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Enhancing the quality of road slabs with silicon fibers

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Abstract. The physico-mechanical properties of concrete reinforced with macro- and micro polypropylene fibers for road slabs were studied. The effect of low-modulus synthetic fibers on strength, density, water resistance, and frost resistance were determined. Macro fibers increase compressive and flexural strength, while microfibers improve structure, reduce porosity, and enhance frost resistance. Combined reinforcement with micro-silica increases flexural strength by up to 35%, frost resistance up to F375, and water impermeability up to W14. The use of multidimensional fibers and micro-silica is recommended to improve concrete properties.

Keywords: *fiber-reinforced concrete, synthetic fibers, strength, frost resistance*.

1. Introduction

The study was conducted in response to the requests of construction companies seeking to enhance the strength, density, and frost resistance of road slabs while simultaneously reducing their weight and thickness. This goal was achieved through the development of multi-component fiber-reinforced concrete (FRC) with volumetric reinforcement [8]. Among the various reinforcement options, polypropylene fibers have proven to be the most promising due to their corrosion resistance, cost-effectiveness, and ease of integration into concrete mixtures [4].

To ensure compliance with industry standards, the behavior of fiber-reinforced concrete incorporating polypropylene fibers was analyzed at different stages of deformation, following the guidelines of EN 197-1:2011 [2]. The study included a comprehensive evaluation of the material's mechanical properties, including flexural strength, tensile behavior, and fracture resistance, which are crucial for improving the performance of concrete under dynamic and cyclic loading conditions.

Additionally, a detailed graphical representation of the experimental results is provided (Figure 1), illustrating the influence of fiber reinforcement on the structural performance of the material. These results help quantify the benefits of fiber inclusion and establish guidelines for optimizing fiber dosage in practical applications.

Analysis revealed that a low fiber content does not significantly influence the strength of concrete, whereas an increase in fiber dosage initially reduces strength but later enhances the cement matrix structure, leading to a strength improvement of up to 17%. However, an excessive fiber content results in structural defects and segregation, which require further investigation [3].

To enhance the performance of concrete and reduce porosity, ultrafine silica dioxide, a byproduct of ferrosilicon production, is incorporated. This study explores methods for improving road slabs through volumetric fiber reinforcement and cement matrix modification with microsilica.

Additionally, the research addresses cost reduction strategies, including the decrease in cement and steel reinforcement consumption, simplification of production technologies, and implementation of automation in manufacturing processes [2].

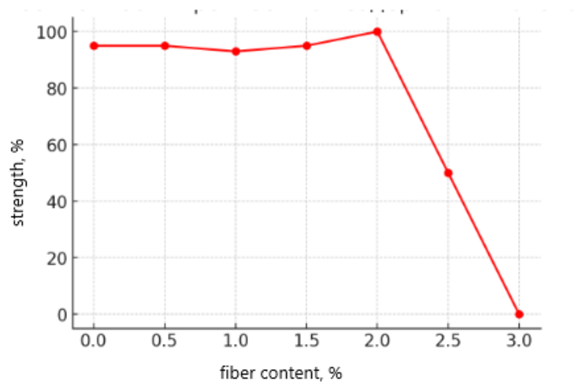

Figure 1. Strength variation of fiber-reinforced concrete depending on the volumetric content of low-modulus fibers [authors' data]

The objective of this study is to determine the optimal concrete composition for road slabs with enhanced performance characteristics.

Objectives:

• Development of a heavy concrete mix with dual-component reinforcement and its analysis according to EN 197-1:2011.

• Modification of the cement matrix with microsilica and evaluation of the resulting properties.

• Testing the frost resistance, density, and water impermeability of the final material.

2. Materials and methods

The selection of raw materials and concrete mix components was carried out based on data provided by manufacturers and in accordance with international standards. A C25/30 heavy concrete mix, commonly used for road slab production, was chosen as the control composition due to its well-documented mechanical properties and durability. To improve the performance characteristics of the concrete, an optimal combination of microsilica and polypropylene fibers was determined through theoretical calculations. These components were selected to enhance the compressive strength, density, and frost resistance of the material while maintaining workability and long-term durability under operational conditions [16].

The experimental program consisted of several key stages:

• Selection of raw materials and admixtures in compliance with regulatory standards to ensure consistency and reproducibility of the results.

• Development of C25/30 heavy concrete compositions incorporating microsilica as a pozzolanic additive to refine the cement matrix and improve its microstructure.

• Addition of polypropylene fibers to assess their influence on mechanical performance and crack resistance, with evaluations conducted at different dosage levels.

• Testing of density, frost resistance, and water absorption to determine the effect of mineral and fiber reinforcement on durability indicators.

• Comparative analysis of experimental results against the control concrete mix to identify improvements in physical and mechanical properties.

• Formulation of conclusions and practical recommendations for optimizing fiber-reinforced concrete mixtures for road slab applications.

The cement used in this study was CEM I 42.5 N, supplied by HeidelbergCement (Kazakhstan), with a compressive strength of at least 50.1 MPa after 28 days. This cement meets the requirements of EN 196-2:2013 and EN 933-1:2012, ensuring its suitability for high-performance concrete applications [9].

By integrating microsilica and polypropylene fibers into the concrete matrix, this research aims to establish an effective methodology for enhancing road slab durability while reducing material consumption and long-term maintenance costs.

Table 1. Mass composition of CEM I 42.5 N cement, % [authors' data]

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	Other admixtures
20.30	5.75	5.36	63.18	3.07	0.77	0.78	0.48	0.36

The testing of CEM I 42.5 N cement confirmed its compliance with EN 12620:2013 [9]. The fineness of grinding was 92.9%, normal consistency was 26.1%, and the setting time was recorded as follows: initial setting at 2 hours 01 minutes and final setting at 4 hours 18 minutes.

For fine aggregate, sand from LLP «Marka» (Kazakhstan) was used, with an average grain size of 2.55 mm and a dust content of 1.03% (meeting the standard limit of ≤1.5%). The sand consumption ranged between 800–1000 kg/m³. The coarse aggregate was a mixture of crushed stone fractions from 5 to 80 mm, where the 5–20 mm fraction provided the required concrete characteristics in compliance with EN 13263-1:2005+A1:2009.

Crushed stone fractions of 5–10 mm and 5–20 mm was sieved through 2.5 mm or 1.25 mm meshes, retaining 95–100% of the material, which conforms to BS EN 13263-1:2005+A1:2009. The permissible deviation of residue on the 0.5(d+D) sieve was within the range of 30–80%.

The modifying additive used was microsilica MK-95 (LLP «Tau-Ken Temir», Kazakhstan), consisting of spherical particles (~0.1 μm) with a specific surface area of 15–25 m²/g and a bulk density of 150–250 kg/m³. The mass fraction of SiO_2 was 95.9%, the moisture content was 1.07%, pH was 7.89, and the density was 0.44 g/cm³. These values meet the requirements of GOST 21924.0-84 and correspond to the manufacturer's specifications [10].

A polycarboxylate-based hyperplasticizer, PKE (AR 122, LLP «ARPG», Kazakhstan), was used to maintain workability within P1–P5 classifications at a dosage of 5–8 kg/m³.

The strength variations of the main compositions compared to the experimental concrete mixtures on the 1st and 28th days of curing were assessed based on the change in strength (ΔRt, %) using the formula proposed by Akhmetov et al. [6].

$$\Delta R_t = \left(\frac{R_t^{contr} - R_t^{base}}{R_t^{contr}} \right) \cdot 100\% \tag{1}$$

Where R_{base} and R_{contr} represent the compressive strength of concrete or mortar in the main and experimental compositions at time t, measured in MPa.

Reinforcing fibers are categorized into microfibers (with a diameter of tens of micrometers and a length of up to 25 mm) and macrofibers (with a diameter of several millimeters and a length of tens of millimeters). In this experiment, two types of synthetic fibers were used: FibroLux macrofibers and Fibrin microfibers, both manufactured by LLC Fibrolux (Saint Petersburg). Their characteristics are presented in Table 2.

Table 2. Technical characteristics of the fibers used [authors' materials]

Characteristic	Value	
Fiber Name	FibroLux	Fibrin
Fiber Type	Macro Fiber	Macro Fiber
Material	Modified Polypropylene	Modified Polypropylene
Density (kg/m³)	920	907
Length (mm)	50	15
Equivalent Diameter (mm)	0.75	0.02
Tensile Strength (MPa)	415	385
Chemical Resistance	-	-
Melting Temperature (°C)	170	170
Ignition Temperature (°C)	> 350	> 350
Modulus of Elasticity (MPa)	-	-
Electrical Conductivity	-	-

The tests were conducted to evaluate the compressive strength, water impermeability, and density of fiber-reinforced concrete. Macro- and microfibers FibroLux and Fibrin (LLC «Fibrolux», Saint Petersburg) were used, along with the polycarboxylate-based hyperplasticizer PKE (LLP «ARPG», Astana) [7].

The control concrete mix of C25/30 strength class was designed in accordance with EN 206:2013+A1:2016 and consisted of cement, sand, crushed stone (5–10 mm, 10–20 mm), PCE-based admixture AR 122, and water. The addition of microsilica enhanced the density and modified the rheological properties of the mixture.

Compressive strength and flexural tensile tests were performed on the 28th day, following EN 12350-2:2019. Strength values were calculated with correction factors applied. Macrofibers improved compressive strength but had little effect on frost resistance and water impermeability, whereas microfibers primarily contributed to these durability properties. The optimal fiber combination resulted in enhanced overall performance [12].

Water impermeability was assessed following EN 12350-2:2019, where pressure was increased by 0.2 MPa until filtration was observed. The water resistance class was determined according to Table 3.

The average concrete density was calculated based on the mass and volume of the samples. It was established that fiber reinforcement affects both the density and overall characteristics of the concrete.

Table 3. Water impermeability of concrete [Authors' data]

Water resistance of samples, MPa	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Concrete water resistance class (W)	W2	W4	W6	W8	W10	W12	W14	W16	W18	W20

3. Results and discussion

During laboratory tests, the physical and mechanical properties of the samples were obtained, as presented in Table 4.

Table 4 contains the concrete mix compositions with the addition of microsilica per 1 m³, along with compressive strength data measured on the 7th and 28th day of curing.

Table 4. Composition of C25/30 concrete with microsilica MK-95 [Authors' data]

№	W/C	Cement		Sand		Crushed Stone (5–10 mm)		Crushed Stone (10–20 mm)		AR-122		MC-95		Water		Compressive Strength on Day 2 (MPa)		Compressive Strength on Day 7 (MPa)	
		kg	%	kg	%	kg	%	kg	%	kg	%	kg	%	kg	%	MPa	%	MPa	%
1*	0.37	400	16.1	971	39.2	287	11.6	667	26.9	5.9	0.24	-	-	148	6.0	23.3	71.3	33.1	101,1
2	0.37	400	16.0	971	38.5	287	11.5	667	26.8	5.9	0.24	10	0.4	152	6.1	24.8	75.7	34.2	104.6
3	0.36	390	15.7	971	39.0	287	11.5	667	26.8	5.9	0.24	20	0.8	147	5.9	25.2	77.1	36.6	111.9
4	0.36	380	15.3	971	39.0	287	11.5	667	26.8	5.9	0.24	30	1.2	147	5.9	26.0	79.6	37.9	115.8
5	0.35	370	14.9	971	39.1	287	11.6	667	26.8	5.9	0.24	40	1.6	144	5.8	26.6	81.4	39.3	120.2
6	0.35	360	14.5	971	39.1	287	11.6	667	26.8	5.9	0.24	50	2.0	144	5.8	27.2	83.3	41.8	127.7

The average compressive strength of C25/30 concrete was 32.7 MPa (100%). Partial replacement of cement with microsilica MK-95 increased strength, particularly at early curing stages. The introduction of active SiO_2 contributed to the formation of a denser structure, which aligns with theoretical studies [5].

Replacing 50 kg of cement with MK-95 increased strength by 12% on the 7th day and by 25% on the 28th day while maintaining rheological properties and reducing cement consumption to 360 kg/m³.

The analysis of test results revealed that different types of fiber reinforcement enhanced only specific properties. Polypropylene microfibers improved compressive and flexural strength by 27%, but their primary effect was in increasing frost resistance, water impermeability, and wear resistance [6].

Combined reinforcement with fibers of different sizes proved effective in enhancing the overall performance of the concrete.

Table 5. Test results of polypropylene fiber-reinforced concrete [Authors' data]

№	Indicator	Values of indicators with the use of polypropylene fibers				
		Without fibers Concrete	Fibrin microelement (0.1%)	Fibrin microelement (0.2%)	FibroLux FibroLux microelement (0.8%)	FibroLux FibroLux microelement (1.1%)
1	Average density ρ, kg/m³	2346	2371	2368	2379	2400
2	Compressive strength Rсж, MPa	33.9	37.2	36.9	40.7	43.2
3	Flexural strength R, MPa	5.44	5.47	5.52	6.61	7.23
4	Frost resistance F, cycles	220	280	340	225	230
5	Water resistance class W	W8	W14	W14	W8	W10
6	Wear resistance G, g/cm²	0.77	0.58	0.56	0.72	0.74

Reinforcement of heavy concrete with low-modulus fibers presents a promising approach for enhancing its performance characteristics. The optimal combination of macro- and microfibers ensures high strength and durability, aligning with international standards [7].

Experimental results demonstrated that volumetric fiber reinforcement increases compressive strength by 25%, flexural strength by 30%, water resistance (W8 → W14), frost resistance by 61%, and wear resistance by 40%. These improvements contribute to the overall longevity of concrete structures, particularly in aggressive environmental conditions.

Thus, the application of low-modulus synthetic fibers is highly effective for road slabs, especially when employing multi-scale fiber reinforcement. This approach significantly improves mechanical and durability characteristics while optimizing the overall performance of self-compacting concrete [12].

4. Conclusions

Based on extensive laboratory and industrial testing, it can be concluded that the partial replacement of cement with silicon dioxide in concrete compositions is both economically and scientifically justified. Unlike traditional concrete mixes, modified concretes allow for a reduction in cement consumption of up to 20%, while simultaneously demonstrating improved density, frost resistance, and volumetric water absorption. The introduction of microsilica promotes the formation of additional crystallization centers, reduces porosity in the concrete structure, and partially substitutes cement with reactive pozzolan, which positively affects the material's strength properties.

Experimental studies have shown that volumetric fiber reinforcement of concrete with polypropylene fibers significantly enhances its performance characteristics. Macro fibers improve strength and deformation resistance, while microfibers contribute to modifying the cement matrix structure, increasing frost resistance, water impermeability, and abrasion resistance. The combined use of macro and microfibers in optimal proportions enables the production of high-strength and durable fiber-reinforced concrete, suitable for constructing road slabs with enhanced strength and resistance to adverse environmental conditions.

Test results confirmed that fiber-reinforced concrete exhibits an increase in compressive strength of up to 25%, flexural strength of up to 35%, frost resistance up to F375, and water impermeability up to W14. These findings validate the effectiveness of the proposed methodology and allow for the recommendation of these compositions for further industrial trials in the production of road slabs with reduced cross-sections and a mass 10–20% lower than standard slabs, while maintaining high resistance to crack formation.

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Кремний талшықтарымен жол плиталарының сапасын арттыру

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Аңдатпа. Жол плиталарына арналған бетонның макро- және микрополипропилен талшықтарымен физика-механикалық қасиеттері зерттелді. Төмен модульді синтетикалық талшықтардың беріктікке, тығыздыққа, суға және аязға төзімділікке әсері анықталды. Макроталшықтар бетонның қысуға және иілуге беріктігін арттырады, ал микроталшықтар құрылымын жақсартып, кеуектілікті азайтады және аязға төзімділікті күшейтеді. Біріктірілген арматуралау және микрокремнеземді қолдану бетонның иілуге беріктігін 35%-ға, аязға төзімділігін F375-ке, су өткізбейтіндігін W14-ке дейін арттырады. Бетонның қасиеттерін жақсарту үшін көпөлшемді талшықтар мен микрокремнеземді қолдану ұсынылады.

Негізгі сөздер: *фибробетон, синтетикалық талшықтар, беріктік, аязға төзімділік.*

Повышение качества дорожных плит с кремниевыми волокнами

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Аннотация. Исследованы физико-механические свойства бетона с макро- и микрополипропиленовыми волокнами для дорожных плит. Определено влияние низкомодульных синтетических волокон на прочность, плотность, водо- и морозостойкость. Макроволокна повышают прочность на сжатие и изгиб, а микроволокна улучшают структуру, уменьшают пористость и повышают морозостойкость. Комбинированное армирование и микрокремнезем увеличивают прочность на изгиб до 35%, морозостойкость до F375, водонепроницаемость до W14. Рекомендовано применение многомерных волокон и микрокремнезема для улучшения свойств бетона.

Ключевые слова: *фибробетон, синтетические волокна, прочность, морозостойкость.*

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