СТРОИТЕЛЬСТВО

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REGULATION OF STRUCTURE FORMATION IN COLD-RECYCLED MIXTURES VIA OPTIMIZATION OF THE DISPERSED PHASE AND AGGREGATE SKELETON

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Abstract

In the context of increasing resource conservation and environmental efficiency in road construction, cold recycling is becoming a priority method for pavement rehabilitation. However, the widespread use of Reclaimed Asphalt Pavement (RAP) is limited by its high heterogeneity and the lack of unified approaches to mix design that would consider the structural role of each component. The aim of this work is to develop principles for regulating structure formation processes in cold mixtures by optimizing the aggregate skeleton and the composition of the dispersed phase.

Within the framework of the study, the physico-mechanical properties of four groups of organic-hydraulic mixtures with a high RAP content were investigated. A combined system based on cationic bitumen emulsion and Portland cement was used as a binder, while activated mineral powder was used as an inert filler.

It was established that the partial replacement of cement with mineral powder leads to a significant improvement in performance characteristics: the indirect tensile strength increases, and the efficiency of hydraulic binder utilization increases by more than two times. The developed mathematical model revealed the non-linear nature of the dependence of the elastic modulus on the filler content and allowed determining the point of structural optimum. It is proven that a mechanical increase in the RAP proportion with an excess of binder mastic leads to a particle push-apart effect and a critical reduction in strength due to the disruption of contacts in the mineral skeleton. This justifies the necessity of applying a comprehensive approach to mix design that considers the volumetric parameters of the skeleton.

The introduced criteria for evaluating deformability and homogeneity allowed identifying a contradiction between the strength, elasticity, and technological reliability of the mixtures. The results justify the necessity of transitioning to a multi-criteria mix design approach to ensure a balance between the stiffness of the mineral skeleton and the relaxation capacity of the binder matrix.

Keywords: cold recycling, Reclaimed Asphalt Pavement (RAP), bitumen emulsion, Portland cement, mineral filler, structure formation, elastic modulus, deformability, mixture homogeneity.

РЕГУЛИРОВАНИЕ ПРОЦЕССОВ СТРУКТУРООБРАЗОВАНИЯ ХОЛОДНЫХ РЕГЕНЕРИРОВАННЫХ СМЕСЕЙ ПУТЕМ ОПТИМИЗАЦИИ ДИСПЕРСНОЙ ФАЗЫ И ЗЕРНОВОГО КАРКАСА

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Реферат

В контексте повышения ресурсосбережения и экологической эффективности дорожного строительства холодная регенерация становится приоритетным методом восстановления дорожных одежд. Однако широкое применение асфальтогранулята ограничивается его высокой неоднородностью и отсутствием единых подходов к проектированию состава, которые учитывали бы структурную роль каждого компонента. Целью данной работы является разработка принципов регулирования процессов структурообразования холодных смесей путем оптимизации зернового каркаса и состава дисперсной фазы.

В рамках исследования были изучены физико-механические свойства четырех групп органо-гидравлических смесей с высоким содержанием асфальтогранулята. В качестве вяжущего использовалась комбинированная система на основе катионной битумной эмульсии и портландцемента, а в качестве инертного наполнителя применялся активированный минеральный порошок.

Установлено, что частичная замена цемента на минеральный порошок приводит к существенному улучшению эксплуатационных характеристик, предел прочности на раскол возрастает, а эффективность использования гидравлического вяжущего увеличивается более чем в два раза. Разработанная математическая модель выявила нелинейный характер зависимости модуля упругости от содержания наполнителя и позволила определить точку структурного оптимума. Доказано, что механическое увеличение доли асфальтогранулята при избытке вяжущей мастики приводит к эффекту раздвижки зерен и критическому снижению прочности из-за нарушения контактов в минеральном каркасе, что обосновывает необходимость применения комплексного подхода к проектированию, учитывающего объемные параметры скелета.

Введенные критерии оценки деформативности и однородности позволили выявить противоречие между прочностью, эластичностью и технологической надежностью смесей. Сделан вывод о необходимости перехода к многокритериальному проектированию, обеспечивающему баланс между жесткостью минерального каркаса и релаксационной способностью вяжущей матрицы.

Ключевые слова: холодная регенерация, асфальтогранулят, битумная эмульсия, портландцемент, минеральный порошок, структурообразование, модуль упругости, деформативность, однородность смеси.

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Introduction

Given the global focus of the road industry on reducing the carbon footprint and the rational use of natural resources, the transition from traditional Hot Mix Asphalt (HMA) technologies to energy-efficient cold pavement rehabilitation methods is becoming particularly relevant [1–3]. Cold recycling allows for a significant reduction in energy consumption and greenhouse gas emissions, as well as a decreased demand for virgin mineral aggregates through the reuse of Reclaimed Asphalt Pavement (RAP). In this context, Cold Recycled Mixtures (CRM) are considered not only a technologically viable but also an environmentally sound solution for modern road construction. At the same time, the durability and operational reliability of recycled layers are decisively determined by the structure formation processes occurring in the material at various curing stages [4, 5].

Modern CRM represent complex multicomponent systems in which mechanisms characteristic of both asphalt mixtures and hydraulically stabilized materials are simultaneously realized. The structure of such mixtures is formed through the interaction of the aggregate skeleton consisting of RAP and virgin aggregates, the dispersed phase in the form of bitumen emulsion or foamed bitumen, and active fillers, primarily cement or its analogues [4, 6–10]. As a result, a hybrid cement-bitumen matrix is formed, the properties of which significantly depend on the ratio and distribution of phases within the material volume.

Early approaches to CRM mix design were largely based on methodologies borrowed from HMA practice, with a dominance of strength criteria [1, 6, 10, 11]. However, accumulated field experience has shown that focusing exclusively on achieving high strength values, especially with increased cement content, often leads to the formation of an excessively stiff and brittle structure prone to reflective and thermal cracking [6, 12].

In recent years, the concept of mix design based on performance indicators (performance-based design, balanced mix design) has become increasingly widespread in international practice [13, 14]. Within this approach, the cold recycled mixture is viewed as a multiphase composite system in which a balanced combination of strength, cracking resistance, deformability, and moisture resistance must be ensured. The key factor here becomes not so much the absolute content of binder components, but rather the nature of structure formation and the quality of the formed aggregate skeleton.

Studies show that optimizing the gradation of RAP and virgin aggregates allows for the formation of a stable spatial skeleton capable of effectively withstanding external loads and limiting the development of permanent deformation [15]. Simultaneously, the dispersed phase (bitumen emulsion combined with hydraulic components) determines the structural cohesion, its viscoelastic properties, and resistance to cracking [7, 16, 17]. Changes in the fineness, content, and distribution of fine particles significantly affect the curing kinetics, pore structure, and durability of the material [18, 19].

Despite a significant number of studies, the issues of targeted regulation of CRM structure formation processes through the coordinated optimization of the dispersed phase and the aggregate skeleton remain insufficiently systematized. In most regulatory and practical guidelines, these aspects are considered in isolation, without accounting for their mutual influence on the formation of the performance properties of the recycled layer. As a result, existing mix design approaches rarely quantify the interaction between aggregate skeleton volumetrics and dispersed phase saturation, which significantly limits the predictability of cold recycled mixture performance.

In this regard, a relevant scientific and technical challenge is the development of approaches allowing for the control of the structure of cold recycled mixtures at micro- and macro-levels to enhance their cracking resistance, resistance to deformation, and overall durability.

This work is aimed at investigating and substantiating methods for regulating the structure formation processes of cold recycled mixtures by optimizing the parameters of the dispersed phase and the aggregate skeleton, which aligns with modern trends in the development of pavement materials science and road construction technologies.

Theoretical Foundations of Structure Formation in Organic-Hydraulic Composites

The development of effective mix design methods for CRM requires a fundamental rethinking of the role of components in the formation of the material structure. Unlike traditional HMA, where the mineral skeleton is viewed as an aggregate of inert particles, in cold recycling technologies, the primary structure-forming element is RAP. From the perspective of physicochemical mechanics [20], RAP represents not a monolithic stone material but a particulate composite in which mineral grains are coated with a film of aged, oxidized bitumen. Under cold mixing conditions, which occur without thermal activation, the aged binder does not transition into a viscous-flow state, and the diffusion of oils from the new bitumen emulsion into the depth of the old bitumen film is significantly limited by kinetic and temperature factors. Consequently, RAP granules retain their internal defects and microcracks formed during the service life and milling of the old pavement.

This feature dictates the necessity of abandoning traditional design methods oriented exclusively toward achieving maximum packing density (e. g., according to Fuller-type gradation curves [21]). The striving to minimize porosity by filling the intergranular space with fine fractions and binder often leads to the formation of structures lacking a rigid skeleton, in which coarse RAP grains are separated by the mortar phase. In such systems, the external load is transferred not through the contacts of strong stone grains but through the weaker and more compliant mastic, leading to reduced shear stability and the accumulation of permanent deformation [22]. In this case, the objective function of the design becomes the creation of a packing arrangement that ensures the direct interlocking of coarse particles, forming a rigid load-bearing skeleton capable of withstanding traffic loads and compensating for the internal defects of the RAP granules.

The space within the formed mineral skeleton is filled by a secondary structure–asphalt–mineral mastic–formed as a result of the interaction between bitumen emulsion, water, and dispersed phase components. According to the theory of structure formation of road composites [4, 5], the introduction of fine particles into an organic binder initiates a clustering process, the formation of aggregates consisting of filler particles surrounded by oriented solvation shells of bitumen. The properties of this microstructure critically depend on the nature and fineness of the fillers.

Of particular scientific and practical interest is the effect of the combined use of inert (mineral filler) and active (Portland cement) fillers [4]. Possessing a high specific surface area, the mineral filler performs the function of a physical densifier, filling micropores and increasing the viscosity of the mastic. Portland cement acts as an active modifier; its hydration products form new crystalline formations that reinforce the bitumen film at the micro-level. In such a system, a "cluster-in-cluster" strengthening mechanism is realized, where cement particles create rigid micro-reinforcement within a viscoelastic medium [4]. This theoretical premise allows for the hypothesis that optimizing the composition of the dispersed phase by partially replacing cement with mineral filler can ensure the necessary material strength while maintaining its deformability, thereby reducing the risk of brittle failure characteristic of purely cementitious systems.

Materials

The experimental verification of the theoretical premises was conducted within the framework of an international scientific and technical cooperation program supported by the National Key R&D Program of China (Project No. 2025YFE0199500). The studies were carried out at the laboratory facilities of the Gaoyuan Company, located in Xinxiang (Henan Province, PRC). Access to the high-tech testing equipment at this site allowed for the implementation of the research program in compliance with strict metrological requirements and in full accordance with the regulatory framework of the PRC in the field of road construction.

Reclaimed Asphalt Pavement, obtained by cold milling of an existing asphalt concrete pavement, was used as the main component of the organic-hydraulic mixture. Given the high variability of the properties of the recycled material, sampling was performed using the quartering method to ensure the representativeness of the sample.

The gradation of the RAP was determined by dry sieving in accordance with the T 0302 method of the JTG E42 standard [23]. To assess the homogeneity of the material, three parallel samples were tested. The results of the sieve analysis are presented in Table 1.

Table 1 – RAP Gradation

Sieve size, mm	Sample 1, % passing	Sample 2, % passing	Sample 3, % passing	Average value, % passing
16,0	100,0	100,0	100,0	100,0
13,2	96,7	98,1	97.3	97,4
9,5	87,5	89,8	80,2	85,8
4,75	49,0	56,8	33,8	46,5
2,36	30,5	34,5	16,5	27,2
1,18	21,3	21,9	10,2	17,8
0,6	12,7	11,7	5,5	10,0
0,3	6,6	5,6	3,0	5,1
0,15	3,3	3,0	1,6	2,6
0,075	1,4	1,4	0,8	1,2

To determine the residual binder content in the RAP, the ignition method in a muffle furnace was used according to T 0735 [24]. Based on the test results, the aged bitumen content was 4,46 % (oil-aggregate ratio of 4,66 %).

To optimize the particle size distribution and form a rigid load-bearing skeleton, virgin mineral aggregates from basalt rocks were introduced into the mixture: cubical crushed stone of fractions 10–15 mm, 5–10 mm, and 3–5 mm, and crushed stone screenings of 0–3 mm. The physico-mechanical characteristics of the aggregate, including crushing value, abrasion resistance, and the content of flat and elongated particles, fully complied with the requirements of the JTG F40 standard [25] for asphalt mixtures. The gradation of the virgin aggregates is presented in Table 2.

The mix design of the cold recycled mixture was carried out using a calculation-experimental method. The objective function was the formation of a particle size distribution oriented towards the standard range for dense-graded asphalt concrete of type AC-13 (according to JTG F40 [25]), which in this study was used as a structural benchmark rather than a regulatory requirement to ensure a stable aggregate skeleton. This approach allowed for a comparison of structure formation processes in cold recycled mixtures with the classical principles of mineral skeleton formation in asphalt concrete while preserving the specifics of the organic-hydraulic system. The calculation of component proportions was performed based on the material balance equation

$$P_i = a \cdot A_i + b \cdot B_i + c \cdot C_i + \ldots, \qquad (1)$$

where P_i is the passing percentage on sieve *i* for the designed mixture;

A_i, B_i, C_i are the passing percentages on sieve *i* for each component (RAP, crushed stone, screenings);

a, *b*, *c* are the proportions of the components.

Figure 1 presents the results of the gradation design.

Table 2 – Gradation of Mineral Aggregates

Sieve size, mm	Crushed stone 10–15 mm, % passing	Crushed stone 5–10 mm, % passing	Crushed stone 3–5 mm, % passing	Screenings 0–3 mm, % passing	Mineral filler, % passing
16,0	100,0	100,0	100,0	100,0	100,0
13,2	72,4	100,0	100,0	100,0	100,0
9,5	8,1	100,0	100,0	100,0	100,0
4,75	0,1	11,1	98,7	99.4	100,0
2,36	0,0	0,1	8,5	73,7	100,0
1,18	0,0	0,1	1,5	46,7	99,5
0,6	0,0	0,1	0,5	27,3	95,2
0,3	0,0	0,1	0,4	17,3	88,4
0,15	0,0	0,1	0,4	12,4	76,0
0,075	0,0	0,0	0,3	9,3	65,5

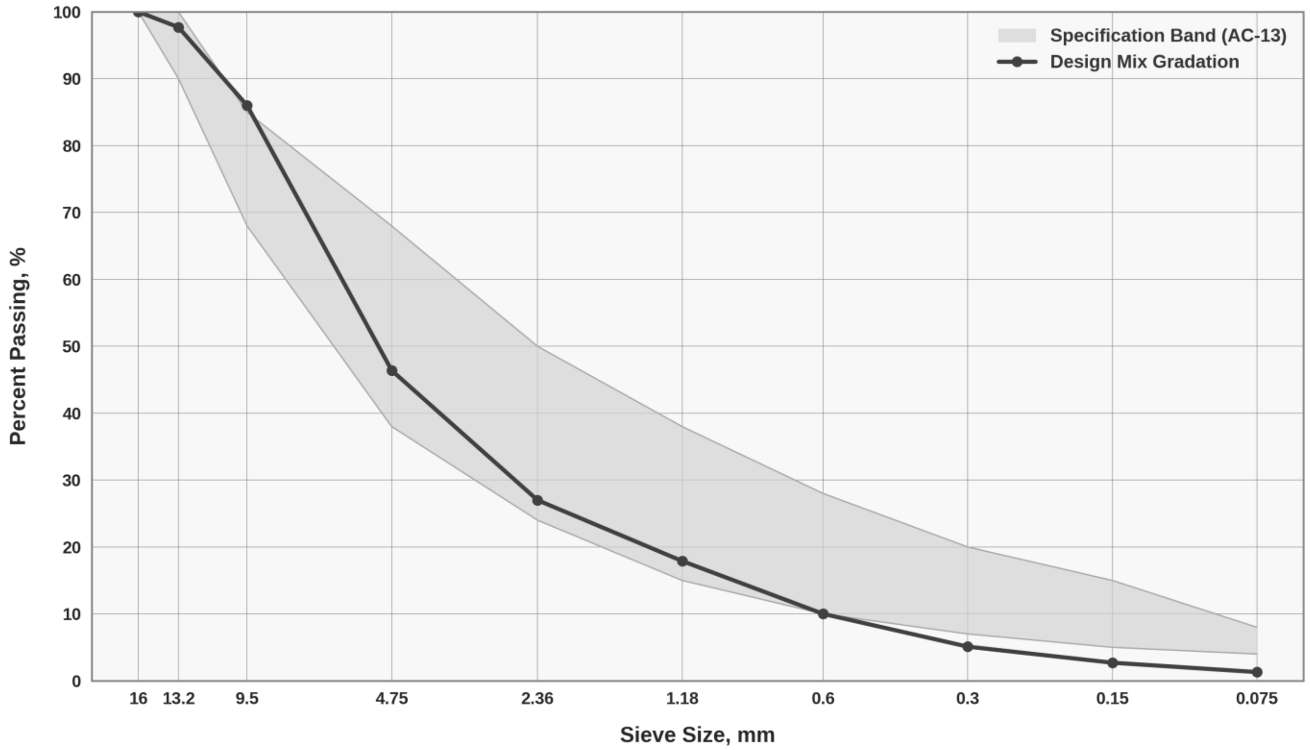

Figure 1 – Gradation curve of the designed organic-hydraulic mixture relative to the standard limits for AC-13 asphalt concrete

To fill micropores and densify the mastic part of the recycled mixture, activated mineral powder obtained by grinding limestone rocks ($CaCO_3$) was used as a dispersed filler. The gradation of the mineral powder, presented in Table 2, was characterized by a high degree of fineness, which ensured a developed specific surface area for interaction with the binder.

The formation of the binder matrix was ensured by a combined system consisting of organic and hydraulic components. A cationic slow-setting bitumen emulsion of the BCR (Bitumen Cold Recycling) grade, modified with a polymer (SBR latex), was used as the organic binder. This type of emulsion, specially developed for cold recycling technologies, is characterized by high adhesion to mineral materials and a controlled breaking time, which meets the requirements of the JTG F40 standard [25]. The role of the active hydraulic binder, ensuring early strength gain and the formation of secondary crystallization bonds, was performed by Portland cement of grade P.O 42.5, the physico-mechanical properties of which met the requirements of the PRC national standard GB 175 [26].

Research Methodology

The experimental research program was developed to separately evaluate the influence of the mineral skeleton structure and the binder mastic composition on the material's performance properties. The experiment involved the design and testing of four groups of mixtures (Table 3).

In the first three groups (mixtures A, B, C), the macrostructure parameters remained constant: RAP content (50 %) and the gradation of the mineral skeleton (crushed stone of 10–15 mm fraction at 10 % and screenings of 0–3 mm at 40 % were used). The bitumen emulsion content also remained constant (7,0 %). The variable factor was the ratio of the dispersed phase components: active (cement) and inert (mineral filler) fillers.

The fourth group (mixture D) was aimed at studying the possibility of maximizing the use of the recycled resource. The RAP proportion was increased to 60 %. To compensate for the change in gradation and prevent segregation, the structure of the virgin aggregate was changed; instead of 0–3 mm screenings, a narrow fraction of crushed stone (3–5 mm) was used. To fill the increased Voids in Mineral Aggregate (VMA), the mineral filler content was raised to 8,0 %, and the emulsion content was increased to 10,5 % to ensure complete coating of the increased specific surface area of the mixture.

Comprehensive evaluation of physico-mechanical characteristics and operational reliability of the developed organic-hydraulic mixtures was conducted in strict accordance with the regulations of the PRC industry standard JTG E20 [24]. The testing program included the fabrication of laboratory specimens, simulation of the curing process, and determination of key indicators: bulk density, water absorption, splitting tensile strength, and elastic modulus.

Specimen compaction was carried out in accordance with method T 0702 [24]. Pre-prepared mineral components (RAP and crushed stone) and fillers were mixed with the calculated amount of water and bitumen emulsion in a laboratory forced-action mixer until complete homogenization of the mixture was achieved. Compaction was performed using an automatic Marshall compactor. To simulate pavement performance under heavy traffic loads, a compaction regime providing 75 blows of the compaction hammer on each side of the specimen was applied. As a result, standard-sized cylindrical specimens (diameter 101,6 ± 0,2 mm, height 63,5 ± 1,3 mm) were obtained.

Table 3 – Matrix of experimental compositions of organic-hydraulic mixtures

Mixture components	Unit	Mixture A (Control)	Mixture B (Hybrid)	Mixture C (Saturated)	Mixture D (High RAP)
1. Mineral skeleton (100 %)					
Reclaimed Asphalt Pavement (RAP)	%	50,0	50,0	50,0	60,0
Crushed stone 10–15 mm	%	10,0	10,0	10,0	10,0
Crushed stone 3–5 mm	%	–	–	–	22,0
Crushed stone screenings 0–3 mm	%	40,0	40,0	40,0	–
Mineral filler ($CaCO_3$)*	%	–	–	–	8,0
2. Additives (over 100% of skeleton)					
Portland cement (P.O 42.5)	%	2,0	1,0	2,0	2,0
Mineral filler ($CaCO_3$)*	%	–	1,0	2,0	–
Bitumen emulsion (BCR)	%	7,0	7,0	7,0	10,5
Added water	%	3,0	3,0	3,0	3,0

Note: In Mixture D, the mineral filler (8 %) is included in the mineral skeleton composition for gradation correction, whereas in Mixtures B and C, it was introduced as an additive over 100 % to modify the mastic.

A critically important stage of preparation was the simulation of the curing process. Since cold mixtures gain strength gradually due to moisture evaporation and bitumen coalescence, freshly compacted specimens (in molds) were placed in a forced-draft oven. Curing was conducted at a temperature of 60 ± 1 °C for 48 hours. This accelerated curing regime allows simulating the physico-mechanical properties of the material corresponding to a long service period in real road conditions. After removal from the oven, specimens were cooled at room temperature for at least 12 hours before testing.

Evaluation of volumetric properties, bulk density, and water absorption of specimens was conducted using the hydrostatic weighing method in accordance with method T 0705 (saturated surface-dry method) [24]. Before weighing in water, specimens were conditioned in a water bath at 25 ± 0,5 °C for 5 minutes to equalize temperature. Based on the obtained data, the bulk density of the skeleton and Voids in Mineral Aggregate (VMA) were calculated, which allowed evaluating the quality of grain packing in the designed mixtures.

The indirect tensile test (splitting test), specified by method T 0716 [24], was used as the main criterion for strength and deformability. This method most accurately models the stress state of the pavement under traffic loads causing tensile stresses in the bottom zone of the layer.

Tests were conducted on a universal electromechanical testing machine equipped with a load frame with force and displacement sensors. Before testing, specimens were conditioned in an environmental chamber at a temperature of 15 ± 0,5 °C for 4 hours. The choice of 15 °C is due to the need to evaluate material behavior under conditions characteristic of the spring-autumn period, when the risk of cracking is highest.

Specimen loading was applied through steel loading strips 12,7 mm wide located along the cylinder generators. The displacement rate of the loading head was 50 mm/min. During loading, the "load-deformation" curve was continuously recorded. Based on the data obtained, two key parameters were determined: Splitting Tensile Strength (R_t), the maximum stress the specimen withstands before failure; and Indirect Tensile Stiffness Modulus (S_t), a material stiffness characteristic calculated from the linear portion of the deformation diagram.

Research Results

During laboratory testing, datasets on physico-mechanical indicators were obtained for each series of specimens. To assess material homogeneity and the reliability of results, values for each individual specimen were recorded. A complete summary of the experimental data is presented in Table 4.

As seen in Table 4, the specificity of materials based on RAP lies in their high inherent heterogeneity. Unlike mixtures based entirely on virgin aggregates, the properties of RAP can vary even within a single batch. Therefore, for an objective assessment of the quality of organic-hydraulic mixtures, it is insufficient to operate only with average strength values. The stability of properties, characterizing the technological reliability of the material, becomes a critically important parameter.

To quantitatively assess homogeneity, the coefficient of variation (C_v) was used, calculated by the formula

$$C_v = \frac{S}{\overline{X}} \cdot 100\%, \qquad (2)$$

where S is the sample standard deviation;

$\overline{X}$ is the arithmetic mean of the indicator in the sample.

Mixture C (2 % cement + 2 % mineral filler) demonstrates high homogeneity; the coefficient of variation for the elastic modulus is only 3,0 %. This indicates that the increased content of the dispersed phase and binder creates a saturated matrix capable of leveling (smoothing out) local defects and the variability of the RAP properties itself. Such a system possesses a high margin of technological reliability.

At the same time, Mixture B (1 % cement + 1 % mineral filler), which showed high average results for strength and elasticity but insufficient technological reliability, is characterized by an exceptionally high coefficient of variation – 34,3 %. A detailed analysis of the sample set reveals the presence of a specimen with a sharply reduced modulus (1824 MPa), which is almost two times lower than the group average. From a physicochemical perspective, this is explained by a deficit of free mastic. In Mixture B, the amount of binder and filler is optimized "at the limit." In those local zones where the RAP turned out to be more porous or "dry" (with a high degree of oxidation of the aged bitumen), the amount of new emulsion and cement paste was insufficient to create strong contacts. This led to the formation of "dry friction" zones or weak bonds, which became sites of premature failure.

When investigating volumetric properties, it was established that mixtures (A, B, C) with a fixed RAP content (50 %) demonstrate close average density values, varying in a narrow range from 2,327 to 2,339 g/cm^3. The highest packing density was achieved in Mixture B, where a combined dispersed phase system was used. At the same time, the transition to Mixture D with an increased RAP content (60 %) led to a noticeable decrease in average density to 2,284 g/cm^3, which is explained by the lower specific gravity of RAP particles compared to natural aggregate, as well as a change in the skeleton gradation.

Water absorption indicators, characterizing the pore structure of the material, revealed a significant influence of the filler type. Control Mixture A, containing only cement, demonstrated the highest water absorption in its group (2.31 %). The partial replacement of cement with mineral filler in Mixture B led to a decrease in this indicator to 1.77 %, which indicates more effective colmatation of micropores by the inert filler. However, a further increase in the total volume of the dispersed phase in Mixture C (2 % cement and 2 % filler) caused a reverse effect–an increase in water absorption to 2.26 %, comparable to the control mixture. The lowest water absorption value (1.53 %) was recorded for Mixture D, which is likely due to the high content of bitumen emulsion (10,5 %) and mineral filler (8 %), creating a dense, binder-saturated mastic structure filling the intergranular space.

Analysis of mechanical characteristics determined by the indirect tensile test at 15 °C demonstrates a clear dependence of strength on the composition of the dispersed phase. The introduction of mineral filler into mixtures with 50 % RAP ensured a stable increase in splitting tensile strength (R_{15}). Thus, Hybrid Mixture B showed a strength increase of 8,5 % relative to Control Mixture A (from 1,344 to 1,459 MPa), and Mixture C reached the maximum value in the series – 1,495 MPa. Meanwhile, increasing the RAP proportion to 60 % in Mixture D led to a sharp drop in strength to 1,087 MPa, which is the lowest indicator among all investigated variants.

Table 4 – Complete results of physico-mechanical tests

Group / Mixture	Specimen No.	Water absorption, %	Bulk density, g/cm^3	Splitting Tensile Strength (R_{15}), MPa	Stiffness Modulus (S_{15}), MPa
A	1	2,23	2,336	1,425	3286
	2	2,33	2,331	1,263	3263
	3	2,37	2,330	1,344	**4421**
Average value		2,31	2,332	1,344	3657
Coefficient of variation (C_v)		3,1%	0,1 %	6,0 %	**16,8 %**
B	1	1,73	2,342	1,410	3689
	2	1,82	2,338	1,464	**1824**
	3	1,75	2,336	1,504	3519
Average value		1,77	2,339	1,459	**3011** (3604)*
Coefficient of variation (C_v)		2,6 %	0,1 %	3,2 %	**34,3 %**
C	1	2,16	2,324	1,535	4561
	2	2,26	2,320	1,496	4300
	3	2,35	2,337	1,453	4390
Average value		2,26	2,327	1,495	4417
Coefficient of variation (C_v)		4,2 %	0,4 %	2,7 %	3,0 %
D	1	1,55	2,285	1,065	2621
	2	1,50	2,287	1,071	2680
	3	1,53	2,281	1,126	2464
Average value		1,53	2,284	1,087	2588
Coefficient of variation (C_v)		1,6 %	0,1 %	3,1 %	4,3 %

Note: The average value for Mixture B is calculated considering all specimens for a correct assessment of dispersion.

The dynamics of the elastic modulus (S_{15}) have a different character. Mixtures A and B showed comparable stiffness levels; however, Mixture C demonstrated a sharp jump in modulus to 4417 MPa, which is more than 20 % higher than the control group indicators. This indicates the formation of a rigid crystallization skeleton with an increased content of active and inert fillers. Conversely, Mixture D is characterized by a critical reduction in stiffness (2588 MPa), which correlates with the drop in strength and confirms the degradation of structural bonds upon oversaturation of the mixture with binder and an increase in the proportion of recycled material. A visual comparison of the mechanical characteristics of the investigated mixtures is presented in Figure 2.

Analysis of the experimental data allows identifying an important technological pattern regarding the role of active and inert fillers. A comparison of Control Mixture A (2 % cement) and Hybrid Mixture B (1 % cement + 1 % mineral filler) demonstrates that the partial replacement of the hydraulic binder with an inert filler does not lead to a reduction in strength characteristics. On the contrary, the splitting tensile strength for Mixture B (1,459 MPa) was 8.5 % higher than that of Mixture A (1,344 MPa).

To quantitatively assess this effect, the specific cement efficiency indicator (A_f) was introduced, defined as the ratio of the tensile strength to the percentage of cement in the mixture

$$A_f = \frac{R_{15}}{C_{cem}}. \qquad (3)$$

Calculation shows that for Mixture A, the A_f indicator is 0,67 MPa/%, while for Mixture B it increases to 1,46 MPa/%. This indicates that in the presence of mineral filler, the efficiency of cement performance increases by more than two times. The mechanism of this phenomenon can be explained by the fact that the mineral filler densifies the mastic, allowing a smaller amount of cement to form higher-quality crystallization bonds in a smaller pore volume.

However, the increase in strength should not be achieved at the expense of cracking resistance. It is known that an excess of rigid bonds makes the material brittle, especially at low temperatures. To evaluate the balance between strength and elasticity, the deformability coefficient (K_d) was introduced

$$K_d = \frac{R_{15}}{S_{15}} \cdot 1000. \qquad (4)$$

The higher the K_d value, the higher the material's ability to relax stresses without failure (greater strain at break). The calculation of coefficients is summarized in Table 5.

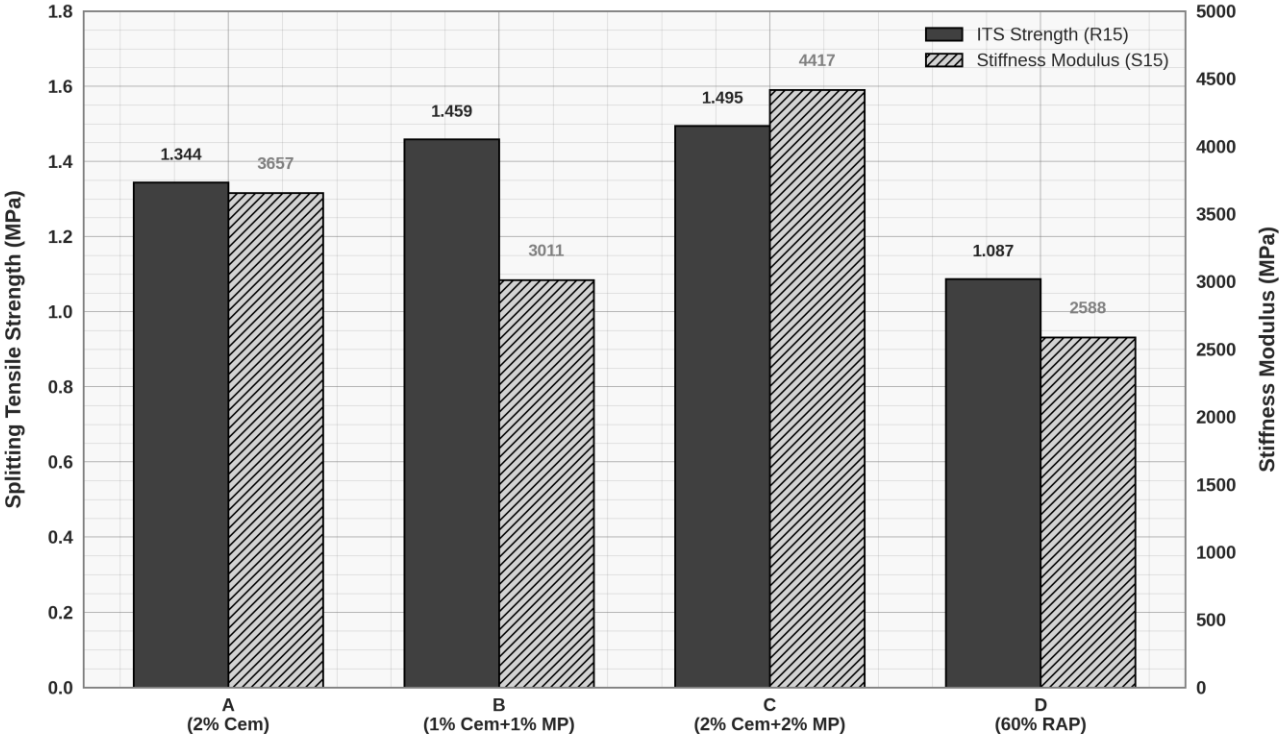

Figure 2 – Comparative diagram of splitting tensile strength (*R_{15}*) and stiffness modulus (*S_{15}*) for different mixture compositions

Table 5 – Calculated indicators of efficiency and deformability

Mixture	Cement, %	R_{15}, MPa	S_{15}, MPa	Cement Efficiency, A_f	Deformability Coeff, K_d
A	2,0	1,344	3657	0,67	0,367
B	1,0	1,459	3011	1,46	**0,484**
C	2,0	1,495	4417	0,75	0,338
D	2,0	1,087	2588	**0,54**	0,420

Mixture C possesses maximum strength but the lowest deformability coefficient (K_d = 0,338). This indicates high stiffness and potential brittleness of the material, which increases the risk of thermal and reflective cracking. Mixture B demonstrates the best balance. With high strength, it possesses the maximum deformability coefficient (K_d = 0,484) among the compliant mixtures. Thus, the strategy of replacing part of the cement with mineral filler is not only economically viable (reducing the consumption of expensive binder by 50 %) but also technically justified, as it allows obtaining a material with enhanced cracking resistance and durability.

For a comprehensive visualization of the identified property contradictions, a multi-criteria map of the operational potential of the investigated mixtures was constructed (Figure 3). On the diagram, the abscissa represents the stiffness modulus (S_{15}), characterizing the load-bearing capacity, and the ordinate represents the deformability coefficient (K_d), reflecting cracking resistance. The size of the marker (bubble) is proportional to the coefficient of variation (C_v); that is, the larger the marker, the lower the technological reliability of the mixture.

The graphical interpretation of the data clearly demonstrates a structural dilemma: Mixture C is localized in the region of high stiffness and stability (minimum marker size) but is characterized by insufficient elasticity (lower zone of the graph). In contrast, Mixture B occupies the leading position in deformability but possesses critically low technological reliability, as indicated by the maximum marker diameter.

To identify quantitative patterns of changes in material stiffness depending on the dispersed phase composition, a regression analysis of the obtained experimental data was conducted. Comparison of the test results of all four groups of specimens, including the mixture with high filler content, allowed establishing that the dependence of the stiffness modulus (S_{15}) on the mass fraction of mineral filler has a pronounced non-linear character. The simple linear assumption that increasing the amount of fine particles invariably leads to an increase in stiffness is refuted by the sharp drop in indicators in Series D.

At the first stage, to describe the established pattern, a second-order polynomial model approximating the average values for each group was selected. This model reflects the physics of structure formation processes in filled systems, where the positive effect of densification is replaced by the negative effect of particle "separation" (push-apart effect) with an excess of the dispersed phase. Using the least squares method, the empirical coefficients of the regression equation were determined

$$S_{15} = 3365 + 684.4 \cdot x - 103.4 \cdot x^2. \qquad (5)$$

Analysis of the obtained model shows that the coefficient of the highest-order term of the equation has a negative value (−103,4), which geometrically corresponds to a parabola opening downwards and indicates the existence of a global maximum point. Differentiation of Equation (5) allows determining the theoretical optimum of the mineral filler content, which is 3,31 %. According to this model, it is at this point that the ultimate structural density of the mastic is achieved (Figure 4).

As seen from the analysis of the primary data, for Mixture B, a significant deviation of individual measurements from the theoretical curve is observed. To increase the reliability of the analysis and account for the material heterogeneity factor, mathematical modeling was performed again using the full dataset (N = 16), including individual values for each specimen. The refined regression equation, taking data dispersion into account, takes the form

$$S_{15} = 3382 + 478.2 \cdot x - 72 \cdot x^2. \qquad (6)$$

The graphical interpretation of this dependence is presented in Figure 5. Visual analysis of the scatter plot demonstrates significant data dispersion, characteristic of RAP-based materials; however, the general non-linear trend remains clearly preserved.

The coefficient of determination of the refined model was R^2 = 0,45. Such a value is an important scientific result; it indicates that the variation in the mix design (filler content) explains 45 % of the variability in the stiffness modulus. The remaining 55 % of the variance is due to the stochastic nature of the RAP and the internal heterogeneity of the structure, which confirms the necessity of considering the reliability factor during design.

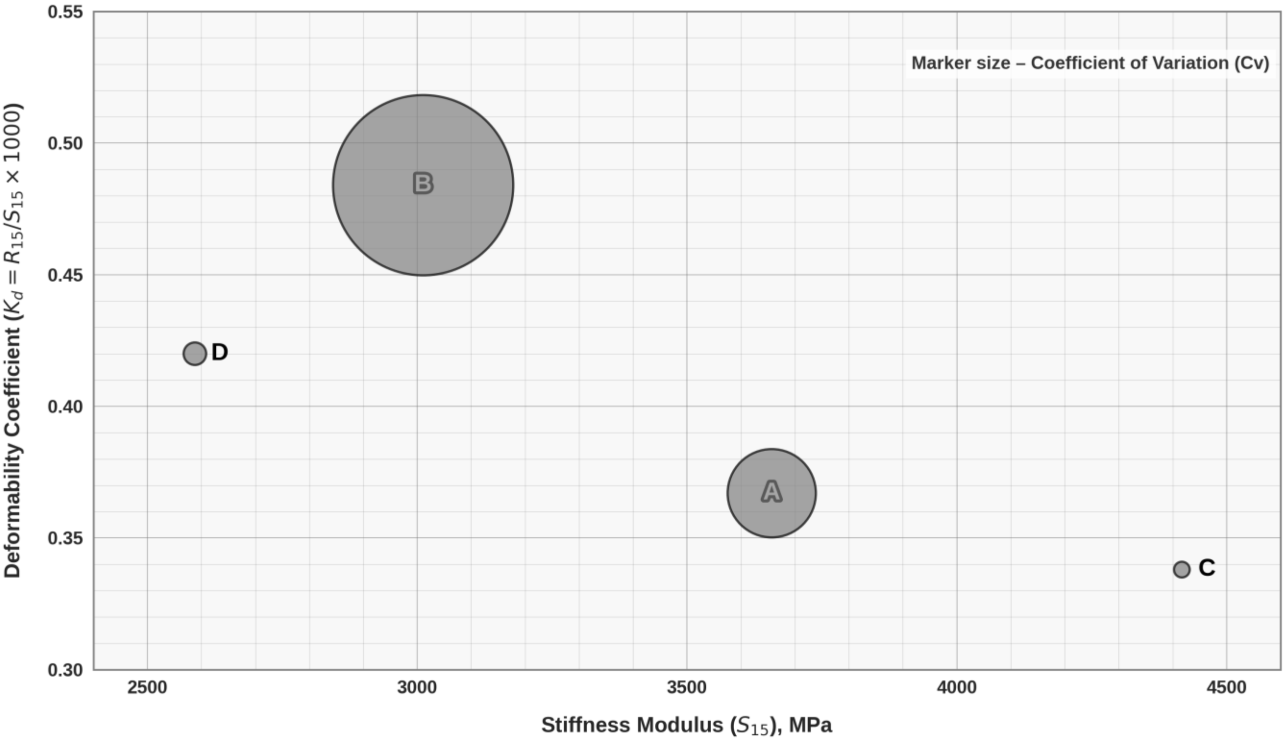

Figure 3 – Multi-criteria map of the operational potential of mixtures: relationship between stiffness (S_{15}), deformability (K_d), and technological reliability (marker size is proportional to C_v)

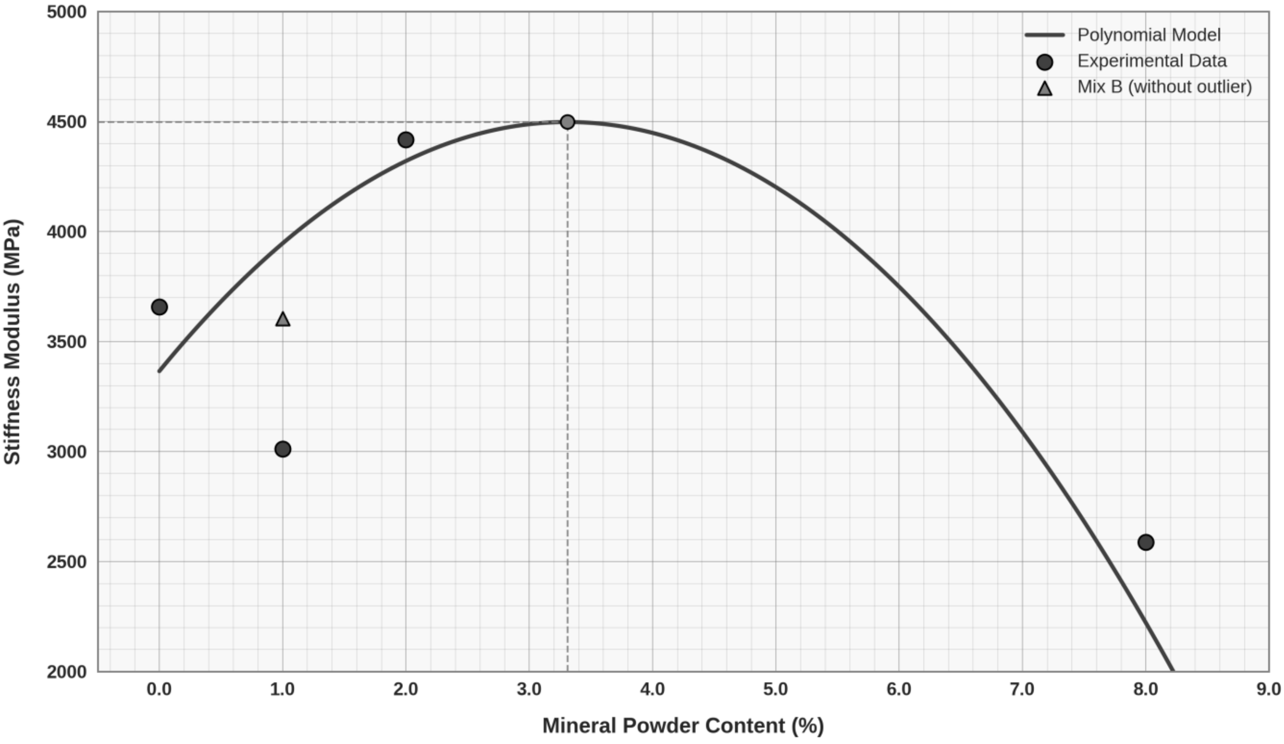

Figure 4 – Approximation of the dependence of stiffness modulus on mineral filler content using a polynomial model (based on average values)

Nevertheless, the refined model also allows for the precise determination of the point of structural optimum. Differentiation of Equation (6) yields

$$\frac{dS}{dx} = 478{,}2 - 144 \cdot x = 0 \Rightarrow x_{opt} \approx 3{,}32\,\% . \qquad (7)$$

Calculation shows that the maximum material stiffness is achieved at a mineral filler content of 3,32 %, which practically coincides with the result of the primary modeling. A further increase in the amount of filler (up to 8 % in Mixture D) shifts the system to the descending branch of the parabola.

Both mathematical models (Figure 4 and Figure 5) provide a theoretical justification for the observed decline in the physico-mechanical characteristics of Mixture D. The filler content in this mixture (8 %) significantly exceeds the calculated optimum, shifting the system into the region of "structural oversaturation." In this state, the excess volume of the dispersed phase and binder begins to act as a separator, pushing apart the coarse aggregate particles and preventing the formation of rigid contacts within the mineral skeleton, which leads to the reduction in stiffness modulus recorded in the experiment.

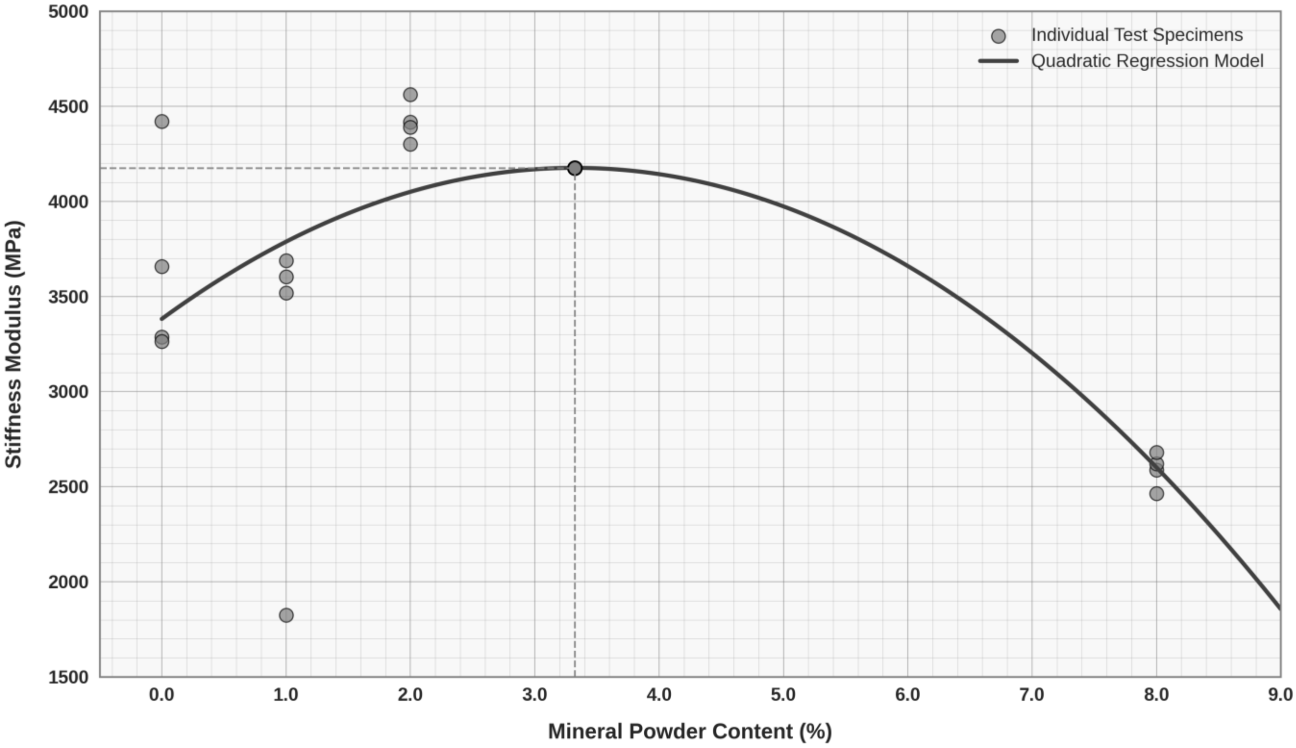

Figure 5 – Statistical model of the dependence of stiffness modulus on mineral filler content (based on the full dataset)

Discussion

Analysis of the obtained experimental data indicates that the partial replacement of Portland cement with inert mineral filler is an effective method for optimizing the composition of cold recycled mixtures. A comparison of Control Mixture A and Hybrid Mixture B shows that reducing the cement content from 2 % to 1 % with the simultaneous introduction of 1 % mineral filler not only did not lead to a loss of strength but also ensured its increase. This confirms the theoretical premises regarding the synergistic interaction of the dispersed phase components, where the mineral filler ensures dense packing of the mastic, and cement hydration products form a reinforcing skeleton within it.

At the same time, a detailed analysis of statistical indicators, particularly the coefficient of variation (C_v), reveals significant differences in the technological reliability of the investigated systems. Mixture B, despite high average indicators, demonstrated significant property heterogeneity (C_v), indicating the high sensitivity of this mix design to mixing quality and local variations in RAP properties. The presence of specimens with reduced characteristics in this series indicates the risk of forming zones with a binder deficit. Conversely, Mixture C, with an increased content of the dispersed phase, showed a minimal coefficient of variation (C_v = 3,0 %), which speaks to the high stability of the structure and the ability of the saturated mastic to level out defects in the raw material.

An integral assessment of physico-mechanical properties through calculated coefficients allows for a deeper understanding of the nature of material behavior. Calculation of the specific cement efficiency (A_f) showed that in Hybrid Mixture B, the binder works more than twice as effectively as in the purely cementitious system A. Furthermore, analysis of the deformability coefficient (K_d) revealed that Mixture C, possessing maximum strength, is characterized by the lowest elasticity, creating risks of brittle failure at low temperatures. Mixture B, on the contrary, demonstrates the most balanced combination of strength and deformability, which is critically important for ensuring pavement cracking resistance.

Particular attention should be paid to the role of the mineral skeleton, which was clearly manifested in the analysis of the results for Mixture D. The critical reduction in physico-mechanical characteristics upon increasing the RAP proportion to 60 % and raising the filler content is explained by the effect of structural oversaturation. The excess volume of mastic led to the separation of coarse aggregate particles, disruption of "stone-on-stone" contacts, and loss of the internal stability of the skeleton. This confirms the necessity of mix design based not only on the principle of dense packing but also taking into account the volumetric parameters of the aggregate skeleton.

Summarizing the research results, it can be concluded that the traditional design approach oriented exclusively toward maximizing strength is not optimal for cold recycled mixtures. A transition to a new mix design concept is necessary, based on finding a balance between three factors: the structural strength of the skeleton; the elasticity of the binder mastic; and the technological reliability (homogeneity) of the material. The development of a comprehensive design methodology that considers these criteria and allows predicting the operational behavior of the mixture at the selection stage will be the subject of further research by the authors.

Conclusion

Based on the conducted experimental studies, mathematical modeling, and theoretical analysis of structure formation processes in cold recycled mixtures, the following conclusions have been formulated:

It has been experimentally confirmed that the partial replacement of Portland cement with inert mineral filler is an effective way to optimize material properties. The mixture with a combined filler (1 % cement + 1 % mineral filler) demonstrated an 8,5 % increase in strength compared to the control mixture with pure cement (2 %), while the specific binder efficiency (A_f) increased by more than two times. This proves that the dense packing of the mastic plays a role no less significant than hydration hardening.

It was established that the dependence of the stiffness modulus on the dispersed filler content is non-linear and is described by a second-order polynomial model. The optimal filler content was calculated to be 3,32 %, corresponding to the maximum material stiffness. Exceeding this threshold leads to an "oversaturation" effect and a reduction in physico-mechanical characteristics, which was confirmed by the decline in properties of the mixture with 8 % filler.

It is proven that a mechanical increase in the proportion of Reclaimed Asphalt Pavement (up to 60 %) without considering the volumetric parameters of the skeleton leads to a critical degradation of material properties. The excess volume of mastic causes the separation of coarse aggregate particles, disrupting "stone-on-stone" contacts, which confirms the necessity of applying gradation design methods to ensure shear stability.

Comparative analysis revealed a contradiction between strength and operational reliability. Mixtures with high binder content (Type C) possess high homogeneity (C_v = 3,0 %) but low deformability (K_d = 0,338), creating a risk of brittle failure. Optimized economical mixtures (Type B) possess high elasticity (K_d=0,484) but low technological reliability (C_v=34,3 %) due to sensitivity to RAP heterogeneity.

The results of the work justify the necessity of transitioning from simple strength-based design criteria to a comprehensive methodology that considers the balance of three factors: the structural strength of the skeleton, the elasticity of the mastic, and technological homogeneity.

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