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Development of Fiber-Reinforced Concrete for Road Pavement Surfaces Enhanced with Complex Additives

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Abstract

This study aims to develop high-performance road pavement concrete capable of withstanding increasing traffic loads while ensuring long service life and reduced maintenance needs. The research focuses on enhancing the mechanical characteristics of fine-grained concrete used in the outer pavement layer through the incorporation of complex additives and dispersed reinforcement. The methodology involved modifying the concrete matrix using the superplasticizer Melflux 5581F, microsilica MK-85, and varying percentages of basalt fibers introduced through different preparation techniques. Mechanical testing, including compressive and flexural strength evaluations, was performed on 40×40×160 mm specimens cured under standard conditions and tested at 7 and 28 days. The analysis showed that Melflux 5581F significantly enhanced strength without increasing cement content, while MK-85 further improved compressive and flexural strengths by up to 50.59% and 46.28%, respectively. The addition of basalt fibers increased flexural strength, with optimal formulations achieving 89.49 MPa in compressive strength and 11.14 MPa in flexural strength. These findings demonstrate that the combined use of chemical, mineral, and fiber additives, together with appropriate technological approaches, substantially improves the performance of road concrete. The proposed modified concrete exhibits enhanced durability, offering a promising solution for extending pavement service life and reducing repair frequency.

Keywords: Road Surface; Fine-Grained Concrete; Micro-reinforcement; Basalt Fibers; Wear Resistance; Durability; Superplasticizer; Microsilica, Strength Indicators.

1. Introduction

Currently, asphalt and cement concretes are used nearly equally for road surfaces, each offering advantages and disadvantages. Although cement concrete road surfaces have a longer service life even under high loads, they have low tensile strength. This implies that they can spontaneously fail when subjected to bending without significant plastic deformation, which can considerably impact the safety and durability of the concrete road surface [1-3]. The results of various studies indicate that the primary cause of concrete corrosion and aging is its high brittleness, which leads to crack formation [4]. This significantly damages road infrastructure and negatively affects the economy.

The enhancement of the mechanical properties of cement concrete pavements primarily relies on improving the structure of the cement matrix and contact zones. Modern methods are employed to modify concrete structures to achieve pavements with enhanced characteristics. These methods include the incorporation of mineral and chemical additives,

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as well as the use of dispersed reinforcement with basalt fibers [5-7]. The properties of fiber-reinforced concrete are influenced by several factors, including the type, quantity, and length of the fibers, and the method of their introduction. This complexity makes it challenging to identify consistent patterns in the research findings. Numerous scientific studies reflect this variability, suggesting different approaches to improving the mechanical properties and durability of concrete [8-10].

According to Nassani [8] and Chen et al. [11], the compressive and flexural strengths of concretes can be enhanced. The mechanical properties of fiber-reinforced concretes have been improved using three types of hybrid microfibers: steel-glass, steel-basalt, and glass-basalt fibers. The effects of hybrid reinforcement were also investigated by varying the fiber content ratios. In all combinations, an increase in strength was observed compared to the control specimens.

Furthermore, the flexural strength and freeze resistance of fiber-reinforced concrete can be improved by basalt microfibers [9], which are particularly important for pavement concrete applications. By investigating and analyzing the impact of different amounts of basalt fibers on the properties of concrete, it was determined [10] that the mechanical properties of concrete, particularly the tensile strength, flexural strength, and impact viscosity index, were improved in all cases. However, no significant increase in compressive strength was observed. This study compared the effects of basalt fibers with lengths of 12 mm and 22 mm, introduced at volumes of 0.05%, 0.1%, 0.3%, and 0.5%. The inclusion of basalt fibers of varying lengths consistently increased the viscosity of the concrete mix, resulting in decreased workability and making placement more challenging. When comparing fibers 22 mm long with those 12 mm long, the mix containing the longer fibers tended to have a lower thickness. This is attributed to the difficulty in evenly distributing longer fibers within the cement matrix, which leads to a reduced cone slump value. Furthermore, it was observed that the incorporation of 22 mm basalt fibers into concrete resulted in a higher slump compared to the use of 12 mm fibers at an equivalent volume fraction. This behavior may be attributed to the greater number of shorter fibers per unit volume, which leads to a higher fiber distribution density. Consequently, the uniform dispersion of the fibers within the concrete matrix becomes more challenging, potentially causing a reduction in slump.

After studying the mechanisms for enhancing the strength of road concrete, as well as assessment methods and service life considerations aligned with modern energy-saving and emission reduction policies, it was concluded that the performance properties of road cement concrete are influenced by the raw material components and the concrete's internal structure. Improvements in the structure occur through various means, including reducing pore volume, altering the nature of the pores, enhancing the structure of the contact zone, and minimizing microcracks, etc. These issues were addressed by modifying the concrete composition. This involves using high-strength cement, selecting aggregates with an optimal grain size, and incorporating various types of additives. Notably, the rubber crumb should not exceed 30% of the volume of fine aggregate, while the fiber content should be up to 2% of the total volume of concrete. It is important to note that an excessive amount of rubber crumb can weaken the concrete, whereas high quantities of fiber can increase the surface area of the contact zone and introduce defects [1].

The method used to assess the mechanical characteristics of road surfaces should be aligned with their operating conditions. For cement concrete used in highways and urban roads, the evaluation focuses on the flexural strength and crack resistance. In contrast, airport runway surfaces are assessed based on their impact resistance. Given that the total length of roads worldwide is continually increasing and that existing roads are being renovated, there is a significant demand for natural resources. Today, the importance of resource conservation and environmental protection is more relevant than ever. As a solution, it is proposed to partially replace both fine and coarse aggregates in cement concrete road surfaces with Reclaimed Asphalt Pavement (RAP) aggregates generated from the repair of asphalt concrete surfaces [11-13].

Research indicates that the introduction of nanosilica and fibers into concrete creates a synergistic effect, enhancing both the frost resistance and mechanical properties [14]. Incorporating various metallic and non-metallic fibers can improve the crack resistance, impact toughness, and wear resistance of road surfaces [15]. Furthermore, the use of natural fibers, such as coconut fibers, together with 15% microsilica has been shown to enhance road surface characteristics. This combination allowed for an 8% reduction in the coating thickness. Since microsilica is a byproduct of industrial processes, its inclusion not only lowers the cost of concrete but also benefits the environment [16].

According to Karapetyan et al. [17] and Grigoryan [18], the properties of both heavy and lightweight fine-grained concretes can be enhanced using basalt fibers up to 12 mm in length. The characteristics of road cement concrete are also improved by mineral nanofibers, and eight years of road traffic experience demonstrate the practical applicability of nanofiber-reinforced concrete [19]. Studies have also investigated road cement concretes modified with polyester fibers and SBR latex [20], combined basalt and bamboo fiber reinforcement [21], and road pavements made from polypropylene fiber-reinforced concrete (PFRC) [22]. Furthermore, according to Hu et al. [23] and Wang et al. [24], the Flexible Concrete Blanket (FCB) reinforced with basalt fibers enhances mechanical properties, with the inclusion of fibers in composite materials significantly increasing both tensile and flexural strength [25]. The enhancement of the physical and mechanical properties of concrete through the use of complex additives – including mineral, chemical, and dispersed reinforcement – has been investigated in [26–28] and numerous other studies.

The incorporation of these fibers into composites helps prevent crack propagation, thereby increasing the stability and longevity (service life) of the concrete. The selection of such additives in concrete technology is based on their effectiveness, which may vary depending on the type of aggregate and cement used [29-31]. When evaluating methods for improving the physical and mechanical properties of fiber-reinforced concretes, attention was given not only to the use of mineral and chemical additives, but also to the application of various technological approaches during the preparation of the concrete mixture.

2. Materials and Methods

2.1. Rew Materials

The components of road concrete consist of Portland cement, river sand, basalt fibers, superplasticizer, microsilica, and water.

2.1.1. Binder: Portland Cement

The binder used in this study is 42.5 grade Portland cement produced by the Ararat plant [32]. The physical and mechanical properties, as well as the chemical composition of the cement, were determined following the standards outlined in references [33-35]. These details are presented in Tables 1 and 2.

Table 1. Physical and mechanical properties of cement composition

Characteristics	Days	Results obtained
Standard consistency (%)	-	31
Specific gravity (g/cm^3)	-	3.1
Blain's fineness (m^2/kg)	-	350.5
Compressive strength (MPa) (EN 196-1)	3 days	21
	7 days	37
	28 days	50.9
Setting time (min) (EN 196-3)	Initial	50
	Final	310

Table 2. Chemical composition of cement

Chemical composition of cement (wt. %)								
Al_2O_3	SiO_2	Fe_2O_3	CaO	MgO	SO_3	Loss of ignition	Insol. Resid.	Free CaO
3.21	28.2	1.25	52.5	5.1	2.8	3.7	2.1	1.13

2.1.2. Fine Aggregate: Sand

River sand from the Ranchpar mine, with a fineness modulus of 3.1, was used as the fine aggregate. The grain size is presented in Table 3 and illustrated in Figure 1. The chemical composition is provided in Table 4, according to GOST 8735-88 standard

Table 3. Physical properties of river sand

Bulk Density		1525	kg/m^3
Real Density		2.49	g/cm^3
		Sieve Residue	
		Partial	**Total**
Sieve Size (mm)	2.5	15.40	15.40
	1.25	24.60	40.00
	0.63	27.10	67.10
	0.315	20.10	87.20
	0.16	10.90	98.10
Particle Content of < 0.16 mm		1.9	

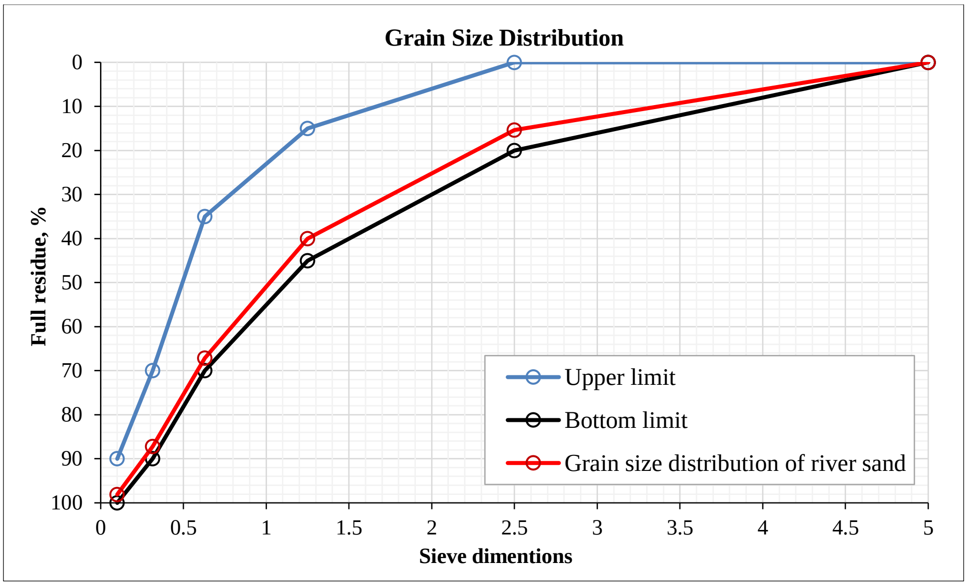

Figure 1. Grain size distribution of river sand

Table 4. Chemical composition of sand

Chemical composition (% by mass)									
SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	CaO	MgO	Na_2O+K_2O	SO_3	Loss on ignition
57.3	0.6	14.6	6.2	-	8.3	4.8	-	-	4.6

2.1.3. Chemical Additive: Melflux 5581F

The use of modern superplasticizers can significantly reduce the water-to-cement ratio, thereby increasing the strength and durability of concrete. In this study, the German-made polycarboxylate-based superplasticizer Melflux 5581F (BASF® Construction Solutions) was used. This additive is recognized as one of the most effective and versatile plasticizers of the latest generation, commonly used in the production of artificial stones with cement and gypsum binders. It functions as both a water-reducing and anti-shrinkage agent and is typically used in dosages ranging from 0.05% to 1% of the cement mass. According to the manufacturer's specifications, it can reduce water demand by up to 40% without adversely affecting the setting times.

2.1.4. Mineral Additive: Microsilica MK-85

Microsilica MK-85 was utilized as a mineral additive in this study. It is a by-product of ferroalloy production generated during the smelting of ferrosilicon and its alloys. This microsilica is a very fine powder consisting of amorphous silica, with a specific surface area of approximately 20 m²/g. The average particle size of microsilica is about 0.1 µm, which is roughly 100 times smaller than that of typical cement grains. Owing to its unique physicochemical characteristics, microsilica is widely employed in the production of high-strength concrete.

2.1.5. Basalt Fiber

In this study, basalt fibers measuring 10 to 12 mm in length and 17 µm in diameter were utilized for dispersed reinforcement.

2.1.6. Water

Water that meets the requirements of the standard GOST [36] was used for mixing and maintaining the concrete mix throughout the hardening period, and for washing the aggregates.

2.2. Mixing and Sample Preparation

The preparation of a fine-grained fiber concrete mixture using the specified raw materials was conducted in an E 095 type of mortar mixer by "Matest". The mixture was then molded into 40 mm ×40 mm ×160 mm molds. After being stored under normal conditions in a C 302-12 type chamber ("Matest"), the samples were tested at 7 and 28 d using S 337 and C 089 types of compression testing machines ("Matest"). The study examined the influence of various factors on the improvement of concrete properties. These factors include not only different proportions of components added to the mortar but also the technological methods employed in its preparation. Specifically, the following techniques were investigated:

- Activation of microsilica using a PM 200 (Retsch, Germany) planetary ball mill.
- Gradual incorporation of fibers into the prepared mortar.
- Joint grinding of cement, MK-85, superplasticizer, and fibers were in a ball mill.
- Pre-treatment of fibers and superplasticizer in water prior to their incorporation into the mortar.

2.3. Analytical Methods

The GOST 12730.3-2020 standard (Concrete. Method for calculating water absorption) was followed in determining the samples' density and water absorption. Dynamic Light Scattering (DLS, Litesizer 500 by Anton Paar) was used to measure the synthesized material's particle size. A 50 kN Unitronic compression testing machine was used to determine the flexural strength (F) of the 40 × 40 × 160 mm specimens according to the standard test method for flexural strength of cement-based materials, operating within the machine's maximum capacity of 50 kN. Three-point bending was applied to the prism specimens at a loading rate of 0.05 kN/s.

The compressive strength (Rcom) of 40 × 40 mm specimens was evaluated in accordance with EN 196-1 (Methods of Testing Cement Part 1: Determination of Strength). Compressive tests were performed at specimen ages of seven and twenty-eight days using automatic testing equipment (Concrete compression machine 2000kN automatic, Servo-Plus Progress C089, Matest) with a loading rate of 2.4 kN/s.

Figure 2 illustrates the raw materials used for preparing basalt fiber–reinforced concrete, along with the complete sequence of mixing, compaction, specimen formation, curing, and testing.

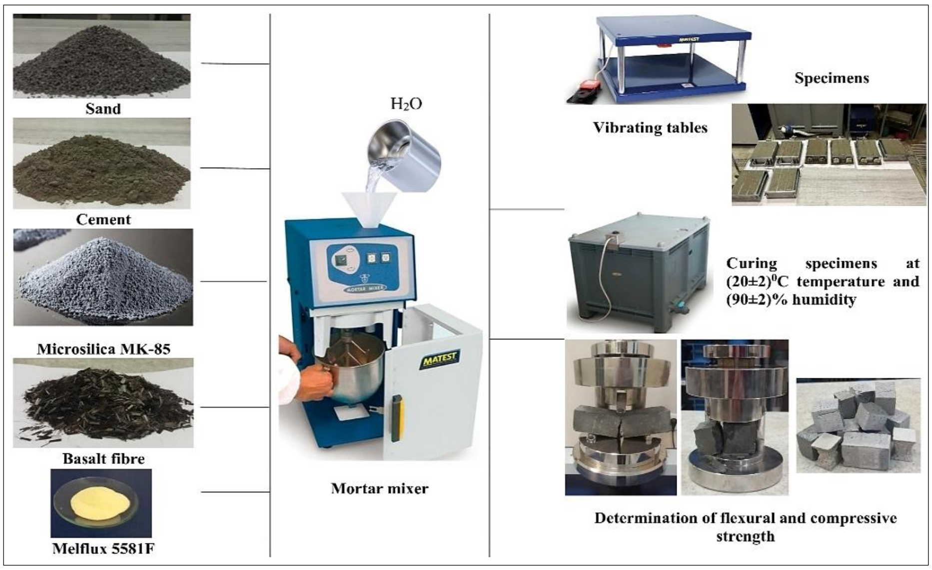

Figure 2. Flowchart of fiber-reinforced concrete production

3. Results and Discussion

This study aimed to explore methods for enhancing the properties of road cement concrete by incorporating chemical and mineral additives and basalt fiber. To achieve this, sand with an optimal grain size was selected using experimental methods (Figure 1). The research workflow was divided into several stages in accordance with the study objectives. In the first stage, the potential to improve the mechanical properties of fine-grained concrete was examined by using a mineral admixture (MK-85) and a chemical admixture (Melflux 2651F). The corresponding results are presented in Table 5 and Figures 3 and 4. Most chemical additives that enhance the properties of concrete and mortar are surfactants. By adsorbing from the liquid to the surface during phase separation, they reduce the surface tension and thereby improve rheological behavior. Adsorption decreases the interfacial energy, facilitating particle fragmentation (or deflocculation). This process releases a significant amount of adsorbed water, which enhances the plasticity of the mixture. Such improvement is particularly important when using microsilica and subsequently basalt fiber. Additionally, as the additive adsorbs onto the particles, the solid-phase particles acquire a uniform charge. This uniform electrostatic charge causes mutual repulsion between particles, which increases the degree of hydration of the cement minerals.

Table 5. Compositions and physical, mechanical properties of fine-grained concretes

No.	Cement M500 (42.5) g	Sand (g)	Melflux 5581F % cement	MK-85 % cement	Basalt fiber 12 mm (% cement)	W/C	Flexural strength (MPa)		Compressive strength (MPa)		Density (g/cm^3)	Water absorption (%)
							7 days	28 days	7 days	28 days		
1	520	1240	-	-	-	0.35	4.68	4.88	28.25	36.61	2.13	5.87
2	520	1240	0.7	-	-	0.35	5.07	6.18	39.80	51.65	2.17	4.18
3	520	1240	0.7	10	-	0.35	5.29	9.04	61.83	77.78	2.15	4.05

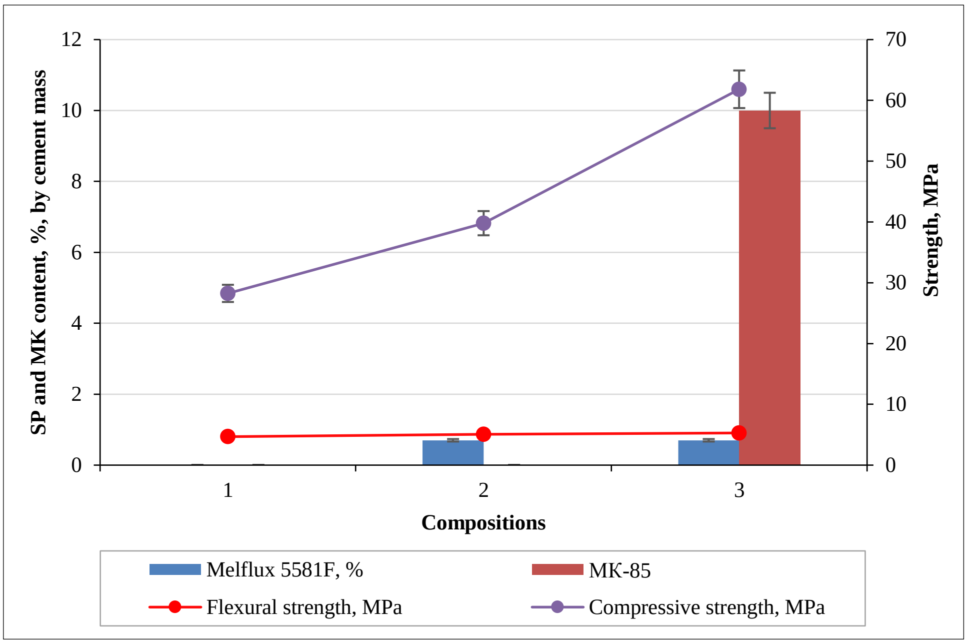

Figure 3. Flexural and compressive strengths of fine-grained concrete (1-3 compositions) at 7 days

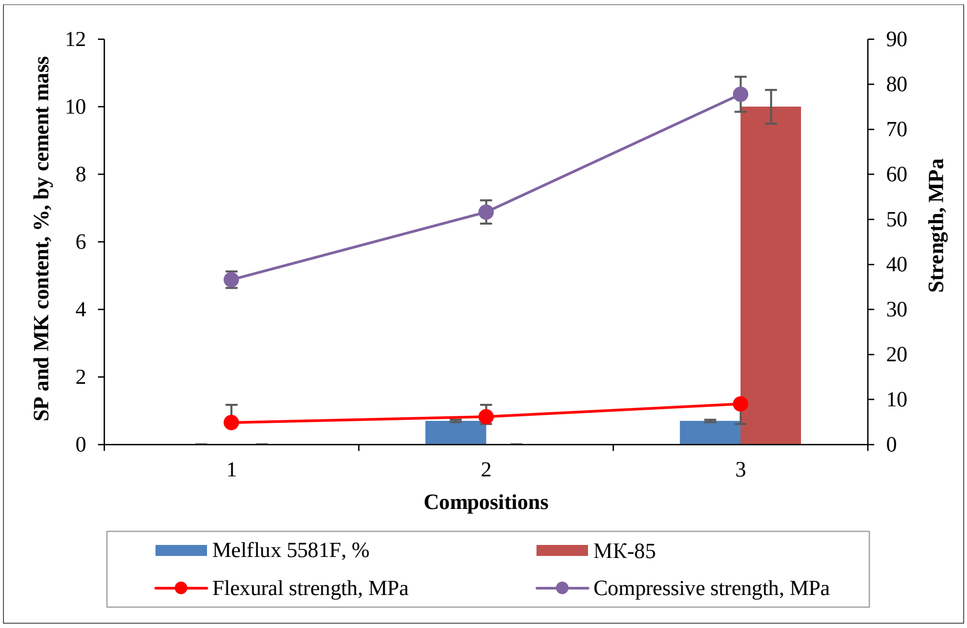

Figure 4. Flexural and compressive strengths of fine aggregate concrete (1-3 compositions) at 28 days

The results showed that modification with chemical and mineral additives led to an increase in compressive strength by 112.45% and an increase in flexural strength of 85.25% compared to the reference sample.

To further enhance the flexural strength, various percentages of basalt fibers were incorporated into the composition of the specimens. The test results for the samples prepared using these fibers are presented in Table 6 and Figures 5 and 6. In all fiber-reinforced compositions, the MK-85 content (10%) was kept constant, while the dosages of the superplasticizer and basalt fibers were varied.

Table 6. Compositions and physical and mechanical properties of fine-grained concrete

No.	Cement g M500 (42.5) q	Sand (g)	Melflux 5581F % cement	MK-85 % cement	Basalt fiber 10 mm %	W/C	Flexural strength (MPa)		Compressive strength (MPa)		Density (g/cm^3)	Water absorption (%)
							7 days	28 days	7 days	28 days		
4	520	1240	0.7	10	1	0.35	7.02	10.74	68.20	87.29	2.22	5.17
5	520	1240	1.0	10	1	0.35	7.52	9.51	60.94	80.47	2.08	5.6
6	520	1240	0.7	10	2	0.35	8.19	10.35	71.18	87.46	2.16	4.05
7	520	1240	1.0	10	2	0.35	9.51	11.14	62.98	84.27	2.14	5.5
8	520	1240	1.0	10	4	0.35	7.74	8.62	56.18	75.95	2.06	7.86
9	520	1240	1.0	10	5	0.35	5.39	7.28	21.72	51.72	2.07	7.83

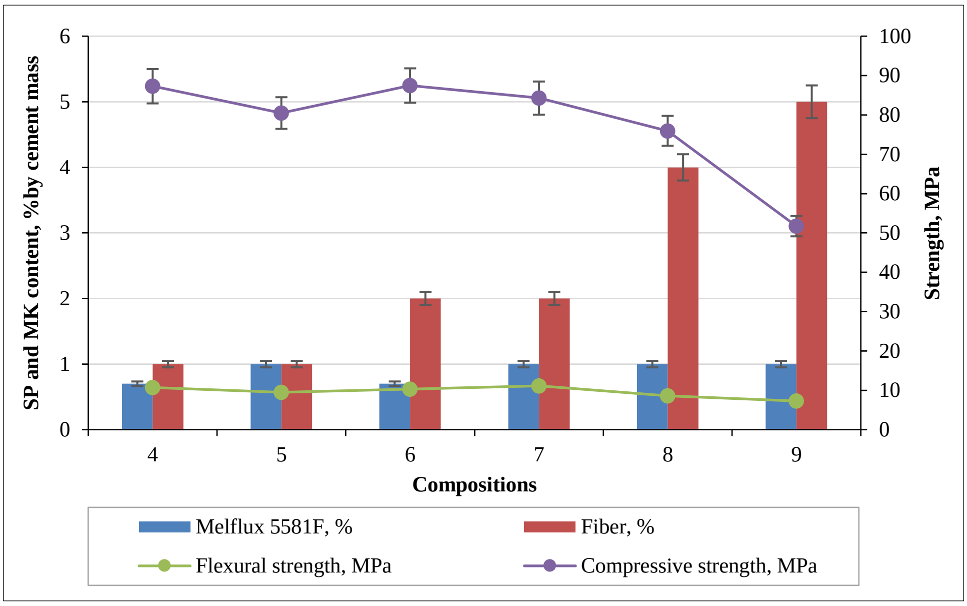

Figure 5. Flexural and compressive strengths of fine-grained concrete (4-9 compositions) at 7 days

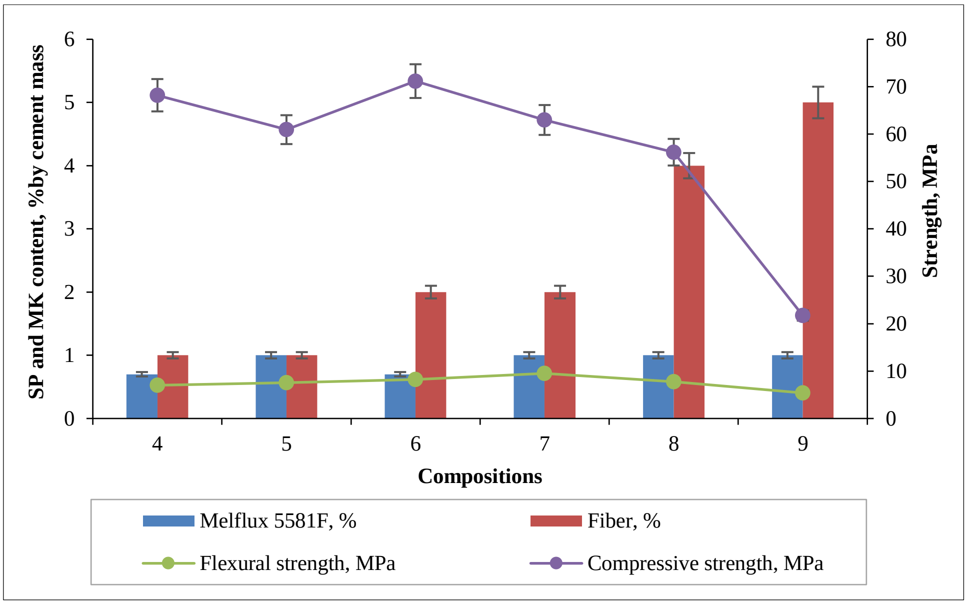

Figure 6. Flexural and compressive strengths of fine aggregate concrete (4-9 compositions) at 28 days

In the case of first method (Table 7, No. 10*), the microsilica was ground in a planetary ball mill for 70 minutes. The grinding procedure consisted of 30 minutes of right rotation, followed by a 10-minute pause, and then 30 minutes of left rotation, at a speed of 550 rpm. Dynamic Light Scattering (DLS) analysis showed that the resulting fine powder had a maximum particle size of 450 nm. After griding, the material was subjected to ultrasonic dispersion. The results of this research are presented in Figure 7.

Table 7. Composition and physical, mechanical properties of fine-grained concrete

No.	Cement M500 (42.5) g	Sand (g)	Melflux 5581F (% cement)	MK-85 (% cement)	Basalt fiber 12 mm (% cement)	W/C	Flexural strength (MPa)		Compressive strength (MPa)		Density (g/cm³)	Water absorption (%)
							7 days	28 days	7 days	28 days		
10*	520	1240	0.7	10	2	0.35	7.68	7.9	70.06	89.49	2.18	6.8
11	520	1240	0.7	10	2	0.35	8.19	10.35	71.18	87.46	2.16	4.05
12	520	1240	0.7	10	2	0.35	6.51	9.62	53.25	70.67	2.17	3.75
13	520	1240	0.7	10	2	0.35	7.56	10.18	65.19	88.31	2.13	5.65

* MK-85 underwent fine grinding using a planetary ball mill.

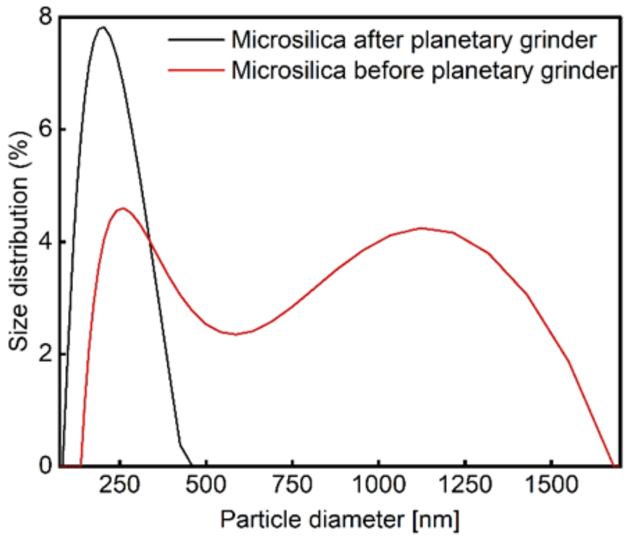

Figure 7. Particle size distribution of microsilica according to Dynamic Light Scattering (DLS) analysis before and after grinding

When finely dispersed microsilica is used, thousands of spherical microparticles effectively envelop the cement grains. This process densifies the cement stone and fine-grained concrete by filling the voids with solid hydration products, thereby enhancing the bond between the aggregate and cement stone. The benefits of using microsilica are superior to those of active mineral additives derived from volcanic tuffs, pumice, and slag, which are abundant in our Republic. The high pozzolanic activity of microsilica significantly improves various properties of concrete, including compressive and flexural strengths, wear resistance, frost resistance, chemical stability, and water permeability.

Using microsilica enables a reduction in cement consumption while maintaining strength, thereby contributing to a lower carbon footprint and a reduced environmental impact.

In the second method (Table 7, No. 11), a mixture of cement, microsilica, and Melflux 5581F was prepared in a mortar mixer. After mixing these components, sand was added, and the mixing continued. Subsequently, measured water was incorporated, followed by the addition of basalt fiber in small portions to create a homogeneous mortar.

In the third method (Table 7, No. 12), cement, MK-85, superplasticizer, and fiber were co-ground in a A091-02 type of dry grinding laboratory ball mill (Matest) for a duration of 60 seconds.

In the fourth method (Table 7, No. 13), after 4-hours of storage period, an aqueous mixture of basalt fiber and Melflux 5581F superplasticizer was added to the dry mixture, and mixing continued until a homogeneous mass was achieved.

The mixtures prepared using the four methods, which had the same composition, were molded in molds measuring 40mm × 40mm × 160mm. After 24 hours, the specimens were demolded and transferred to a normal sample curing chamber. Flexural and compressive strengths were tested at 7 and 28 days (EN 196-1). The test results for the mortar admixtures are also presented in Figures 8 and 9.

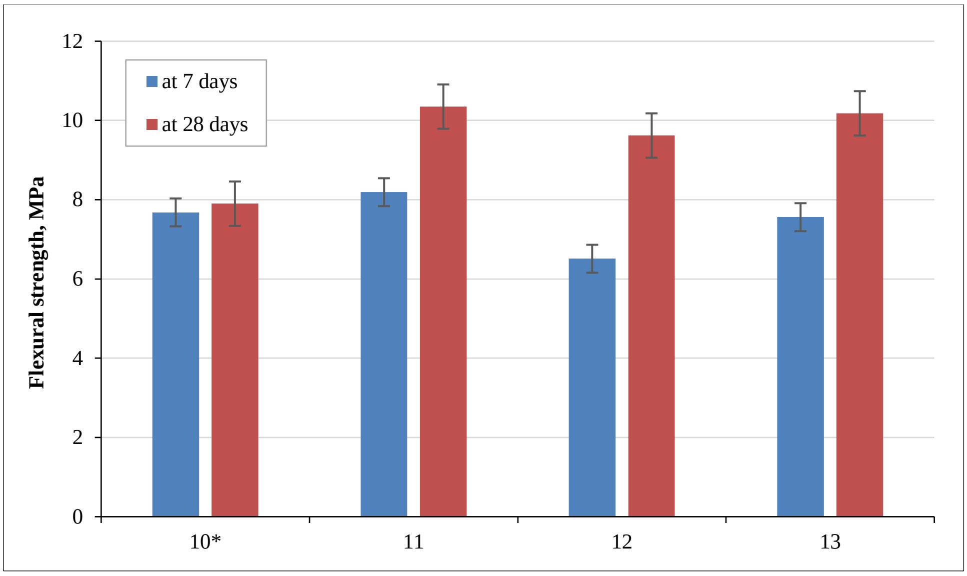

Figure 8. Flexural strengths of fine-grained concretes (10-13 compositions)

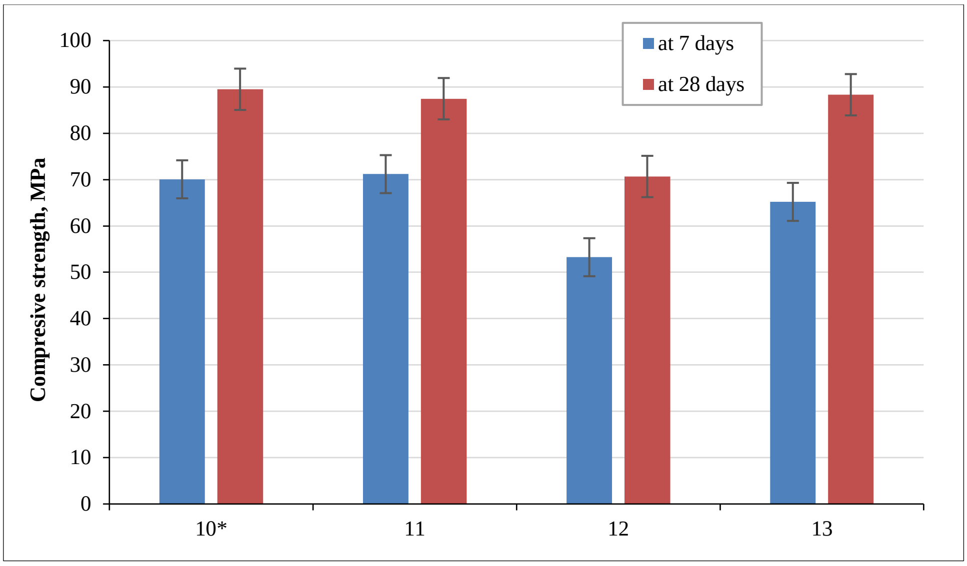

Figure 9. Compressive strengths of fine-grained concretes (10-13 compositions)

Water absorption and permeability are critical characteristics determining durability of concrete. Both parameters are interrelated and influenced by the porosity and character of the concrete. These indicators also depend on the capillary porosity of the concrete, caused from excess water. To enhance the workability of the concrete mixture, the superplasticizer Melflux 5581F was used in various percentages (0.7% and 1.0%) relative to the cement mass. An increased amount of superplasticizer enhances the workability of the mixture due to the electrostatic effect. As a result of the repulsion between cement particles and the displacement of water molecules from the adsorbed layer on the cement grains, the density of the cement pastes decreases, leading to the formation of capillary pores and increased water absorption. As shown in Table 6, the optimal amount of plasticizer is 0.7% of the cement mass. At this level, the mixture achieves uniform compaction, and the resulting consistency confines the binder more effectively, leading to increased density of the cement paste and improved durability-related properties.

The conducted experiments demonstrated that the mechanical performance and durability-related properties of fine-grained concrete are strongly influenced not only by the type and dosage of mineral and chemical admixtures, but also by the sequence and method of their incorporation. The combined use of Melflux 5581F and microsilica (MK-85) significantly improved both flexural and compressive strengths of the reference mixture due to enhanced dispersion, intensified hydration, and densification of the cement matrix.

The comparative assessment of the four preparation methods showed that the mixture produced by Method 11, where cement, microsilica, and superplasticizer were first homogenized, and the basalt fibers were subsequently introduced gradually at the final stage, ensured the most uniform structure and the highest mechanical properties at both 7 and 28 days. This method provided optimal dispersion of solid particles, minimized fiber agglomeration, and facilitated the formation of a dense and well-hydrated cementitious matrix. In contrast, the methods involving joint grinding or prolonged pre-soaking of fibers resulted in reduced strengths due to fiber damage, non-uniform distribution, or altered surface activity.

Overall, the results confirm that the efficiency of basalt fiber reinforcement and the pozzolanic action of microsilica depend strongly on the technological sequence of mixing, and that properly selected chemical and mineral additives can more than double the strength of fine-grained concrete, while also improving its density and reducing water absorption.

4. Conclusions

To investigate the properties of road cement concrete pavements with complex modifications, 13 batches of test specimens were prepared. These included both a basic concrete and modified versions incorporating mineral additives, chemical additives, and basalt fiber. Based on the analysis of how different mixing techniques affected the resulting material properties, the following conclusions were drawn:

- Composition (3), modified with MK-85 and Melflux 5581F additives, demonstrated a 112.45% increase in compressive strength and an 85.25% increase in flexural strength at 28 days compared to composition (1).
- The introduction of 2% basalt fibers by weight of cement resulted in an increase in compressive and flexural strengths for the composition (6) at 28 days. Relative to composition (3), compressive and flexural strengths increased by 12.45% and 14.49%, respectively. Additionally, when compared to the reference composition (1), the improvements were significant, with an increase of 138.9% in compressive strength and 112.1% in flexural strength.
- When microsilica MK-85 was additionally dispersed using planetary ball milling to a particle size of approximately 450 nm and incorporated into composition (10), a 23.67% reduction in flexural strength was observed compared to composition (11). However, compressive strength increased by approximately 2.32%, reaching a maximum value of 89.49 MPa.
- By applying various techniques to prepare the mixture, concrete was obtained that achieved 81.4% of its design strength at an early age of 7 days, reaching a strength of 71.18 MPa (composition 11).
- The highest flexural strength among all investigated mixtures was obtained for composition (7), which contained 2% basalt fiber and 1.0% Melflux 5581F superplasticizer, achieving a value of 11.14 MPa.

5. Declarations

5.1. Author Contributions

Conceptualization, A.K., M.B., and A.A.; methodology, N.M., A.G., and A.A.; software, A.K., S.E., N.E., and M.M.; validation, A.K., A.A., and M.B.; formal analysis, A.K. and M.B.; investigation, S.E.; N.E., and A.G.; resources, A.A.; data curation, M.B. and A.A.; writing—original draft preparation, A.K., M.B., S.E., and A.A.; writing—review and editing, N.M. and A.K.; visualization, A.K., N.M., and N.E.; supervision, A.K. and M.B.; project administration, A.K.; A.A., N.M., and M.B.; funding acquisition, M.B. and A.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding and Acknowledgments

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

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