries that are the leaders in innovative development. But this innovative consumer goods cannot yet be produced in catching up countries, since catching up countries have not achieved the appropriate level of technological development.

In such a situation, the fund of demanded working time is greater than the fund of saved working time. The lag of production innovations from consumer innovations limits economic growth from the aggregate supply side.

Next, we will consider changes in the supply and demand for material resources under the influence of innovation.

At the level of the national economy, saving most types of material resources ultimately means saving labor costs at all stages of production of these resources. The replacement of one material resource with another in production can be considered as a redistribution of labor resources from one type of production to another.

Therefore, the consequences of the impact of innovation on saving or increasing the consumption of most types of material resources can be considered through saving or increasing the consumption of labor resources. An exception to this rule is scarce resources.

For the purposes of this research, by scarce resources we mean those that are in limited availability in the individually considered country. The amount of such resources in the national economy cannot be arbitrarily increased in accordance with increased needs.

For individually considered countries, such resources may, for example, be oil, productive arable soils, water resources in the regional aspect, working radio frequency bands, rare earth metals, etc. They can neither be produced within the country nor imported in required quantity from other countries. They cannot be effectively replaced by other, more accessible resources, including labor.

Therefore, when predicting the consequences of the development of production innovations and consumer innovations, in particular when solving problems about the impact of innovations on economic growth, changes in the consumption of scarce resources cannot be expressed in terms of labor costs. Scarce resources must be analyzed separately.

Here it is necessary to pay additional attention to the fact that changes in the needs and wants of the population and society under the influence of innovations can lead to both an increase and a decrease in the consumption of various types of resources, including scarce ones. For example, at one time the spread of a car with an internal combustion engine led to an increase in the consumption of gasoline and diesel fuel, and the transition to electric vehicles, which currently takes plase, leads in a number of countries to a decrease in the consumption of these resources.

Below, with regard to scarce resources, two possible situations in the national economy are considered. When considering them, we proceeded from the assumption that consumer innovations lead to an increase in the need for a scarce resource, and production innovations lead to a decrease.

1. Production innovations develop slower than consumer innovation. This is the very situation due to which certain types of resources become scarce. The need for a resource has already developed as a result of consumer innovations, but the available (or produced) quantity of this resource cannot be increased with the existing level of technology to fully satisfy the need. It is the accelerated development of consumer innovations compared to production ones that makes certain types of resources scarce.

In this situation, the lag of production innovations from consumer innovations limits economic growth from the aggregate supply side.

2. Production innovations develop faster than consumer innovations. As science and technology develop, solutions can be found to save a certain scarce resource, or even completely abandon its use. In this case, the resource ceases to be scarce, and the needs and wants of the population can be satisfied.

In this situation, an increase in aggregate supply in the presence of aggregate demand, that previously could not be satisfied, transfers the national economy to a state in which a greater volume of national output and consumption is achieved, that is, economic growth occurs.

**Conclusion**

Production innovations cause changes in the structure of the supply of production resources, and consumer innovations cause changes in the structure of the need for production resources. As a result, at the level of the national economy, the supply of certain types of production resources often does not equal the need for them. At the same time, both production and consumer innovations develop unevenly both over time and territorially, across countries.

For countries that are leaders in innovative development, the lag in the development of a new consumer-economic paradigm from the developed new techno-economic paradigm is fraught with oversaturation of domestic markets and a subsequent recession in the economy. The export of excess amounts of consumer goods to other countries, to new geographic markets, can postpone the problem of oversaturation and recession for some time.

As a result of the export of innovative consumer goods from countries that are leaders in innovative development to catching up countries, in these catching up countries the opposite situation may occur an advanced development of the consumer-economic paradigm compared to the techno-economic paradigm. In exchange for imported innovative consumer goods, catching up countries usually export their natural resources, reducing their reserves. At the same time, in a catching-up country, the demand of the population is “diverted” from consumer goods produced within the country to imported goods. This situation is not conducive to the development of the manufacturing sector of the catching-up country. Instead of investing in the innovative development of the production sector, limited resources of society are directed to expanding consumption.

Comparing the degree of correspondence between the techno-economic and consumer-economic paradigms in the national economy will allow to foresee in advance the possibility of a slowdown in economic growth for countries that are leaders in innovative development, as well as to foresee the threat to the development of countries taking a catching-up position in innovative development. The balanced development and application of production and consumer innovations are necessary to ensure a sustainable and continuous increase in the standard of living of the population.

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# MODERN APPROACHES TO ASSESSING THE IMPACT OF INVESTMENT PROJECTS ON THE SOCIO-ECONOMIC SYSTEM OF THE REGION

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**Abstract**

The issues of socio-ecological and economic interaction of society, nature and business, the consequences of the implementation of investment projects on the socio-economic system of the region are considered. The concept of the socio-ecosystem of regions and business entities of the region is revealed. A critical review of approaches to the socio-economic assessment of investment projects in the following areas is presented: scientific-theoretical, regulatory, practical. The importance of making decisions on providing support for the implementation of investment projects, taking into account the criterion of social responsibility of the initiator of the project, is substantiated. The characteristic of the social responsibility of the initiator of the investment project is given. The development of new approaches to the definition and assessment of the social and environmental impact of the implementation of an investment project on the economy of the region is proposed, which, unlike existing approaches, will allow us to assess both the potential losses from the project for the socio-ecosystem of the region and the contribution to improving the welfare of society.

**Keywords:** investment project, corporate social responsibility, socio-ecosystem, socio-economic assessment, sustainable socio-economic development.

**СОВРЕМЕННЫЕ ПОДХОДЫ К ОЦЕНКЕ ВЛИЯНИЯ ИНВЕСТИЦИОННЫХ ПРОЕКТОВ НА СОЦИОЭКОСИСТЕМУ РЕГИОНА**

**Е. О. Дружинина**

**Реферат**

Рассмотрены вопросы социально-эколого-экономического взаимодействия общества, природы и бизнеса, последствия реализации инвестиционных проектов на социоэкосистему региона. Раскрыто понятие социоэкосистемы регионы и субъектов хозяйствования региона. Представлен критический обзор подходов к социально-экономической оценке инвестиционных проектов по следующим направлениям: научно-теоретический, нормативно-правовой, практический. Обоснована важность принятия решений по предоставлению поддержки при реализации инвестиционных проектов с учетом критерия социальной ответственности инициатора проекта. Дана характеристика социальной ответственности инициатора инвестиционного проекта. Предложена разработка новых подходов к определению и оценке социального и экологического влияния реализации инвестиционного проекта на экономику региона, что, в отличие от существующих подходов, позволит оценить как потенциальные потери от проекта для социоэкосистемы региона, так и вклад в улучшение благосостояния общества.

**Ключевые слова:** инвестиционный проект, корпоративная социальная ответственность, социоэкосистема, социально-экономическая оценка, устойчивое социально-экономическое развитие.

## Introduction

The issue of socio-ecological and economic interaction between society, nature and business is currently relevant for a number of reasons. The need for continuous economic development and economic efficiency generates negative consequences for the environment, leads to its degradation, reduction of the area of natural ecosystems, depletion of the ozone layer and other limited resources, often even irreplaceable in the foreseeable future.

The relevance of the problems of socio-ecological and economic contradictions, the need to ensure the unity of the economic, environmental and social dimensions of sustainable development of the state and its regions, and the problems of nature management economics are confirmed by domestic scientists E. E. Vasilyeva, E. B. Dorina, S. V. Dorozhko, M. V. Myasnikovich, V. S. Fateev, A.V. Neverov, O. S. Shimova, O. V. Kolesnikov, and others. N. Lopachuk and others [1, 2, 3, 4, 5, 6, 7, 8].

Solving this problem is one of the priorities of public policy in many countries. Thus, O. S. Shimova notes in her writings that at the UN conference in 1992, concern about the state of the planet's biosphere was raised to the political level, and environmental management was declared an integral responsibility of the governments of all countries [9].

Currently, the Republic of Belarus has developed a National strategy for Sustainable Socio-economic development of the Republic of Belarus until 2030. The Belarusian model of sustainable development takes into account the UN Sustainable Development Goals, national interests and peculiarities of the Belarusian economy. The main characteristics of the model include: strong effective state power, participation of civil society in solving problems of sustainable development, effective state and public support for socially vulnerable groups of the population, environmentally sound state policy, and others [10].

Regional concepts of sustainable development have been adopted at the regional level, aimed at achieving a reasonable balance in solving social, economic and environmental problems of the region, meeting people's needs for material and spiritual well-being, and a favorable state of nature, based on mechanisms for implementing these requirements and monitoring their implementation [11].

A socio-ecological and economic system (socioecosystem) is a dynamic system that includes an ecosystem, physical and geographical environment, population, economy, culture, and politics. The components of the system are characterized by a certain commonality: the unity of the territory, close interaction with each other, and the integrity of the functions performed.

Economic entities of the region are private, state-owned and other enterprises engaged in the production, purchase and sale of goods, performance of works, provision of services, engaged in production activities independently on a certain territory within the administrative borders [31].

The enterprise operates in the territory of its presence – a region that also represents a complex socio-economic system, includes elements of a certain territory of a natural, industrial, demographic, social and institutional nature, as well as many direct and inverse relationships between these elements [32].

The issues of assessing the impact of investment projects on the region, its ecological and social system are attributed to the prerogatives of the institute of expertise (public environmental expertise, state environmental expertise, etc.) and thus do not allow for a complete study of projects in these aspects. In addition, existing project assessment methodologies do not allow us to determine the potential impact on the region as a territory of sustainable development and to answer the question of whether this investor is involved in achieving territorial development goals.

A critical review of approaches to socio-economic assessment of investment projects should be carried out in the following areas: scientific and theoretical, regulatory and legal, practical.

**Scientific and theoretical direction**

Public performance indicators take into account the socio-economic consequences of an investment project for society as a whole, including both direct results and costs of the project, as well as external ones: costs and results in related sectors of the economy, environmental, social and other non-economic effects.

External effects are recommended to be taken into account in quantitative form if appropriate regulatory and methodological materials are available for their assessment. In some cases, when these effects are very significant, in the absence of these documents, it is allowed to use the estimates of independent qualified experts. If external effects do not allow for quantitative accounting, it is recommended to conduct a qualitative assessment of their impact, which is indicated by economists [12].

Economic scientists point out that special coefficients of transition from market prices to shadow prices are used to assess the public effectiveness of projects. For our country, such coefficients or at least approximate methods for constructing shadow prices have not yet been developed. Social efficiency is assessed using a special social discount rate. The lower this rate, the more projects will be evaluated as effective, and the more they will qualify for state support. Therefore, it is clear that such a standard should be formed simultaneously with the approval of the state budget, but the methods of its formation are still unclear [13].

In the economic literature, there are a number of methods and proposals for analyzing an investment project from the point of view of various goals and users of the analysis. For commercial investors (including banks), it is customary to analyze economic efficiency, state authorities assess budget efficiency (methods described in [14] and others) and the return on state support, but they are not fully provided with assessment methods for applying regulatory measures in the region. According to the Russian researcher E. V. Zaitseva, when analyzing the possibilities of applying foreign experience in implementing state investment policy, "the use of fiscal incentives for investment activity should be purposeful, taking into account as much as possible not only the macroeconomic situation, but also regional development features" [15, p. 34].

One of the central places in the assessment of socio-economic efficiency is the assessment of environmental parameters of the project. The environmental factor in project and investment analysis is considered by Belarusian authors L. N. Moroz, A.V. Neverov, I. P. Usova, O. S. Shimova, Russian authors A. K. Borlakova, G. A. Makhovikova, I. P. Nuzhina, E. V. Ryumina and others [16, 17].

The environmental result of the investment project implementation includes changes in the quality of the environment, development of natural resources, improvement of the environmental situation due to the modernization of production, introduction of environmental technologies, meeting the environmental needs of society from the perspective of a decent life, etc. When calculating the environmental impact of any investment project, the maximum possible preservation of the useful properties of the natural environment for society is taken into account. Negative environmental consequences entail costs for compensation of economic damage and prevention of pollution.

The authors note that environmental analysis is carried out by checking the availability of valid permits for project financing and implementation issued by authorized bodies in the field of state environmental expertise. At the same time, the authors point out that *at the pre-investment stage*, the environmental efficiency indicators of the project include the presence of an environmental protection program in the project documentation, indicators for reducing harmful emissions into the atmosphere and reducing noise, and others. In general, environmental impact assessment as a result of the implementation of planned activities is focused on determining and verifying qualitative indicators, expressed in kind, reflecting the impact on environmental components (intensity (input of pollutants per unit of time, per unit area, to the population); scale of impact distribution; frequency of impact over time (single, discrete, continuous); duration (duration) of the impact; spatial boundaries of the impact; significance of the impact. In our opinion, the disadvantage is the complexity of determining the cost indicators of potential damage at the pre-project stage, which does not allow us to assess the scale of consequences, and, consequently, effectively manage environmental risks.

Another important area of assessment of socio-economic efficiency is the assessment of social impact. The social result of the investment project implementation achieved within the project includes a system of decent remuneration, professional development, additional development of employees, provision of social guarantees, and others, while the external impact is an increase in the level of employment, life of the population, changes in morbidity, reduction of social tension in society, ensuring social stability, and others. The social component of investment projects is represented in the works of Belarusian authors I. M. Babuk, B. I. Gusakov, I. N. Kuropatenkova, Russian authors A. S. Bogdanova, A. I. Zimin, T. G. Kasyanenko, E. N. Sindyashkina and others [18, 19, 20, 24].

In the methodology proposed by E. M. Sindyashkina, considerable attention is paid to the assessment of certain types of socio-economic effects of investment projects. However, the assessment of integral socio-economic efficiency is more formalized, since it mostly characterizes only the components of the social effect, and not their cost assessment.

Russian researcher O. S. Nagaeva in her work "Assessment of the socio-economic efficiency of regional investment projects" provides a fairly complete list of factors affecting the region of investment projects, classifying the types of impact on economic, environmental, social and financial, offering a methodology for assessing the compliance of the project indicator with the target parameters of the region. At the same time, two variants of the project are evaluated – with state support and without support, and the forecast of resource development of the region is taken into account. This approach is based on classical indicators of investment efficiency and does not allow us to measure the social effect objectively [21].

T. S. Novikova, when presenting the methodology for assessing the public effectiveness of innovative projects, proceeded from the principles and approaches used by most authors – comparing the costs and results of the indirect impact of projects on society. However, this method involves the use of subjective expert assessment in many parameters and does not allow us to measure the social effect reliably. Despite an attempt to systematize and quantify the socio-economic effects of investment projects, it is necessary to point out a number of significant shortcomings of this methodology: the proposed indicators do not cover all socio-economic effects of investment projects, a group of environmental performance indicators is not identified, the methodology does not take into account the negative socio-economic consequences of investment projects, as well as indirect effects. In addition, separate measurement of social and environmental effects does not allow us to give a comprehensive assessment of the impact of the project on the region and assess the degree of this impact [22].

V. N. Livshits, S. A. Smolyak, T. S. Novikova, P. L. Vilensky and other authors use the same methods and indicators for assessing the public effectiveness of a project as for commercial effectiveness: net discounted income, discounted payback period, yield index and internal rate of return. At the same time, the project's cash flows, based on which its commercial effectiveness is estimated, are adjusted for shadow prices, redistributive, external and indirect effects. However, it seems that the assessment of commercial efficiency and the assessment of socio-economic efficiency of the project have different goals. The commercial efficiency assessment is


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designed to assess the return on investment for the private investor, while the socio-economic efficiency assessment should assess the economic, social and environmental impact of the project on the territory. In this regard, the assessment of these two types of effectiveness should be carried out using different methods.

N. N. Mikheeva, T. S. Novikova, and V. I. Suslov suggest evaluating investment projects based on a set of inter-industry interregional models. However, while the methodology allows evaluating the commercial effect at the meso - and macro-level, it does not sufficiently take into account the social effect of the investment project implementation. Applying the methodology in one direction gives a fairly extensive result on the role of the project in the economy, but the question remains whether the project does not have a large-scale negative impact on the implementation area and society [23].

Summarizing the results of scientific research by these authors, we can distinguish the following ways to take into account environmental and social factors when evaluating investment projects:: 1) determining the amount of damage prevention as the sum of costs for its elimination and adding it to the calculated amount of net discounted income; 2) direct accounting of the cost assessment of social and environmental consequences (results) in calculations.

The disadvantages of methods for taking these factors into account when evaluating projects include:

1) inaccuracy and inability to calculate environmental impacts at the stage of business planning, so the economic damage (damage) from environmental degradation is calculated already during the project implementation;

2) determining the value of the total losses caused by environmental degradation as a result of the implementation of an investment project in most cases in the form of expert assessments, i. e. it is subjective in nature;

3) difficulty in identifying public benefits, which often cannot be measured not only in terms of money, but also in terms of quantity.

In connection with the above, further development of methodological approaches to assessing the socio-economic efficiency of investment projects for the region of their implementation is required.

Despite the inclusion of social and environmental parameters for the assessment of investment projects in the project-investment analysis, it should be noted that they are focused on points, the calculation of individual indicators of identified risks. Ensuring the complexity of socio-economic assessment is possible if a system of indicators is developed based on a systematic approach. The methodological basis for developing a system of indicators, according to the author, can be the principles of social corporate responsibility, since non-financial activities of the organization and interaction with interested parties increasingly affect the competitiveness of products in domestic markets and abroad, the effective use of resources, the investment attractiveness of the company, its market value. The concept of CSR is generally accepted in the global business-community, has an interdisciplinary nature, and combines theoretical and practical aspects.

**Regulatory and legal direction**

Investment projects implemented on the territory of the country's regions fall under the unity of criteria for their evaluation through a unified approach to methodological support for business planning and evaluation of the effectiveness of investment projects, regulated by the Rules for the Development of Business Plans approved by Resolution No. 158 of the Ministry of Economy of the Republic of Belarus of 31.08.2005. The main methods of project efficiency from the investor's perspective are net discounted income, discounted payback period, internal rate of return, and return on investment index are considered.

The business plan includes an assessment of the project's external environment through PEST analysis, which consists in identifying and evaluating the impact of macro-environmental factors (political, economic, social, and technological) on the results of project activities. The analysis of these factors is carried out on the basis of an expert assessment of qualitative indicators. This approach has a number of difficulties: identifying factors that have the greatest impact on the project when covering a large amount of data; interpreting the results of the analysis; taking into account the mutual influence of environmental factors. The disadvantages of PEST analysis include: subjectivity of assessment; short-term orientation in the analysis, which does not give a significant effect in strategic planning; complexity of analysis for a diversified project activity. Only political, economic, social, and technological factors of the organization's external environment that affect the project are evaluated, and the project's impact on the external environment is not disclosed.

It should be noted that according to a number of authors B. I. Gusakov, D. G. Matveev, A. S. Golikova [24, 25, 26, 27], the applied methodology for evaluating the effectiveness of investment projects presented in this methodological document has a number of shortcomings: the categories of object, subject and subject of investment efficiency assessment are not specified; a mixed approach is presented approach to calculating performance indicators: combining elements of economic and financial analysis of an investment project; it does not contain an assessment of the public significance of the project, as well as the procedure for evaluating the Pareto-effectiveness of the project for society and stakeholders, or evaluating other types of efficiency.

A. P. Smolsky points out in his works that the analysis of the main parameters of business plans for investment projects of individual business entities carried out during the expert examination revealed a number of serious shortcomings in planning. Thus, the author notes that the planned actions for the use of state support funds in the implementation of an investment project were indicated in business plans and other documents, but when planning technical re-equipment, the issues of determining specific equipment models and opportunities for its use were not worked out in detail [28]. Mistakes in planning lead to inefficient work on project implementation in the future.

In our opinion, the results of project analysis, especially when attracting state support, should reflect not only compliance with legal requirements, but also allow identifying projects with high social and environmental risks and projects of socially responsible orientation.

The obligation to separately disclose the social and environmental effects (losses) of a project, resource efficiency, and other components of socially responsible investment is not provided for in the rules for developing business plans. Thus, in the system of criteria for evaluating commercial investment projects, the social and environmental factor is defined as an additional criterion, depending on the specifics of the project (scale, significance, type of state support). Environmental and social factors are related to external effects, which makes it difficult to determine the impact of such factors on the environment and society. Not all indicators can be quantified. Therefore, the requirements for taking into account social and environmental impacts *are not sufficiently* specified in the methodological recommendations for developing business plans and evaluating the effectiveness of investment projects.

At the regional level, based on the Rules for developing Business Plans for investment projects, local governments form their own requirements for the content of the business plan within the framework of the investment policy of the region. For example, in the Brest region, as **anaddition to the content of the section of the business plan "Characteristics of the organization and its development strategy", it is indicated that** when describing the organization from indicators that reveal the social and environmental aspects of the project, it should reflect "social facilities in the organization's infrastructure, their share in the cost of fixed assets", and when describing the strategy for the development of the organization, conduct an environmental assessment of the project – an analysis of the impact of future production on the environment, the volume of waste, the intended places of their disposal, processing [29].

**Practical application**

Social and environmental requirements for investment projects are included in the guidelines of the World Bank and other world development banks, and are the basis for making investment decisions according to the methodology of the BMF Group, UNIDO and others.

In international practice, investment performance assessment is not strictly regulated. Based on the recommendations and key principles of evaluation of international structures, individual countries develop national methodologies for evaluating the effectiveness of investment projects, which provides a unified methodology and allows comparing the results of evaluations obtained in different countries. The most well-known foreign methods that have become widely used in the theory of investment management and in practice are: the methodology of Goldman, Sachs&Co; the methodology of Ernst&Young; the methodology of the European Bank for Reconstruction and Development (EBRD); the approaches of the World Bank (the World Bank for Reconstruction and Development (IBRD), the International Bank for Reconstruction and Development (IBRD)). International Finance Corporation (IFC) method; cost-benefit method; UNIDO (United Nations Industrial Development Organization) method; Little-Mirlis method. At the same time, certain methodologies (such as those of UNIDO, the EBRD, the IBRD, and others) provide for determining the public effectiveness of an investment project along with evaluating its commercial effectiveness. The development of Russian methods for evaluating the effectiveness of an investment project, based on borrowing foreign experience, has led to the addition of a section on calculating public efficiency.

In 2003, commercial banks developed the Equator principles based on environmental and social standards applied by the International Finance Corporation (IFC) (a private sector member of the World Bank Group). The principles are adopted by large international banks, which make up about 80% of the global financial market, to assess environmental and social risks and are applied globally for loans in the field of bank project financing with a total capital expenditure of at least 50 million US dollars [30].

After a critical analysis of approaches to assessing socio-economic (public) effectiveness, it should be noted the following:

– To date, ensuring only the commercial efficiency of investment projects does not meet the requirements of sustainable development of society and requires compliance with the socio-economic efficiency of projects. Regulatory support and practical application of investment project assessment do not sufficiently take into account the social and environmental consequences of investment decisions, and there is no systematic approach to their assessment.

– Scientific research on the assessment of social and environmental impacts of investment projects is carried out mainly in the direction of their qualitative assessment due to the complexity, complexity and specificity of quantitative assessment. Certain scientific developments that allow applying quantitative assessment to determining the results of investment implementation in the socio-economic system make a significant contribution to the development of the theoretical foundations of investment analysis, but do not allow us to assess the potential harm or determine the contribution of a particular investor to the regional economy in value terms.

– Methodological support for the evaluation of investment projects, which includes indicators of economic efficiency, parameters of the effectiveness of participation in the project for individual participants, elements of assessing public significance, budget payback, and others, does not allow us to assess the contribution of a particular project initiator to the socio-economic system of the region. The development of methodological support for assessing social responsibility would reveal aspects of the project's impact on the socio-ecological system and, consequently, show the importance of applicants for local government support for the region.

The development of new approaches to determining and assessing the social and environmental impact of an investment project on the regional economy, in contrast to the existing ones, makes it possible to assess the potential losses from the project for the socio-economic system of the region or, on the contrary, the contribution to improving the welfare of society. It is proposed to use the initiator's social responsibility profile as a criterion for selecting investment projects for priority financing and other forms of investment support. Social responsibility of the initiator of an investment project (SOIP) characterizes the ability and readiness of business entities within the investment project to meet the requirements and norms of not only domestic standards on social responsibility, but also international ones, to be responsible for the consequences of their actions and to contribute to the development of the social and environmental sphere.

**Conclusions**

The study of various approaches to assessing the socio-economic efficiency of investment projects allows us to conclude that at the present stage of regional development, the social and environmental aspect is becoming increasingly important in the process of making effective management decisions. In order to maintain a favorable socio-economic environment, regional government bodies are forced to take levers of influence on financial, investment, production and other areas. One of the ways to reduce the negative consequences of the activities of unscrupulous business entities is to introduce the principles of social responsibility at the stage of launching new enterprises and implementing investment projects. Thus, to solve social and environmental problems, developed countries are implementing sustainable development strategies at the macro and meso levels, and standards of corporate social responsibility (CSR) are being implemented at the micro level. The application of social responsibility standards should cover all activities of the enterprise, including investment. The CSR concept is of a strategic nature, and the integration of CSR into the investment project evaluation system ensures the development of economic, managerial and organizational solutions that take into account the interests of stakeholders. The involvement of investment entities in the implementation of investment projects, taking into account the provisions of CSR, and the assessment of their implementation will improve the tools for motivating responsible behavior of investors, increase the validity of decision - making on regulating investment projects of destructive content, maintain a favorable investment climate and encourage the attraction of responsible investments to the regional economy.

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## ЮБИЛЯРЫ

# Уласевич Вячеслав Прокофьевич

## *(к 85-летию со дня рождения)*

Родился 22.06.1938 в д. Ковалевщина Вилейского р-на Минской обл. в семье крестьян. После службы в Вооруженных Силах СССР поступил в Белорусский политехнический институт (в настоящее время Белорусский национальный технический университет), который в 1970 году окончил с отличием (Ленинский стипендиат) по специальности «Промышленное и гражданское строительство». Распределен в Брестский инженерно-строительный институт (в настоящее время Брестский государственный технический университет) как молодой специалист, где и работает по настоящее время: ассистент кафедры «Строительная механика» (1970–1971), старший преподаватель (1971–1980), доцент (1980–1995), профессор кафедры «Строительные конструкции» (1995–2020). В 2020 году избран на должность профессора кафедры «Начертательная геометрия и инженерная графика».

Декан факультета «Промышленное и гражданское строительство» (1986–1988).

Кандидат технических наук (1984). Диссертация «Деформационный расчет и исследование напряженно-деформированных состояний пологих однопоясных распорных систем» защищена на докторском совете при ЦНИИСК им. Куйбышева Госстроя СССР (Москва) по специальности 01.02.03 «Строительная механика». Решением Высшей аттестационной комиссии при Совете Министров СССР в 1986 году присвоено ученое звание доцента по кафедре «Металлические и деревянные конструкции».

Научные интересы: теория и методы расчета стержневых систем повышенной деформативности; бетоны с химическими добавками, полученными из промышленных отходов и стоков; совершенствование методики преподавания учебных курсов кафедр «Строительные конструкции» и «Начертательная геометрия и инженерная графика» с использованием информационных компьютерных технологий.

Опубликовал более 170 научных работ, в т. ч. более 50 учебно-методических разработок. Подготовил и опубликовал (в соавторстве) три учебных пособия под грифом Министерства образования Республики Беларусь.

Осуществляя научное руководство магистрантами и аспирантами, подготовил восемь магистров технических наук по специальности 1-70 80 01 «Строительство» и три кандидата технических наук, два из которых (О. В. Костюк; Д. А. Жданов) – по специальности 05.23.01 «Строительные конструкции, здания и сооружения» и один (О. А. Якубовская) – по специальности 05.23.01 «Строительные материалы и изделия».

Осуществлял многолетнее (1997–2020) научно-техническое сотрудничество с Белостоцкой политехникой (Польша) по теме «Ресурсосберегающий технологический регламент на разработку химических добавок из промышленных отходов и стоков, содержащих гуминовые вещества». По результатам совместных исследований подготовлена (Autor: Mgr inz. Dorota Malaszkiewicz) кандидатская диссертация (Rozprawa doktorska), а также несколько нормативно-правовых актов (Польша).

Являлся научным руководителем задания «Строительство и архитектура 21» «Исследование основных свойств конструкционных бетонов, модифицированных добавками, полученными на основе гуминовых веществ из отходов торфопредприятий» Государственной программы ориентированных фундаментальных исследований (2006–2010 гг.), по материалам исследований которого разработана химическая добавка в бетон.

Выполнено более 40 хозяйственных договоров, среди которых дворец Радзивилов в п. Полонечка и костел в д. Волчин, представляющих собой историко-культурные ценности республиканского значения.

Награды: медаль «За освоение целинных земель» (1968); почетные грамоты Министерства высшего и среднего образования БССР (1976, 1981, 1988); премия специального фонда Президента Республики Беларусь по социальной поддержке одаренных учащихся и студентов (2013); грамота Министерства образования Республики Беларусь (2021).

Автор многочисленных информационных компьютерных программ, успешно используемых студентами многие годы в учебном процессе.

По отношению к своим профессиональным обязанностям – инициативен, исполнителен. Пользуется заслуженным уважением среди коллег по работе, студентов, магистрантов и аспирантов.

Основные публикации:


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