



MECHANICAL AND DURABILITY PERFORMANCE OF CONCRETE ROAD SLABS INCORPORATING MICROSILICA AND BASALT FIBER REINFORCEMENT

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ABSTRACT: This study investigates the combined effects of microsilica modification and basalt fiber reinforcement on the mechanical performance, microstructure, and durability of concrete developed for precast road slab production. Concrete mixtures were optimized using locally available raw materials from the Turkestan region of Kazakhstan, and the influence of different microsilica dosages and basalt fiber contents was experimentally evaluated. The manufacturing process was improved at the industrial facility of Atina LLC, with a low water–cement ratio ($w/c = 0.40\text{--}0.48$) adopted to achieve a dense and durable concrete structure. Specimens were cured under controlled conditions at $20 \pm 2^\circ\text{C}$ for 3, 7, 14, and 28 days. The results showed that 4% microsilica increased the 28-day compressive strength by 15%, while basalt fiber reinforcement improved strength by 18% compared with conventional concrete. These enhancements were attributed to pore refinement, additional calcium silicate hydrate (C–S–H) formation, and crack-bridging effects of basalt fibers. The developed concrete mixture demonstrated improved strength, durability, and potential for application in precast road slabs exposed to aggressive environmental conditions.

Keywords: *Microsilica, Basalt Fiber, Precast Road Slabs, Freeze-Thaw Resistance, Pavement Concrete Durability, Compressive Strength*

1. INTRODUCTION

The long-term road slab durability of concrete pavements is continuously threatened by heavy traffic loads and severe environmental weathering [1]. Traditional rigid pavements are highly susceptible to microcracking, which accelerates structural failure. To mitigate this, recent research focuses on microstructural densification and fiber reinforcement.

A well-established method for refining the concrete matrix is the incorporation of microsilica. Due to its pozzolanic activity and extreme fineness, microsilica generates additional calcium silicate hydrate (C–S–H) gel and physically fills interstitial voids [2]. This microstructural compaction substantially reduces permeability, creating a barrier against moisture ingress.

However, the ultra-dense matrix induced by microsilica increases brittleness. To counteract this, basalt fiber reinforced concrete (BFRC) has emerged as an eco-friendly solution. Distributed basalt fibers act as stress-transfer components that bridge advancing microcracks, thereby enhancing post-cracking ductility and flexural toughness [3].

While microsilica optimizes the pore network to minimize the volume of freezable water, basalt fibers absorb and redistribute the internal hydraulic pressures generated during ice crystallization.

Despite separate advancements, the coupled effects of microsilica-modified matrices and basalt fiber reinforcement under harsh cyclic freeze-thaw conditions remain incomplete. This paper aims to bridge this knowledge gap by systematically evaluating the mechanical performance and durability mechanisms of advanced BFRC incorporating microsilica under severe freeze–thaw environments.

The most intense types of aggressive impacts during road slab operation include: repeated alternating freezing and thawing; alternating water saturation and drying; the action of groundwater containing mineral salts, and others.

Cement consumption, the volumes of cement paste formed to fill the intergranular voids in fine aggregate and cement-sand mortar to fill the voids in coarse aggregate are insufficient. Therefore, the structure of the resulting concrete is characterized by low density and significant total and open porosity with a small volume of closed pores. The

lower the cement consumption, the greater the total and open porosity and the lower the frost resistance of the cement [4-10].

When cement consumption exceeds the minimum required, the relative volume of cement paste in concrete increases, leading to shrinkage stresses in the cement paste. Frost damage, caused by alternating freezing cycles, also causes alternating wetting and drying cycles in concrete, leading to repeated capillary shrinkage and the significant shrinkage stresses it causes. These stresses, combined with stresses caused by frost exposure and external loads, lead to a decrease in concrete crack resistance and, consequently, to a reduction in its frost resistance [11-12].

Despite improvements in compressive strength, conventional concrete remains inherently brittle and exhibits low tensile capacity. To address this limitation, fiber-reinforced concrete (FRC) has been widely adopted. Among various fiber types, basalt fiber has emerged as a promising reinforcement material due to its high tensile strength, chemical resistance, and ecology sustainability. Basalt fibers enhance crack resistance, improve post-cracking behavior, and increase the overall toughness of concrete.

Recent studies have shown that damage mechanism concrete the theoretical model of F-T damage for testing microstructure evolution [13]. Research of concrete with silica fume have also been widely investigated due to their high mechanical strength and good performance in relevant characteristics, related to low permeability and high durability [14]. Study to analysis reasonable fiber content can optimize the internal microstructure of BFRPC [15]. Research revealed that Basalt fibra improved the matrix densification and interface bonding performance through crack bridging and physical anchoring [16]. Study demonstrates that up to 30% RIP can be utilized as a fine aggregate in mortar due to its better mechanical and durability performances [17]. Study established that modification of cement composites with NF and NS additives had a beneficial effect on their properties [18]. Research was some synergistic effect was observed when polyethylene-polypropylene fiber was used for concrete with TRHA and SF [19]. This study to analyze the effect of concrete mix design and maximum aggregate size variation on the compressive strength of normal concrete [20]. Research the rapid expansion of infrastructure development has led to a corresponding increase in the use of concrete as the primary construction material [21, 25]. Concrete is composed of several basic materials, including cement, coarse and fine aggregates, and water, and

also contain various additives [22, 27]. Research the optimal proportion is shown to be important as a higher dose can adversely affect the strength of concrete, due to a deficiency of flowability [23-29]. This research3 improvement of Su (% increase) due to compaction of concrete in bored pile, migration of moisture and reaction with surrounding clay leads to take of design and construction of bored pile in clay5 soil for the sake of efficiency and stability [24]. Study of concrete mix design is to establish the correct proportions of each component material so that the resulting concrete satisfies the required standards of workability, strength, durability, and surface finish in accordance with specified requirements [25]. The research showed that BA reduced increased the degree of hydration by raising the heat peak of hydration increasing the amount of calcium hydroxide at 28 days, and significantly refining the pore structure during the curing period by Markpiban, P. [29]. These findings align with those of another study [30-32]

Therefore, this study aims to investigate the combined effects of industrial waste incorporation, microsilica modification, and basalt fiber reinforcement on the performance and durability of concrete, with a particular focus on road slab applications. The integration of these approaches represents a promising direction for the development of sustainable and high-performance pavement materials.

This study examines the shear performance and interaction mechanisms of high-strength concrete (HSC) transfer beams reinforced with hooked-end steel fibers by Hoang A. [33]. Foamed concrete is a lightweight material recognized for its outstanding thermal insulation properties [34].

In this paper, the effects of microsilica and basalt fiber on the compressive strength development of road concrete were experimentally investigated. Concrete mixtures were prepared using Kazakh locally available materials and specimens were tested after 3, 7, 14, and 28 days of curing. The experimental results were analyzed to determine the optimal modification levels and evaluate their influence on concrete performance. The findings provide a basis for the development of durable and sustainable concrete for road slab applications.

2. RESEARCH SIGNIFICANCE

This study investigates the combined effect of microsilica and basalt fiber reinforcement on the mechanical performance and durability of precast concrete road slabs produced using locally available

materials in Kazakhstan. The novelty of the research the combined use of microsilica and basalt fiber reinforcement for precast road slab concrete produced using regional Kazakhstan raw materials under practical industrial production conditions. Unlike conventional studies that investigate these additives separately, this work evaluates their synergistic influence under practical production conditions. The findings provide an economically viable and environmentally sustainable solution for improving road slab durability while promoting industrial waste utilization in regional construction practice.

3. MATERIALS AND METHODS

3.1 The hydraulic concrete

The selection of raw materials for concrete road slabs is based on operating conditions. Road slabs are designed for road construction and can be used in the layout of buildings and structures.

Road slabs are manufactured in accordance with the requirements of GOST 21509-76 and duly approved process documentation, using working drawings of standard designs series 3.820.1-34c/85.

Road slabs are manufactured based on the requirements for hydraulic concrete.

Hydraulic concrete is used for the construction of structures or parts thereof that are constantly or periodically washed by water, and has a combination of properties that ensure the long-term service life (durability) of structures in these conditions. The requirements for hydraulic concrete depend on the purpose and design of hydraulic structures (massive structures, thin-walled structures, prefabricated hydraulic structures), as well as on climatic conditions (moderate, severe, especially severe) and the operating conditions of the structures or their parts.

Concrete for hydraulic structures must ensure the long-term service life of structures subject to continuous or periodic water wash. Therefore, depending on the service conditions, hydraulic concrete must meet not only strength requirements but also water resistance and often frost resistance. These additional requirements are achieved by properly selecting the concrete composition.

Water resistance and frost resistance requirements vary depending on the nature of the structure and its service conditions. Hydraulic concrete is typically divided into the following types: underwater, which is permanently submerged; located in a variable water level zone; and above-water, which is subject to occasional water wash. Furthermore, a distinction is made

between massive and non-massive concrete, and concrete for confined and non-confined structures.

Concrete that meets all requirements is possible with the correct design of the concrete composition and proper preparation. Placement and compaction of concrete mix, as well as proper care during the initial curing period (3-7 days).

The main technical requirements for concrete, depending on operating conditions, are as follows:

- mechanical strength and ultimate tensile strength (ultimate relative deformation);
- frost resistance, permissible degree of water absorption and linear changes during wetting and drying;
- water resistance;
- resistance to aggressive water exposure;
- absence of harmful interaction between cement alkalis and aggregates (sand, crushed stone);
- permissible degree of heat generation during curing.

3.2 Cement

The type of cement consider the following:

- aggressiveness of the water environment. If the water environment is characterized by sulfate aggressiveness, sulfate-resistant Portland cement, pozzolanic Portland cement, or sulfate-resistant slag Portland cement should be used;
- the location of the concrete in the structure. In areas with variable water levels, pozzolanic and slag Portland cements should not be used due to their low frost resistance;
- the massiveness of the structure. For concrete in massive structures subject to thermal crack resistance calculations, it is necessary to use cements with reduced heat generation—pozzolanic and slag Portland cements.
- the strength class of the concrete. Cement activity should not exceed the concrete's strength class by more than three times if the concrete is designed to be 28 days old.

Cement is a general term for a large group of mineral binders that, with the exception of some special types, possess hydraulic properties. It is produced by finely grinding Portland cement clinker with natural gypsum (3-5%) to regulate setting time, with or without other additives. Additives are added during clinker grinding to impart desired properties to the cement, as well as to reduce clinker consumption and reduce the cost of cement while maintaining or slightly reducing its grade. Clinker is produced by firing a raw mix containing limestone, clay, and certain additives in the required

proportions to form a sintered mixture (at a temperature of 1450-1500°C). Operating conditions are the determining factor in cement selection.

Portland cement appears as a gray-green powder. Its density is 3.1 g/cm³, its bulk density in a loose state is 1100-1300 kg/m³, and in a compacted state, 1400-1700 kg/m³. The water requirement for producing a cement paste of normal consistency is NG = 22-26%. Setting time: setting begins no earlier than 45 minutes and ends no later than 10 hours after the start of mixing. The fineness of Portland cement must correspond to at least 85% passing through a No. 008 mesh sieve. The fineness of Portland cement grinding can also be characterized by the specific surface area of its powder, which is typically 2200-3500 cm²/g. The finer the Portland cement is ground, the faster its strength increases and the higher its activity. Depending on the strength achieved after 28 days of curing, Portland cement is produced in four grades: 400, 500, 550, and 600.

It is necessary to ensure that the strength grade of the cement exceeds the concrete grade by 10-40%.

The strength of higher grades of cement increases faster than that of lower grades. Therefore, using 50 MPa cement instead of 40 MPa cement allows for rapid formwork removal and reduces construction time.

The composition of cement for frost-resistant concrete for hydraulic engineering projects in terms of clinker mineral content should be as follows:

- C₃S - from 45 to 60% or more;
- C₂S - from 15 to 30%;
- C₄AF - from 9 to 19%;
- C₃A - from 3 to 5%;
- C₃A + C₄AF should be less than 20%;
- SO₃ - no more than 3.0%;
- CaO - no more than 1.0%;
- alkalis - no more than 0.6%.

A higher content of C₂S in the cement is also preferable.

Concretes made with this type of cement have a continuous (through) system of capillary pores, which reduces the concrete's water resistance and frost resistance Table 1.

The frost and corrosion resistance of Portland cement-based concrete depend on its mineralogical composition and concrete density. Cements with a high content of tricalcium aluminate have the lowest corrosion and frost resistance.

The optimal cement grinding fineness is recommended to be within the range of 3000-3500 cm²/g. Cement grinding finenesses above 3500 cm²/g can negatively impact the frost resistance of concrete, as cause aggregation

(sticking together) of the finest cement grains.

Table 1. Laboratory data for cements from different manufacturers

Cement	Fineness of grinding based on residue on sieve No. 008, %	Mineral composition	Normal density of cement paste, %	Bulk density, kg/m ³	Setting time		Ultimate strength, MPa after 28 days, not less than
					start	end	
Zhambyltsement PC M500	7.0	C ₃ S–50.1 C ₂ S–31.3; C ₃ A–7.4; C ₃ AF–10.5	2 5	9.6	1:2 0	2:00	53.4
Standard cement PC M500	9.9	C ₃ S–43,62; C ₂ S–32,42; C ₃ A–5,04; C ₃ AF–11,3;	3 0 2 5	9,8 3	3:3 5	4:04	51.2
ShymkentsemenP C M500	9.2	C ₃ S–37,66; C ₂ S–33,27; C ₃ A–5,09; C ₃ AF–13,2;	2 8	10. 9	3:1 7	3:48	36.0
Saztobecement PC M400	7,6	C ₃ S–47,97; C ₂ S–26,99; C ₃ A–4,13; C ₃ AF–12,56	2 6	13. 8	2:5 0	4:00	43.1

Finely ground cements lose their activity more quickly during storage than coarsely ground cements. Stale cements significantly reduce the frost resistance and durability of the cement. Only fresh cements are permitted for highly frost-resistant concrete.

In the first case, partial hydration of the cement occurs through the carbonation of calcium hydroxide, forming aggregates of cement grains. This changes the chemical activity of the cement and its grain size distribution. In aged cement, the presence of a shell of newly formed hydrated minerals on the cement grains is one of the main reasons for the reduced durability of concrete.

In the second case, in the absence of moisture, hydration products that should fill the pores and capillaries are not formed, meaning the concrete remains porous.

Concrete made with aged cement has a water resistance rating 2-6 times lower than concrete made with fresh cement.

Concrete strength can decrease by 20-30%, and its frost resistance can be reduced by 2-10 times, depending on the degree of aging and the type of cement. This is explained by the fact that aggregated particles of aged cement significantly increase the size of the largest pores in the cement paste.

3.3 Aggregates

Natural or artificial aggregates—loose stone materials—are used to prepare concrete. Main component of concrete, accounting for 80-85% of its volume. Form a rigid skeleton of concrete, thereby reducing shrinkage and preventing shrinkage cracks. The quality of the aggregates significantly influences the technical properties of concrete. Aggregates are classified by grain size into fine aggregates (sand), with grain sizes from 0.14 to 5 mm, and coarse aggregates (crushed stone, gravel), with grain sizes from 5 to 70 mm or more.

By bulk density in the dry state, aggregates are classified as heavy aggregates (crushed stone and gravel), with a bulk density of over 1000 kg/m³, and over 1200 kg/m³ for sand, and light aggregates (porous aggregates), with a bulk density less than the values specified above. By origin – natural, formed by the destruction of rocks (natural sand, gravel) or obtained by crushing and subsequent screening of rocks (crushed sand, crushed stone), and artificial, obtained from industrial waste or specially manufactured; by processing type natural, enriched and fractionated; crushed; crushed enriched and crushed fractionated; by purpose dense for heavy concrete, including hydraulic and road concrete; porous inorganic for lightweight concrete; for special-purpose concrete – acid- and alkali-resistant, extra-heavy, X-ray-protective, and decorative.

Crushed stone and gravel meeting the requirements of GOST 9757-90 are used as coarse

aggregate for the preparation of heavy concrete. Crushed stone is a loose material obtained by crushing igneous, sedimentary, and metamorphic rocks, or by crushing dense pieces of waste from various industries. The resulting mixture of crushed stone grains of various sizes is screened into individual fractions. Screened particles smaller than 3 mm are used as sand. Crushed stone grains are angular in shape, with a rough surface, which allows the crushed stone to adhere well to cement-sand mortar.

Gravel is a loose material formed by the natural breakdown of hard rock and consisting of rounded grains. Gravel can be mountain, river, or sea gravel. Mountain gravel has a rough surface and typically contains sand, clay, and organic matter. River and sea gravel are cleaner than rock gravel, but their grains have a smooth surface, which impairs adhesion to cement-sand mortar.

The quality of coarse aggregate is determined by the mineral composition and properties of the source rock (its strength and frost resistance), the aggregate's grain size, grain shape, and content of harmful impurities. The compressive strength of the source rock in a water-saturated state must be at least 1.5-2 times greater than the concrete grade.

Coarse aggregate (crushed stone) from igneous rocks, depending on the largest size, must consist of 2 or 3 fractions and meet the following requirements according to GOST 8267-93:

- compressive strength (crushability), in a water-saturated state, not less than 1000 kgf/cm²;
- content of grains of weak rocks not more than 5%;
- needle-shaped and flaky grain content no more than 5%;
- crushed grain content no less than 80%;
- water absorption no more than 1.0%;
- average grain density no less than 2.6 g/cm³;
- dust, silt, and clay particle content no more than 0.5%;
- sulfuric acid content calculated as SO₃ no more than 0.5%;
- clay in the form of lumps is not permitted;

Crushed stone must be cubic. Impact crushers produce cubic crushed stone.

Crushed stone used must be fractionated. The size of coarse crushed stone for irrigation channels should not exceed 15 mm.

The effect of coarse aggregate on concrete frost resistance is limited to the contact zone between the cement stone and the aggregate in Table 2. Sand is used as a fine aggregate for the preparation of heavy concrete and mortar. It is a loose mixture of grains 0.4-5 mm in size, formed by the natural breakdown of hard rock.

Crushed sand grains have an acute-angled shape and a rough surface. It should be noted that crushed sands are expensive, and therefore are used to beneficiate fine natural sand used in the production of high-strength concrete.

Table 2. Laboratory readings of crushed stone from different quarries

Crushed stone	Content of dust, silt and clay particles	Content of lamellar and needle-shaped grains	Brand by crushability
"Nauryz-25" fraction 5-15 of the Sairam deposit	1	1	1200
Chuya deposit	1.5	4	1200
Temirlanskoye deposit	1.2	2	1000

However, mountain sands are typically more contaminated with harmful impurities than river and sea sands. Artificial heavy sands are produced by crushing hard and dense rock.

3.4 Methodology for Determining Concrete Composition

The concrete composition should be selected in accordance with the requirements of GOST 27006-86 to produce concrete for structures with the strength and other quality indicators established by state standards, technical specifications, or design documentation for these structures, while minimizing the consumption of cement or other binder.

The nominal concrete composition is selected in the following stages:

- Selection and characterization of the starting materials for the concrete;
- Calculation of the initial composition;
- Calculation of additional concrete compositions with composition parameters that differ from those adopted in the initial composition, either up or down;
- Preparation of trial mixes of the initial and additional compositions, sampling, testing of the concrete mix, preparation of samples, and testing of them for all standardized quality indicators;
- processing the obtained results to establish relationships reflecting the influence of composition parameters on the standardized quality indicators of concrete mix and concrete, and intended for assigning a nominal composition, as well as assigning and adjusting working concrete

compositions;

- assigning a nominal concrete composition that ensures the production of concrete mix and concrete of the required quality with minimal binder consumption.

The nominal composition is selected:

- for each type and grade of binder from each manufacturer;
- for coarse aggregate from each quarry with the same maximum size;
- for coarse porous aggregate of each grade, based on the bulk density and strength of each manufacturer;
- for sand from each quarry;
- for chemical additives of each type.

The selection of materials used for concrete production should be based on their specifications and in accordance with the requirements of standards and technical specifications.

The materials used for composition selection must comply with the requirements of the standards or technical specifications for these materials. Before calculating the concrete composition and preparing test batches, materials should be tested according to relevant standards to determine the quality indicators required for the calculations.

Material samples should be taken in the volume required to select the concrete composition. The collected aggregate samples should be dried to a constant weight and sieved, removing fine aggregate larger than 5 mm and coarse aggregate smaller than 5 mm, with the coarse aggregates separated into individual fractions.

The initial concrete composition is calculated based on the actual characteristics of the source materials in accordance with the methods, manuals, and recommendations of duly approved research institutes.

Concrete composition selection for the purpose of substantiating production standards for material consumption is performed for production conditions and using materials whose quality indicators correspond to the average values of the materials used and production conditions for a period of at least six months preceding the composition selection. A low water-cement (w/c) ratio in the range of 0.35–0.40 was adopted to ensure a dense microstructure and improved durability. The reduction in w/c ratio is critical for minimizing capillary porosity and enhancing resistance to aggressive environmental conditions, particularly in road pavement applications. All specimens were subjected to controlled curing conditions to ensure proper hydration. After demolding, the samples were cured in water at a

temperature of $20 \pm 2^\circ\text{C}$ for periods of 3, 7, 14 and 28 days. Adequate curing was essential to achieve the full pozzolanic activity of microsilica and to ensure optimal bonding between basalt fibers. As a result, modified concrete mixtures exhibited lower mass loss and higher residual strength compared to control specimens.

3.5 Model Preparation and Testing Methodology

Concrete mix samples for the preparation of control specimens are selected in accordance with the requirements of GOST 18105.2-80. The selected concrete mix sample should be 1.5-2 times larger in volume than that required for the specimens. Detachable metal molds are used to prepare control specimens. These molds must be sufficiently rigid to resist deformation during specimen molding.

The mold element connections must be tight, preventing loss of cement laitance during specimen molding. The dimensions of the assembled molds must be strictly maintained, preventing deviations in the dimensions of the molded specimens along the length of the ribs. Before placing the concrete mix, the molds must be cleaned, and the interior surfaces must be coated with a thin layer of lubricant that will not stain the surface of the concrete specimens.

Depending on the workability of the concrete mix, various methods of placing and compacting the concrete mix are used. Specimen details include:

- sample size $10 \times 10 \times 10$;
- curing conditions requirements according to GOST 8267-93;
- number of specimens 1, 2, 3, 4, 5;
- testing age (3, 7, 14, 28 days).

The prepared specimens are covered with a damp cloth and stored in the molds in a room with an air temperature of $20 \pm 2^\circ\text{C}$ for 24 hours. Afterward, removed from the molds, marked with non-perishable paint on the top edge, and placed in a normal curing chamber, where are stored until testing at a temperature of $20 \pm 2^\circ\text{C}$ with a relative humidity of at least 90%.

The specimens are tested on hydraulic presses and testing machines. The scale of the press force meter for the testing machine is selected such that the expected breaking load is in the range of 20-80% of the nominal load permitted by the selected scale. Microsilica from the Ferrosilav plant in Kazakhstan was used for the experiment. In Table 3 microsilica was introduced into concrete from 2%, 4%, 6%, 8% and 10% of 420 kg cement, respectively 8.4 kg, 16 kg, 24 kg, 32 kg, 40 kg. According to GOST 8736-93.

Table 3. Structure Mix with Microsilica

Mix ID	Cement, kg	Sand kg	Aggregate kg	Water kg	Microsilica kg	W/C
1	420	570	1250	205	-	0.48
2	420	570	1250	170	8.4	0.40
3	420	570	1250	170	16	0.40
4	420	570	1250	185	24	0.44
5	420	570	1250	190	32	0.45
6	420	570	1250	195	40	0.46

Basalt Fiber from the Russian Basalt plant in Chelyabinsk (Russia) was used for the experiment in Tables 4-5.

Table 4. Structure Mix with Basalt Fiber

Mix ID	Cement, kg	Sand kg	Aggregate kg	Water kg	Basalt Fiber, kg	Basalt Fiber, % by cement mass	W/C
1	420	570	1250	200	-	0	0.48
2	420	570	1250	170	18	0.0043	0.40
3	420	570	1250	170	24	0.0057	0.40
4	420	570	1250	185	30	0.0071	0.44
5	420	570	1250	190	36	0.0086	0.45

The water-to-cement ratio varied from 0.40 to 0.48 depending on the dosage of silica fume and basalt fibers. Increasing the silica fume content significantly increased the specific surface area and water demand of the mixtures, while the incorporation of basalt fibers reduced workability.

Table 5. Basalt Fiber typical value

Property	Typical value
Length	12 mm
Diameter	13–17 μm
Aspect ratio	700–900
Tensile strength	3000–4800 MPa
Elastic modulus	85–95 GPa
Density	2.65–2.75 g/cm^3

Therefore, slight adjustments to the water-to-cement ratio were made to maintain a consistent workability (slump) across all mixtures without compromising the production process. Despite these adjustments, all mixtures remained within the low W/C range required for high-performance pavement concrete.

A microstructural analysis revealed that the combined use of microsilica and basalt fibers has a complex, positive effect on the structure of the cement composite, directly impacting its strength and durability. The introduction of microsilica of the

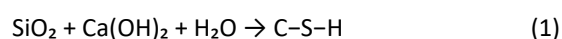
concrete mixture resulted in significant compaction of the cement matrix. This effect is driven by two main mechanisms: the pozzolanic reaction and the filler effect.

4. EXPERIMENTAL RESULTS

The highly dispersed microsilica particles allowed them to effectively fill the intergranular space between cement particles, reducing the overall porosity of the structure and creating a more uniform microstructure.

This reduced the volume of capillary pores, reduced the likelihood of defective zones, and increased the density of the cement paste. An important result of the interaction of microsilica with cement hydration products was a decrease in the content of free calcium hydroxide (Ca(OH)_2).

This is due to a secondary pozzolanic reaction, during which active silicon dioxide (SiO_2) contained in microsilica reacts with calcium hydroxide (Eq.1):



Experimental results were conducted at the Department of Technology of Building Materials, Products, and Structures at M.O. Auezov South Kazakhstan University, which serves as both a training and certification laboratory for product quality assessment at construction enterprises.

The results of these studies are presented below (Figs. 1-2), and the data are in Table 6.

Table 6. Sand from different quarries

Sieve size, mm	5	2.5	1.25	0.63	0.315	0.15	Remains on the pallet
Total residue on sieves, %	No more than 10	0-20	5-45	20-70	35-90	90-100	No more than 10

Prior to the use of chemical additives, studies were conducted to optimize the previous factory-made concrete composition in terms of component consumption, including the ratio of fine to coarse aggregates.

Assessing the Frost Resistance of Concrete. Concrete is considered to have passed the test if the following conditions are met:

- mass loss does not exceed 5%;
- strength reduction does not exceed 25%.

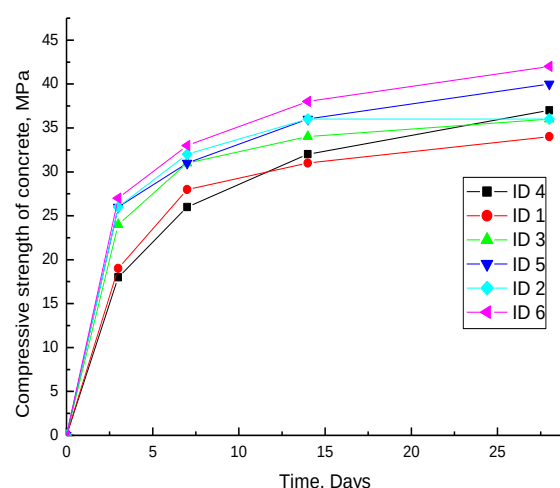


Fig. 1. Effect of microsilica dosage on compressive strength development

Mix 3 containing 4% microsilica (16 kg/m^3) achieved the highest 28-day compressive strength, representing a 15% increase compared with the control mixture. Similarly, Mix 3 containing 24 g of basalt fiber exhibited the highest 28-day compressive strength, corresponding to a 18% increase over the control concrete in Tables 7-8.

Table 7. Compressive strength of concrete containing microsilica

Mix	Modifier	Dosage	Increase vs. control
M1	Control	0%	-
M2	Microsilica	2%	+5%
M3	Microsilica	4%	+15%
M4	Microsilica	6%	+20%
M5	Microsilica	8%	+25%
M6	Microsilica	10%	+30%

Table 8. Compressive strength of concrete containing basalt fiber

Mix	Basalt fiber	Dosage	Increase vs. control
M1	Control	0 g	-
M2	Basalt fiber	18 g	+9%
M3	Basalt fiber	24 g	+18%
M4	Basalt fiber	30 g	+27%
M5	Basalt fiber	36 g	+36%

Modification of the concrete microstructure enhance its mechanical performance, including compressive and tensile strength, improve resistance to crack initiation and propagation, reduce water permeability, and increase durability and resistance to aggressive environmental conditions.

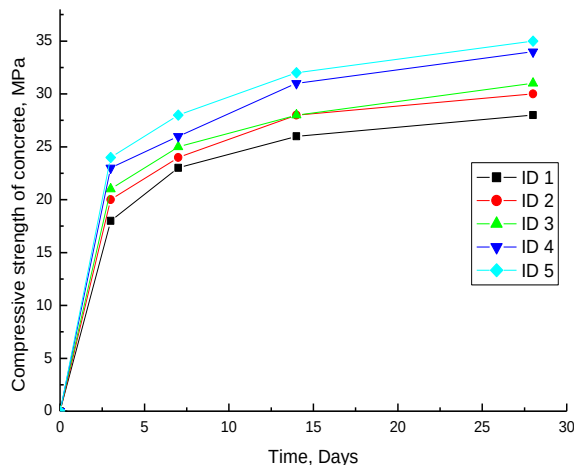


Fig. 2. Effect of basalt fiber dosage on compressive strength development

Tables 9-10 present the compressive strength of concrete containing basalt fibre.

Table 9. Estimated compressive strength of concrete containing basalt fiber

Mix ID	Basalt fiber (g)	3 days (MPa)	7 days (MPa)	14 days (MPa)	28 days (MPa)	Increase vs. control (%)
M1	0	19.0	23.5	27.0	29.8	-
M2	18	20.5	24.8	28.5	31.0	4.0
M3	24	22.0	26.0	30.0	32.0	7.4
M4	30	23.0	27.0	31.0	33.0	10.7
M5	36	24.0	28.5	32.0	35.0	17.4

Table 10. Compressive strength results of concrete with basalt fiber

Mix ID	Age (days)	Average strength (MPa)
Control	28	42.5

5. DISCUSSION

The results of this study confirm that the combined use of microsilica, basalt fibers, and industrial waste materials can significantly enhance the performance and sustainability of concrete, particularly for road pavement applications exposed to aggressive environmental conditions in Table 6. The observed improvement in compressive strength and durability can be primarily attributed to the synergistic effects of microstructural densification and crack-bridging mechanisms. The combination of improved mechanical properties and reduced environmental impact aligns with current trends in sustainable construction.

This reaction results in the formation of additional low-basicity calcium silicate hydrate gel (C-S-H), which is the main binding component of

cement paste. Increasing the amount of C-S-H gel increases structural cohesion, improves adhesion between hydration products, and reduces the number of weak spots in the cement matrix. In addition to its chemical effect, microsilica has a physical effect on the concrete structure. Its finely dispersed particles promote a more uniform distribution of hydration products, prevent the development of large pores, and reduce the size of structural defects. This leads to the formation of a more compact and stable microstructure, capable of withstanding mechanical loads more effectively. The addition of basalt fibers enhanced the positive effect of the modification by improving the interphase transition zone (ITZ) between the cement matrix and the reinforcing component. In conventional concrete, this region is the weakest link in the structure due to increased porosity and the concentration of microcracks. The presence of basalt fibers reduced the development of these defects by providing mechanical reinforcement and limiting crack propagation. Basalt fibers act as a microstructural reinforcing element absorb some of the resulting tensile stress, prevent crack opening, and ensure load redistribution within the composite. Microsilica improved the chemical and physical structure of the cement matrix, increasing its density and strength, while basalt fibers provided additional crack resistance and enhanced the material's deformation capacity. As a result, a more stable multi-component concrete structure with improved performance properties was formed. The results suggest that the combined use of microsilica and basalt fiber concrete modification is an effective way to improve its quality. Improved microstructure contributes to increased compressive and tensile strength, improved crack resistance, reduced water permeability, and enhanced resistance to aggressive environmental influences. Therefore, the developed composition has increased potential for use in structures requiring high strength, durability, and operational reliability.

6. CONCLUSIONS

Based on the analysis of previous scientific and technical studies, as well as the experimental investigation of concrete modified with microsilica and basalt fiber for the production of durable road slabs, the following conclusions can be drawn:

The incorporation of microsilica significantly improved the mechanical performance and microstructural characteristics of concrete. The highly reactive and finely dispersed microsilica particles contributed to pore refinement, reduced

capillary porosity, and enhanced the homogeneity of the cement matrix through both filler effects and secondary pozzolanic reactions. The optimum microsilica content investigated (4%, corresponding to 16 kg/m³) resulted in a 15% increase in 28-day compressive strength compared with the control concrete, confirming its effectiveness in improving matrix densification and strength development.

The addition of basalt fibers provided significant reinforcement effects by improving crack resistance and stress redistribution within the concrete matrix. The fibers enhanced the interfacial transition zone (ITZ), restricted microcrack propagation, and improved the tensile load-transfer capacity of the composite material. The optimum basalt fiber dosage evaluated (24 g) increased the 28-day compressive strength by approximately 18% compared with the reference concrete, demonstrating the effectiveness of fiber reinforcement in improving structural performance.

The combined modification approach using microsilica and basalt fibers produced a denser, stronger, and more durable concrete composite suitable for road slab applications. Microsilica improved the chemical and physical structure of the cement paste by increasing calcium silicate hydrate (C–S–H) formation and reducing weak porous zones, while basalt fibers enhanced toughness and resistance against cracking. The developed mixture showed promising potential for precast concrete road slabs exposed to aggressive environmental conditions due to its improved strength, durability, and operational reliability.

The proposed concrete composition provides a sustainable and technically efficient solution for high-performance road infrastructure. The improved mechanical properties and enhanced resistance to environmental deterioration indicate that the developed mix can reduce maintenance requirements and extend service life compared with conventional concrete road slabs. Further field-scale investigations are recommended to validate the long-term durability performance under actual climatic and traffic loading conditions.

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