

Research Article

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Study of concrete properties based on crushed stone sand mixture and fiber of fly ash of thermal power plants

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Abstract: The study aims to optimize the composition of the main composite, the components of which, in their joint presence, make it possible to obtain the most significant positive synergistic effect. The authors of this article used the fibers of fly ash from thermal power plants as a finely dispersed component added to the crushed stone sand mixture. The result of the study was a high-strength corrosion-resistant material consisting of a crushed stone sand mixture (CSSM) with the addition of the fibers of fly ash. The authors applied the thermogravimetric and standard methods to study and determine the performance and strength characteristics of the obtained material. The combined effect of a complex organic-mineral modifying additive and the cement with the fibers of fly ash provided a compacted and reinforced structure of cement stone. An optimal binder composition was developed, consisting of cement and fiber of fly ash. The authors of this article examined the physical-mechanical and structural-mechanical properties of a CSSM of fine-grained concrete reinforced with a complex additive of cement, fibers of fly ash, and a superplasticizer. The study also provided technological solutions for manufacturing a functional mixture of fine-grained concrete based on the developed complex organic-mineral additive.

Keywords: waste material, fly ash, finely dispersed material

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1 Introduction

Given the Law of Ukraine No. 2623-III “On directions of science and technology development” and the global trend of energy conservation, the current priority directions in the development of modern building materials science are the production of building materials with enhanced structural requirements and energy savings in the production of these materials. Moreover, Ukraine is implementing an urban transport infrastructure development program, which includes constructing and repairing public highways and urban roads [1]. This requires a significant amount of high-quality road-building materials, such as crushed stone, gravel, and mixtures with their addition – fine-grained concrete mixtures.

The principal areas of application of crushed stone sand mixtures (CSSMs) are the construction of concrete and asphalt concrete road pavements, arrangement of ballast and principal layers of railway embankments, arrangement of sites for various purposes, and tracks for the movement of construction cranes. Crushed stone mixtures are also promising in compaction and leveling of road beds before laying top road pavements, arrangement of foundations and coverings of airfields and runways, and production of concrete and asphalt concrete mixtures. The following valuable characteristics of CSSMs make them widespread in construction: low cost since a CSSM is a by-product of crushed stone extraction, easy transportation since they can be transported in any freight transport, and infinite storage period and unpretentiousness to storage conditions.

Treatment of CSSMs with liquid stabilizers such as soluble emulsions based on sulfonated oil, organic materials containing protein or sulfuric, and buffering acids can prevent them from high moisture content and increase the degree of compaction [2]. Stabilizers reduce swelling, shrinkage, dust formation, and the thickness of structural layers. They increase the density of the material, load-bearing capacity, and water resistance.

The use of waste materials can solve such problems as reducing the cost of building materials and recycling non-environmentally friendly products [3]. The current pace of industrial development in Ukraine requires a large amount of electricity, the primary source of which is currently coal-fired thermal power plants (TPPs) due to the existing significant natural reserves. As a result, fuel ash and slag waste are generated annually in large quantities, including fly ash from TPPs. It worsens the environmental situation in the country and requires disposal and large areas of the territory when creating dumps.

Since the high content of amorphous silica in fly ash provides its high pozzolanic activity, the problem of its rational disposal is relevant. Therefore, it is efficient to use these ashes in the composition of mineral binders and as finely dispersed active mineral additives in concrete and crushed stone mixtures. This makes it possible to replace imported and expensive microsilica and highly active metakaolin in order to bind free calcium hydroxide into less soluble and reactive low-basic calcium hydro-silicates [4]. Therefore, the use of fuel fly ash or products based on it is relevant and promising for obtaining an effective fine-grained CSSM or complex mixtures with enhanced performance and strength characteristics. The combined effect of a complex organic-mineral modifying additive and cement with the fibers of fly ash results in a compacted and reinforced structure of a cement stone, which allows obtaining a high-strength and corrosion-resistant CSSM for the construction and reconstruction of road pavements [5].

In the course of the research, the authors analyzed scholar, patent, and regulatory sources. The authors of this article generalized the literature on construction materials science and theoretical and experimental studies on the modification of the crushed stone structure reinforced with the cement of fine-grained concrete and fiber. The authors also studied experimental works on the development of compositions of fine-grained mixtures and their use in road reconstruction, installation of foundations, ballast and principal layers of foundations, railway embankments, and airfield and runway coatings [6,7]. As it turned out, there are insufficient studies on the issues of obtaining effective fine-grained crushed stone mixtures of concrete with a modified structure, enhanced strength and corrosion resistance, and large-tonnage ash waste. Furthermore, no study was conducted on the effect of the fibers of fly ash added to the binder in the composition and structure of cement stone in a fine-grained concrete mixture.

Thus, the study aims to scientifically substantiate that the modification of mixture structure with a complex

organic-mineral additive provides a CSSM of fine-grained concrete, which is effective for civil, industrial, road, and airfield construction. This mixture is based on a binder and consists of Portland cement and fibers of fly ash from TPPs. In order to achieve the stated aim, it is necessary to analyze the existing literary sources on the use of the fibers of fly ash for CSSMs and fine-grained concrete. The solution of the problem under research requires to substantiate the possibility of obtaining a high-strength and corrosion-resistant CSSM of fine-grained concrete characterized by a dense structure, high water resistance, and minor shrinkage and water absorption by using large-tonnage ash waste and modifying the cement stone structure with a complex organic-mineral additive, consisting of fibers of fly ash and water-reducing polycarboxylate superplasticizer.

The authors of this article also set the following objectives: to develop an optimum composition of a binder consisting of cement and fiber of fly ash with a superplasticizer additive, that is, a complex organic-mineral modifying additive and a fine-grained concrete material obtained on its basis; to examine how the modification of the structure of the developed CSSM affects its mechanical and performance properties; to study the physical-mechanical and structural-mechanical properties of the developed CSSM, reinforced with a complex additive consisting of cement, fibers of fly ash, and a superplasticizer; to develop technological solutions for manufacturing an effective mixture of fine-grained concrete based on the developed complex organic-mineral additive with the fibers of fly ash. The need to enhance the performance properties of concrete and cement sand mixtures while minimizing the costs makes this study relevant, and the use of fibers in the composition of sand cement mixture refers this research to new solutions.

2 Methodology

CSSMs are highly applicable in road and airfield construction in Ukraine and the world. The widespread use of these materials is due to their high physical, mechanical, and performance indicators that meet the requirements for roads and airfields of different categories and values. The ability to meet various architectural requirements, significant reserves of natural raw materials (crushed stone), and the possibility of replacing them with cement and other additives contribute to the widespread use of CSSMs. Low energy consumption of the initial components and favorable technical and economic indicators of the

production and use of CSSMs and fine-grained concrete are the determinative factors in their dominance over other building materials.

Therefore, CSSM of concrete type is one of the essential road building materials today. A modern modified CSSM of fine-grained concrete is an almost irreplaceable building material. Such materials obtained with the help of modern technologies can have a compressive strength from 0.3 to 90 MPa, their average density can reach from 200 to 2,800 kg/m³, and their properties can be specific, corresponding to the purpose [8]. These concrete mixtures are widely applicable in the construction and reconstruction of highways, airfields, bridges, and other construction sites [9,10].

In the course of experimental studies, the authors of this article used Portland cement M400 of the Akhangaran cement plant as a binder. The chemical composition of the clinker of the Akhangaran cement plant included the following oxides: CaO – 65.79%, SiO₂ – 22.12%, Al₂O₃ – 4.54%, Fe₂O₃ – 4.17%, SO₃ – 0.64%, MgO – 1.71%, Na₂O – 0.23%, K₂O – 0.38%, and other impurities – 0.20%. The mineralogical composition of Portland cement clinker contained the following minerals: C₃S – 57.5%, C₂S – 17.8%, C₃A – 4.7%, and C₄AF – 12.5%. The results of the study of the physical and physical-mechanical properties of the binder are provided in Tables 1 and 2.

The physical and physical-mechanical properties of the Portland cement used in the study meet the requirements of DSTU B V.2.7-46:2020 “Cement for general construction purposes,” and its activity corresponds to the M400 brand. The authors of this article used the fibers of fly ash as the particulate filler in the studies conducted. Table 3 presents the characteristics of the said fiber.

Table 3: Characteristics of the fibers of fly ash from TPPs

Indicator	Physical-mechanical properties Fibers of fly ash
Average fiber diameter (μm)	160.0
Non-fibrous additives (%)	2–3
Density (g/cm ³)	2.65
Temperature range for use (°C)	–269 to +700
Water resistance (%)	99.6
Chemical resistance (%)	
0.5H NaOH	93.4
2H NaOH	77.3
2H H ₂ SO ₄	98.5
Hygroscopicity (%)	up to 1.0
Mechanical strength (MPa)	4,100
Modulus of elasticity (MPa)	120
Elongation at break (%)	3.1

The CSSM used had a grain size of 40 mm. With the included fractions from 2 to 10 mm, which occupy up to 70% of the volume, the largest are present in an amount of 10%. The composition also contains up to 10% of dust microparticles, which meets the requirements of the C1 fraction. The main field of application of the mixture is the arrangement of road surfaces, especially when it is required to obtain a perfectly flat, smooth surface. The authors of this article used crushed stone and sand from screenings of crushing rocks corresponding to DSTU-N B V.2.3-39:2016. Tables 4 and 5 provide the properties of the crushed stone used.

The superplasticizer C-3 (TU 6-36-0204229-625-90) served as a plasticizing additive. C-3 belongs to the category of anionic surfactants and is a mixture of oligomeric

Table 1: Physical properties of Portland cement

Cement brand	Average density (g/cm ³)	True density (g/cm ³)	Fineness of grinding		Standard consistency
			Specific surface (m ² /kg)	Residue on the sieve 0.08%	
Portland cement M400	1.21	3.20	300	8.5	25.5

Table 2: Physical-mechanical properties of Portland cement

Cement brand	Setting time (hours – min)		Ultimate strength after 28 days of hardening (MPa)		Soundness
	Start	Finish	Bend	Compression	
Portland cement M400	1–40	6–20	5.80	41.80	Sustained over

Table 4: Grain-size composition of the crushed stone

Material (mm)	Grain-size composition (screened through a mesh sieve, mm) (%)			
	40	20	10	5
Fraction of crushed stone 5–10	100	100	95	5
Fraction of crushed stone 5–20	100	58	30	12
Fraction of crushed stone 5–40	92	4.5	3.5	2

and polymeric compounds formed during the condensation of naphthalene sulphonic acids with formaldehyde and neutralization of unreacted β -naphthalene sulphonic acid and sodium sulfate with alkali (NaOH) and technical lignosulfonates.

The C-3 requirements establish that the content of the active substance equivalent to a dry product should be at least 69% in C-3, the ash content should be no more than 38%, pH of 2.5% aqueous solution can vary from 7 to 9, and the water content should be less than 10%. Requirements met by superplasticizer C-3 are shown in Table 6.

The experiments also used tap drinking water that meets the requirements of DSTU B V.2.7-273:2011 “Water

for concrete and mortars. Technical conditions.” The specific surface area of the fillers was determined using a PSKh-12 instrument. The operation principle of this instrument is the measurement of the specific surface of powder materials by the Kozeny–Carman method. This method determines the air permeability and porosity of the compacted layer of powder and the corresponding average weight of particle sizes.

The authors determined the activity of the fillers by CaO absorption from a saturated lime solution with pH = 12.15. The additives were mixed with a saturated CaO solution. The authors sorted 50 mL of the solution with the additive after 2 days of mixing and titrated it. 0.05 N hydrochloric acid solution served as a titer. Then, once a day, the flask with the solution was shaken and titrated every 2 days. The authors introduced 50 mL of a new saturated lime solution to the flask after each titration. Thus, the solution was titrated 15 times within 30 days. The total amount of CaO absorbed by 1 g of the mineral supplement was determined by summing all 15 measurements.

The original method helped to assess the plasticizing and water-reducing effects. This technique can significantly reduce material consumption. The authors of this article used the modified Suttard viscometer to determine the plasticizing and water-reducing effects. The viscometer

Table 5: Crushed stone properties

No.	Name of indicator	Actual indicator	DSTU requirement
1	Content of crushed grains by weight, at least %	92	85
2	Content of lamellar (flaky) and needle-shaped grains by weight, no more than %	13.9	15
3	Content of soft rock grains by weight, no more than %	2.9	5
4	Content of dust and clay particles by weight, no more than %	0.99	2
5	Content of clay in lumps by weight, no more than %	—	0.25
6	Crushability grade, at least	1,000	1,000
7	Abrasion grade	A1	A1
8	Frost resistance grade, not lower than	F150	F50
9	Plasticity grade	P1	P1–P2
10	Water resistance grade	W1	W1–W2
11	Bulk density, kg/m ³	1,418	—

Table 6: Requirements for superplasticizer C-3

Indicator	Requirement
Appearance	Brown liquid with possible sediment
Content of active substance equivalent to a dry product, at least %	69
Water content, no more than %	68
Ash content equivalent to a dry product, no more than %	38
pH of 2.5% aqueous solution	7–9

is a stainless-steel cylinder with an inner diameter of 10 mm and a height of 40 mm. The authors determined the change in water demand and flowability by spreading value at the boundary of gravitational spreading. The following formula provided the determination of the ultimate shear stress:

$$\tau_0 = hd^2p/kD^2, \quad (1)$$

where τ_0 is the ultimate shear stress of the suspension, Pa; h and d stand for the height and diameter of the viscometer, respectively, m; p is the density of the suspension, kg/m³; k is the coefficient of the redistribution of stresses in viscoplastic solids, equal to 2; D – is the spread diameter of the suspension, m.

For a viscometer with the indicated dimensions, the spread at the boundary of gravitational spreading is 22–24 mm, which corresponds to $\tau_0 = 10$ –30 Pa. The authors used the following equation to calculate the water-reducing effect of the superplasticizer:

$$(W/C)_u - (W/C)_p, \quad (2)$$

$$\Delta W = \times 100\%, \quad (3)$$

$$(W/C)_u, \quad (4)$$

where $(W/C)_u$ and $(W/C)_p$ – water-to-cement ratio of the plasticized and unplasticized systems, respectively.

The authors determined the pH medium (hydrogen ion activity) of hydrating cement with and without modifiers by the potentiometric method on a pH-213 millivoltmeter. The specimens for the conducted tests were cement stone powder, ground in a porcelain mortar to pass through sieve no. 008. In order to exclude the carbonization influence and contamination from the walls and bottom of the mold, the authors took the test sample from the middle of the specimen. A weighed portion of cement paste (10 g) was placed in a cone flask and thoroughly mixed for 20–30 s. The authors filtered the obtained cement suspension off and poured the filtrate solution into a glass bowl. The measurements presupposed placing two electrodes into a glass bowl with the test solution. The first electrode was the measurement (indicator) electrode, the potential of which depends on the concentration of the ions determined in the solution. The second electrode was the reference (standard), relative to which the measurement electrode potential is calculated. The potential of the reference electrode remains constant when the concentration of the detected ions changes. After each measurement, the electrodes were dried with filter paper and washed with distilled water.

The RV-8 rotary viscometer used to determine the rheological properties of cement suspensions reinforced

with the fibers of fly ash has two principal working bodies – brass coaxial cylinders. The test suspension was placed between them. The rotation of the inner cylinder with the help of weights relative to the outer one makes it possible to establish the dependence of the viscosity of fluid mixtures on the number of revolutions per second according to the following formula:

$$\eta = kx(P - P_0)/N, \quad (5)$$

where P is the sum of weights rotating the inner cylinder, g; P_0 stands for bearing friction corresponding to a load weighing 1–2 g; N is the number of cylinder rotations per second; k is an instrument constant.

The viscometer also provides for estimating the ultimate shear stress in the test suspension caused by the rotation of the inner cylinder. The formula is as follows:

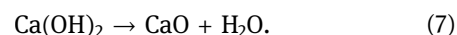
$$\tau = k_1x(P_1 - P_0), \quad (6)$$

where τ is the ultimate shear stress; P_1 is the minimum load at which the rotation of the inner cylinder begins with a gradual increase in the load, g.

The authors also applied thermogravimetric analysis, which involved measuring the change in the weight of the specimens when heated. Cement mixed with water hardens as a result of hydration, followed by the formation of crystalline hydrated silicates, aluminate hydrates, hydrated calcium ferrites, calcium hydroxide (portlandite – Ca(OH)_2), and ettringite.

Differential thermal analysis shows typical endothermic reactions in the structure of a cement stone caused by dehydration of hydrated newly formed structures and destruction of their crystal structure; new compounds formed at high temperatures lead to exothermic reactions. This analysis makes it possible to determine the content of calcium hydroxide, calcite, hydrated silicates, aluminate hydrates, hydrated calcium ferrites, calcium aluminate sulfate hydrates of numerous compositions, diverse complex compounds, and various types and modifications of gypsum and other newly formed structures in a cement stone.

The thermogram of a normal-cured Portland cement stone showed three main endothermic effects caused by the removal of adsorption water from gel-like hydration products and crystalline hydrate water from calcium aluminate sulfate hydrates (100–150°C), as well as by Ca(OH)_2 dehydration (430–580°C) and CaCO_3 dissociation (720–800°C). The endothermic reaction of the decomposition of portlandite of the cement stone upon heating, accompanied by its dehydration and subsequent loss in weight, proceeds according to the following formula:



The calculations of portlandite content in the cement stone are as follows:

$$m_{\text{Ca(OH)}_2} = \frac{a \cdot 74}{18}, \quad (8)$$

where m is the content of Ca(OH)_2 in a cement stone specimen, %; a stands for loss in weight, %; 74 and 18 are molecular weights of Ca(OH)_2 and H_2O .

The authors estimated the flowability of the concrete mixture by the cone slump (CS) in centimeters or the cone flow (CF) diameter in millimeters using the slump cone or cone shape (Figure 1).

The workability of the fine-grained concrete mixture was determined according to CF diameter in mm using the truncated minicone (Figure 2).

The spreading value ($D_{\text{spreading}}$) was calculated by the following formula:

$$D_{\text{spreading}} = \frac{D_1 + D_2}{2}. \quad (9)$$

The average density of a fine-grained concrete mixture is the weight-to-volume ratio of the compacted concrete mixture. The authors used a graduated metal cylindrical vessel with a capacity of at least $1,000 \text{ cm}^3$ to determine the average density of the concrete mixture. The average density of the fine-grained concrete mixture was calculated by the following formula:

$$\rho_{\text{ad}} = \frac{m - m_1}{V} \cdot 1,000, \quad (10)$$

where ρ_{ad} is the average density; m is the weight of a graduated vessel with a concrete mixture, g; m_1 is the weight of a graduated vessel without the mixture, g; V is the volume of graduated vessel, cm^3 .

The authors determined the average density of the fine-graded concrete (FGC) by testing specimens – three cubes of $100 \text{ mm} \times 100 \text{ mm} \times 100 \text{ mm}$ for each composition in a state of natural moisture. The calculation of the density of the concrete specimen was as follows:

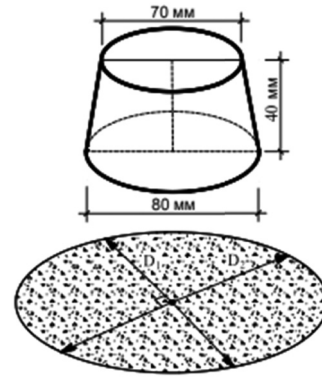


Figure 2: Truncated minicone for determining the flow of a fine-grained concrete mixture.

$$\rho_w = \frac{m}{V} \cdot 1,000, \quad (11)$$

where m is the weight of the concrete specimen, g; V is the volume of the concrete specimen, cm^3 .

The water absorption of the concrete was determined for each composition of the cube specimens of $70.7 \text{ mm} \times 70.7 \text{ mm} \times 70.7 \text{ mm}$, for three times. The authors placed the specimens in a water-filled container so that the water level in the container was about 50 mm higher than the upper level of the placed specimens. The water temperature was $20 \pm 2^\circ\text{C}$ in the container. The samples were weighed on a balance with an error of no more than 0.1% every 24 h of testing. The authors preliminarily wiped the specimens taken out of the water with a damp cloth. The weight of the saturated specimen included the weight of water flowing out of the pores of the specimen onto a balance pan. After the water absorption process was over, the specimens were dried to a constant weight. The authors calculated the water absorption of specimens by weight in percent according to the following formula:

$$W_m = \frac{m_w - m_d}{m_d} \cdot 100, \quad (12)$$

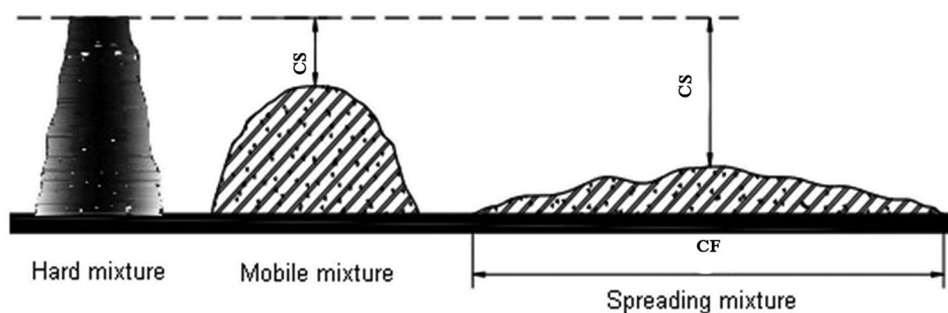


Figure 1: Determination of the workability of a concrete mixture by a slump cone.

where W_m is the water absorption by weight; m_d is the weight of the dried specimen, g; m_w is the weight of the water-saturated specimen, g.

The determination of water resistance of the specimens was in accordance with the “wet spot” method on cylindrical specimens with a diameter of 150 mm and a height of 150 mm. The authors kept six manufactured specimens of FGC of each composition in a normal moisture chamber at $20 \pm 2^\circ\text{C}$ and relative humidity of at least 95%. The water pressure was increased at a step of 0.2 MPa within 1–5 min and maintained at each stage for 16 h. The authors assessed the water resistance of each specimen according to the maximum water pressure at which no water was to seep through it in the form of a wet spot on its end surface, opposite to the surface through which water was supplied under pressure. Water did not seep through four out of the six specimens at its maximum pressure (Table 7).

The strength indicators of the specimens were determined according to GOST 10180-2012 on a hydraulic press. The authors determined the compressive strength of FGCs on cube specimens of $100\text{ mm} \times 100\text{ mm} \times 100\text{ mm}$ and tensile strength in bending on prism specimens of $100 \times 100 \times 400$ at the age of 28 days of normal hardening for each composition and the experiment was carried out three times.

The assessment of the corrosion resistance of concrete in aggressive media was in accordance with GOST 27677-88 and GOST 56687-2015. The authors tested the

specimens of the developed FGC for leaching corrosion and corrosion under the action of 0.001 M hydrochloric acid solution and aqueous solutions of sulfate and sodium chloride of 5 and 3% of concentration, respectively. The obtained results were compared to those of the reference specimens of unmodified FGCs. Three reference specimens and three main specimens from each composition of the FGC for each aggressive media represented 28-day-old prisms of $40 \times 40 \times 160$.

The shrinkage of concrete specimens was determined according to GOST 24544-81. The specimens were six prisms of $70\text{ mm} \times 70\text{ mm} \times 280\text{ mm}$ for each composition under GOST 56687-2015. A length comparator 62-L0035/A helped determine the shrinkage deformations of the concrete specimens. The tests were carried out at $20 \pm 2^\circ\text{C}$ and relative humidity of $60 \pm 5\%$ under conditions excluding direct sunlight on the specimens.

The measurement of the shrinkage deformations presupposed arranging the prepared concrete specimens in the testing device and reading the initial readings according to the device. The authors took the readings according to the specified standard in a day, on 3, 7, and 14 days, and then every 2 weeks until three successive measurements would show an increment of shrinkage deformations that did not exceed the error of the device. In the course of the experimental studies, the authors developed a non-standard empirical method to determine the adhesive strength of a new concrete layer with a previously laid layer. This method makes it possible to simulate the shear forces on the road pavement caused by cars during movement and braking. The ASTM C 1202-17 standard served for defining the density of the specimen structures by their permeability to chlorine ions (Figure 3).

An objective assessment of the accuracy of the measured random variables presupposed statistical processing

Table 7: Water resistance of the concrete specimens

Water resistance (MPa)	0.2	0.4	0.6	0.8	1.0	1.2
Concrete grade for water resistance	W2	W4	W6	W8	W10	W12

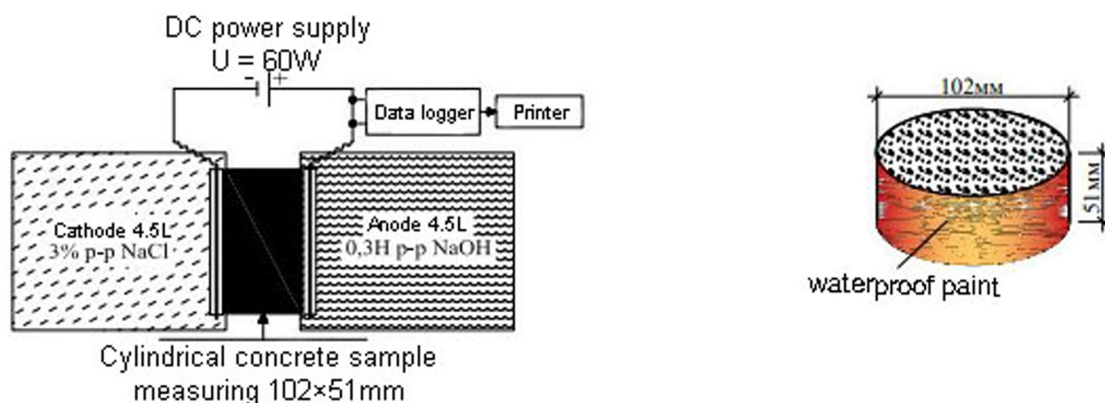


Figure 3: Experimental setup for determining the permeability of a concrete specimen to chlorine ions.

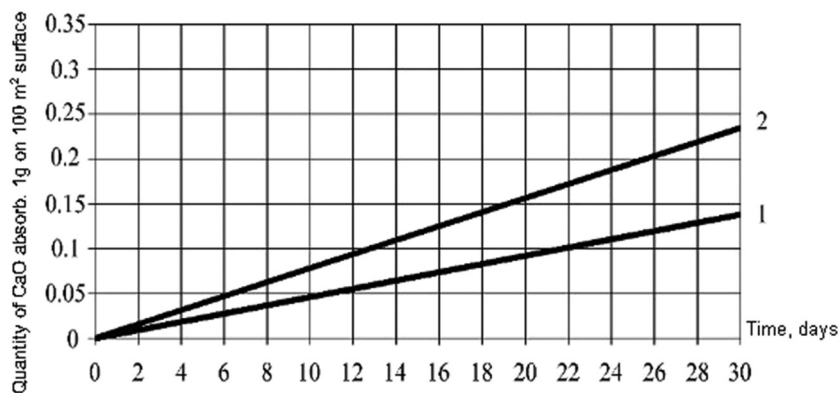


Figure 4: Activity of fibers of fly ash in relation to CaO. 1. Glass fibers; 2. Fibers of fly ash.

of the experimental results. The actual data of physical and mechanical tests were subject to statistical processing with the calculation of the arithmetic mean values of the test results, standard deviation, coefficient of variation, and determination of the number of specimens required to obtain results with a given degree of accuracy. The minimum number of specimens used for each test was at least three to ensure the reliability of the experiment results.

3 Results

The assessment of the chemical resistance of the fibers of fly ash was carried out by boiling $\text{Ca}(\text{OH})_2$ in this solution for 4 h. The authors also tested glass fibers in parallel to compare the results. Figures 4 and 5 show the results of the study on CaO absorption.

In this regard, the authors tested the stability of the fibers of fly ash in a saturated solution of $\text{Ca}(\text{OH})_2$, which is the main component of the liquid phase of hydrating

cement for CaO absorption. According to Figure 4, the fibers of fly ash have the highest activity in CaO, even though the specific surface (γ) is $2,500 \text{ cm}^2/\text{g}$. The above indicates a greater reactive capacity of the fiber to CaO in comparison with glass fibers. The same is true when calculating the CaO absorption per 100 m^2 of the additive surface. Absorption of CaO by the fibers from the saturated lime solution was $0.18 \text{ kg}/\text{m}^2$, which meant its chemical interaction with hydration products of Portland cement.

Thus, the above confirms that the fiber of the fly ash reacts with the hydration products of Portland cement, but this reaction is limited. No more than 10–12% of the fiber surface enters the reaction, which slightly increases their strength and does not affect the strength of the entire fiber-reinforced composite. Since the cement hydration process leads to CaO formation at the initial time of hardening, the fibers of the fly ash will increase the degree of interaction of the alkaline medium with such fibers. The intensity of the interaction of the fibers with the cement matrix gradually decreases since a layer of insoluble hydrated silicates forms on the fiber surface, which prevents the development of fiber corrosion.

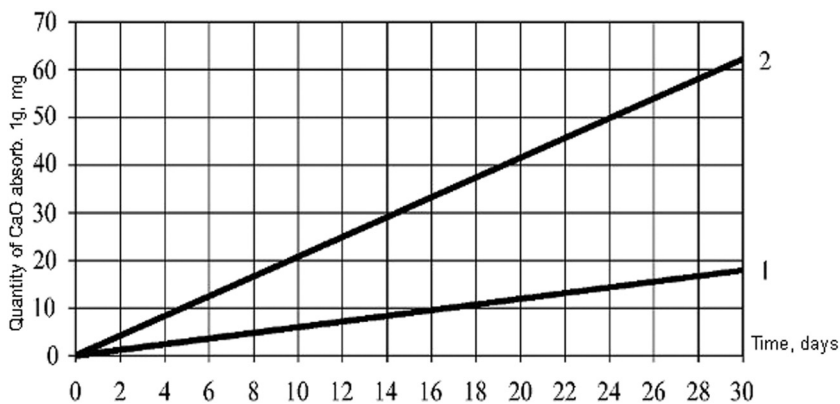


Figure 5: Activity of fibers of fly ash in relation to CaO, referred to 100 m^2 of surface. 1. Glass fibers; 2. Fibers of fly ash.

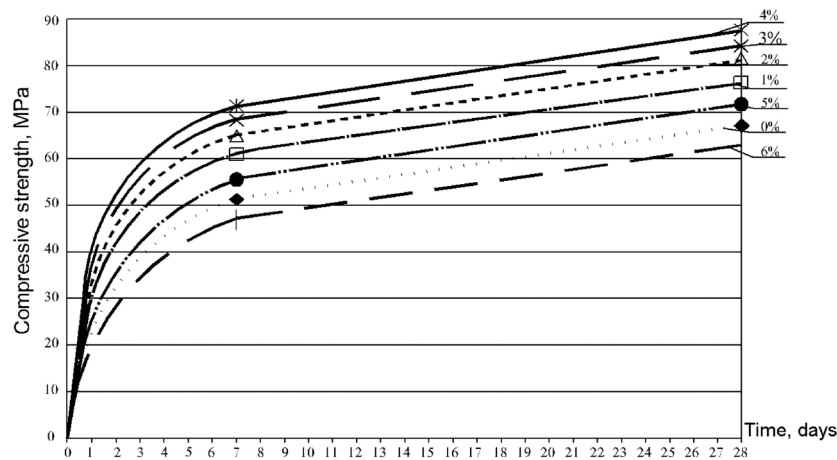


Figure 6: Kinetics of strength of dispersed and fiber-reinforced cement stone.

When studying the effect of dispersed reinforcement on cement stone and concrete, its physical and mechanical properties evoke the most interest. In this article, the authors examined the strength and deformation properties of plasticized cement stone, modified with a superplasticizer and reinforced with the fibers of fly ash (Figures 6 and 7, Table 8).

The numbers on the curves show the percentage of introduced fiber by the cement weight.

The compositions were obtained at a constant water-to-cement ratio ($W/C = 0.25$). The numbers on the curves show the percentage of fibers by weight of the cement.

Figure 8 shows how the fibers of fly ash affect the bending strength of cement stone. The research results indicate the introduction of fibers into the composition of cement stone significantly increases its bending strength. The introduction of fibers in the amount of 3% of the mass of the binder increases the bending strength of cement stone by more than two times.

Table 8: Influence of fly ash fibers on the workability of cement paste and the density of cement stone

Content of basalt fiber (%)	W/C	CF (cm)	Density of cement paste, ρ_{cp} (g/cm ³)	Density of cement stone, ρ_{cs} (g/cm ³)
0	0.24 (Standard consistency)	95	2.19	2.26
1	0.245	95	2.21	2.28
2	0.25	94	2.22	2.29
3	0.255	95	2.23	2.3
4	0.26	94	2.23	2.29
5	0.27	94	2.19	2.27
6	0.28	94	2.17	2.21
0	0.25	98	2.18	2.23
1		97	2.2	2.27
2		94	2.22	2.27
3		91	2.21	2.28
4		85	2.15	2.21
5		75	2.11	2.15

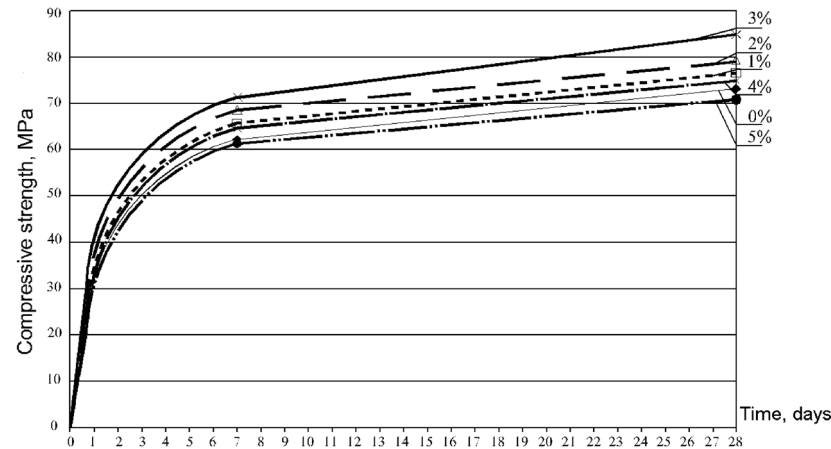


Figure 7: Kinetics of strength of fiber-reinforced cement stone.

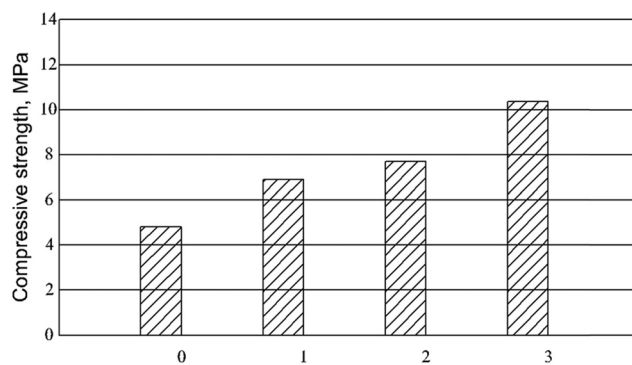


Figure 8: Influence of fibers of fly ash on the bending strength of cement stone, %.

The authors determined the effect of the plasticizer on the physical-mechanical characteristics of the dispersed fiber-reinforced cement stone on test beams of 20 mm × 20 mm × 80 mm and cube specimens of 20 mm × 20 mm × 20 mm. The choice of the plasticizing additive was made according to their composition. The chosen superplasticizer was the most accessible based on condensation products of naphthalene sulphonate C-3.

The specimens were made at 4% fiber content by weight of cement in order to identify the most effective dosage of the C-3 superplasticizer. The assessment of the mobility of the compositions was in accordance with the standard CF. The standard CF is 94–95 cm, corresponding to the standard consistency of the cement paste according to the Vicat apparatus. In order to determine the optimum dosage, the plasticizer was gradually introduced from 0 to 3% at a step of 0.5% of the cement weight. The research results are shown in Figures 9 and 10.

According to Figures 9 and 10, the highest compressive strength was possessed by 3 days old and 28 days old specimens with 2.0% content of superplasticizer C-3 and 4% fly ash fibers by the cement weight, hardened under

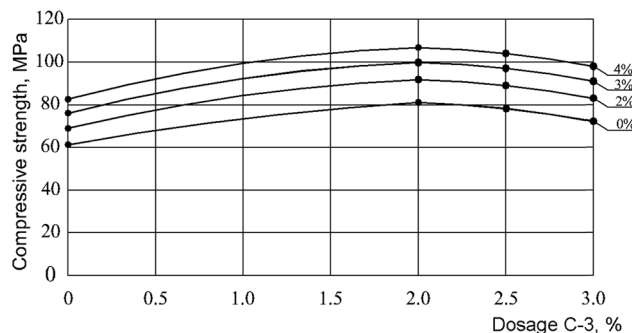


Figure 9: Compressive strength of a 3 days old plasticized, dispersed fiber-reinforced cement mixture.

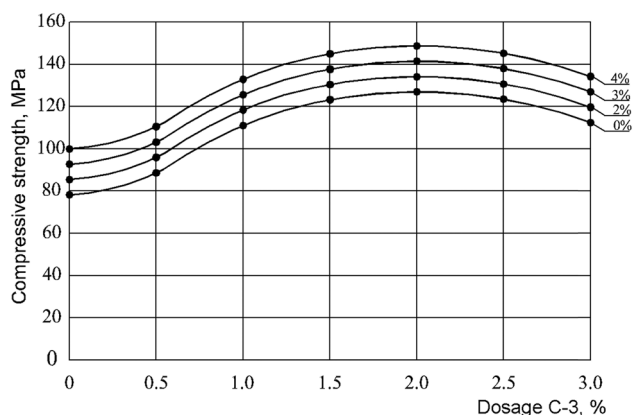


Figure 10: Compressive strength of a 28 days old plasticized, dispersed fiber-reinforced cement mixture.

normal humidity. Their strength was 105 MPa on the third day and 147 MPa on the 28th day, which is 62 and 67% higher than the reference composition with 2.0% of C-3 content at the corresponding hardening time. Figures 9 and 10 show the increase in strength over the reference composition growths over time, which indicates a fuller use of the fibers with the increased strength of the matrix itself. However, the difference in the increase in strength in compositions with 1.5 and 2.0% content of superplasticizer C-3 is 3%, which means the plasticizing limit of the cement paste.

Method of thermal gravimetric analysis was used to examine the influence of complex organic-mineral modifying additives on the features of the phase composition of cement stone. These compositions did not contain sand and polypropylene fiber in order to avoid the influence of thermal destruction of polymer fiber on the endothermic effect of portlandite decomposition. Thermogravimetric analysis of 28 days old cement stone specimens showed endothermic effects at 110–130°C, reflecting the removal of loosely bound adsorption water and water from crystalline hydrates of calcium aluminate sulfate hydrate. The endothermic effect at 430–500°C refers to the decomposition of portlandite. Thus, microsilica introduced in the modifying additive in an amount of 10% of the cement weight makes it possible to reduce the content of portlandite by 2–3% in 28 days old cement stone due to its high pozzolanic activity. This increases the corrosion resistance of the fine-grained concrete.

The authors used the RV-8 rotary viscometer to calculate the coefficient of dynamic (structural) viscosity and the value of the ultimate shear stress of the dispersed fiber-reinforced cement paste. Figure 11 shows how the structural viscosity changes depending on the ultimate shear stress of the cement paste.

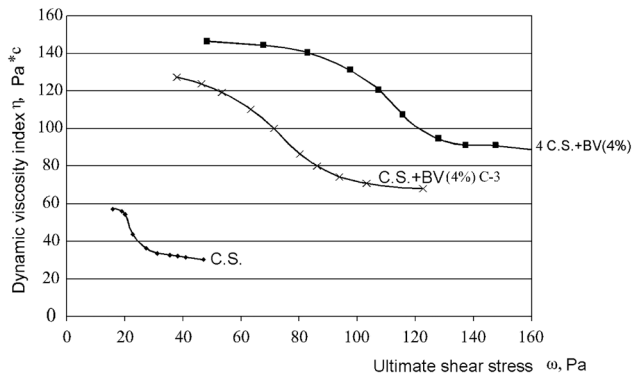


Figure 11: Dependence of the structural viscosity of the fiber-reinforced cement paste of cement stone; cement stone, fiber (4% by weight of cement), and superplasticizer C3; cement stone and fiber.

The viscosity curves are typical for water-dispersed coagulation-type systems such as cement compositions. The increase in τ in a particular interval causes a transition (decrease) in the viscosity of the intact structure to those of the destroyed one. Notably, the introduction of fly ash fibers increases the viscosity by 2–3 times in both

cases, sharply shifting the transition interval toward high shear stresses. The superplasticizer shifts the curve to the left and down, i.e., considerably reduces the structural viscosity of the cement paste containing fly ash fibers.

The authors of this article prepared the specimens of concrete mixture, dispersed and reinforced with the fly ash fibers. The fibers were introduced by joint grinding with cement and a superplasticizer. This method provides a complete distribution of fiber in the Portland cement medium and eliminates the formation of lumps during the preparation of the concrete mixture. The authors prepared the specimens of fine-grained, dispersed fiber-reinforced concrete on the optimum particle size distribution of the sand aggregate, the same cement to sand ratio, the addition of fiber of fly ash by the cement weight, and different ratio of fiber of fly ash to C-3 superplasticizer (Table 9).

Composition no. 5 (fiber content is 4%) showed the best result. Its bending strength exceeds the nonfibrous reference composition by more than 2.2 times in tensile strength in bending and 1.5 times in compressive strength. Notably, the increased percentage of fiber

Table 9: Compositions of FGC with the addition of fiber of fly ash

No.	Cement (kg/m ³)	Stone screening dust (kg/m ³)	River sand (kg/m ³)	C-3, % by cement weight (kg/m ³)	Fiber of fly ash, % by cement weight (kg/m ³)
1	710	1,460	71	—	—
2	710	1,460	71	1.0/7.1	—
3	710	1,460	71	1.0/7.1	1%/7.1
4	710	1,460	71	1.5/10.7	3%/21.3
5	710	1,460	71	2.0/14.2	4%/28.4
6	710	1,460	71	2.0/14.2	5%/35.5

Table 10: Physical-mechanical and performance indicators of the developed compositions

Indicators	DSTU standard	CSSM of fine-grained concrete		
		Composition no. 1	Composition no. 2	Composition no. 3
Average density (kg/m ³)	—	2,138	2,140	2,142
Compressive strength (MPa)				
3 days	—	34.5	39.5	47.1
7 days	22.5–45.0	68.7	52.5	61.6
14 days	—	62.6	71.6	74.1
28 days	38.5–77.0 (W30–W60)	71.4	78.5	81.7
Tensile strength in bending (MPa)				
3 days	—	2.89	3.45	3.79
28 days	4.6–7.7	6.51	7.17	7.48
Adhesion bond strength (MPa)	At least 2.0	5.5	6.8	7.0
Water absorption (%)	Not more than 3.8–5.7	3.4	2.5	2.0
Water resistance (MPa)	At least 0.4–1.2	1.25	1.65	1.72
Porosity (%)	—	7.15	7.08	6.87

insignificantly increases the water demand, indicating its good distribution in the FGC mixture. Physical-mechanical and performance indicators of the developed compositions of CSSM are shown in Table 10.

Experiments also showed that specimens based on modified fine-grained concrete of the second and third compositions have a relative deformation of 1.8 and 2.0 times less than the specimens from fine-grained concrete of the reference composition no. 1 at the age of 28 days, respectively.

4 Discussion

A CSSM of concrete type is one of the essential road building materials today. A modern modified CSSM of fine-grained concrete is an almost irreplaceable building material. Such materials obtained with the help of modern technologies can have a compressive strength from 0.3 to 90 MPa, their average density can reach from 200 to 2,800 kg/m³, and their properties can be specific, corresponding to the purpose. These concrete mixtures are widely applicable in the construction and reconstruction of highways, airfields, bridges, and other construction sites [9,10].

High compressive strength is one of the main properties of a modified CSSM of fine-grained concrete. The CSSM should have a dense, homogeneous, and fine-grained structure to be of high quality and durability [11]. It is possible to achieve this by fulfilling several conditions arising from the following physical foundations of the concrete structure formation: the use of high-quality binders and aggregates; extremely low water-to-cement ratio; maximum permissible content of Portland cement; the use of a superplasticizer and fiber of fly ash, contributing to a dense concrete microstructure; thorough mixing and compaction of the concrete mixture; creation of the most favorable conditions for the hydration of cement in the process of concrete hardening.

It is a good practice to use cement with an activity of at least 50 MPa and low values of standard consistency to obtain high-strength CSSMs of FGC. In addition, it is advisable to use various Portland cement of a particular mineralogical composition for its preparation, depending on the purpose. The preparation of high-strength modified concrete has recently involved using concrete mixtures without coarse aggregates, including fine-grained concrete mixtures [12]. The transition to FGCs potentiates the development of new types of concrete with enhanced structures. CSSMs which do not contain coarse aggregates

have found wide application in the construction of the upper layers of the bases and pavement structures, as well as for strengthening the working layer of the road bed [13].

Significant progress in the development of compositions and the study of properties and possible areas of application of FGCs in transport construction belongs to Krasinikov et al., Petrochenko, Sheinin, Rabynovych, Ferronska, and other scientists [14–18]. The works of Bazhenov and Kharchenko, Tsikrvich et al., Slahaiev, Lezov, Lisovyyk and Prokopets considerably contributed to the development of technology and investigation of performance properties of FGCs [4,19–22].

The technological methods developed in this article (the use of microfillers from waste materials of the fuel and energy and stone processing industries, chemical additives) made it possible to obtain fine-grained concrete with a cement consumption that did not exceed the requirements for heavy concrete with coarse aggregates. Complex additives consisting of fibers of fly ash introduced into the mixture made it possible to reduce its water demand and the shrinkage of concrete. FGCs are technologically advanced since mixtures on their basis are easily pumped by pneumatic pumps and also have high homogeneity and durability [23]. The fine-grained structure of the mixtures obtained has many advantages, with the major advantages as follows: the possibility of obtaining a material with a homogeneous finely dispersed high-strength microstructure; increased workability of mixtures for transportability and use at a construction site; the possibility of obtaining materials with desired properties; the ability to widely use local raw and waste materials. CSSMs also have a lower cost in comparison with mixtures on traditional coarse aggregates; multifunctionality, i.e., it is possible to adjust the dosage of components and technological methods for obtaining various types of mixtures and concretes on the same cement and aggregate with the help of various additives.

The modified CSSM has a more homogeneous structure and lends itself well to various technological conversions. This gave us the opportunity to obtain mixtures with the required performance indicators. The possibility of using fibers of fly ash in cement systems largely depends on its resistance to the action of cement hydration products. Previous studies have shown that the resistance of fibers of fly ash is not lower than other fibers used for dispersed reinforcement of cement systems.

Rabynovych conducted studies on the resistance of mineral fibers to Ca(OH)₂ solution that indicated a high degree of destruction of mineral fibers in an aggressive medium [17]. For example, aluminoborosilicate monofiber

held for 12 months in a saturated lime solution lost 72% of its original strength. However, the researcher noted a high resistance of basalt fiber, which decreased by only 26–32% in strength after exposure to similar conditions. There was also a tendency to the attenuation of reaction of basalt fibers with CaO over time. The most intensive leaching processes were observed during the first 3 months. Thus, studies on the resistance of mineral fibers showed their high resistance to aggressive media of cement stone and saturated lime solutions. For example, long-term tests of fly ash fibers showed that their strength decreased by only 12–15%.

The authors of this article determined the effect of fibers of fly ash on the compressive strength of cement stone on cube specimens of $2\text{ cm} \times 2\text{ cm} \times 2\text{ cm}$ made of cement paste of standard consistency and at a constant water-to-cement ratio. The studied parameter was the percentage of fiber in the mixture, taken by weight from the weighed portion of the cement. The results showed that the cement stone had the greatest strength at 4% of fiber content since it exceeded the reference composition in strength at all times of hardening. The increase in strength was 28% (73 MPa) compared to the reference composition without fiber on the 3rd day of normal storage conditions of the cement stone, on the 7th day – 32% (84 MPa), and on the 28th day – 34% (98 MPa). Even though the water-to-cement ratio increases from 0.24 (standard consistency of the reference composition without fiber) to 0.26 (at 4% of fiber content in the cement paste), the strength increases. Notably, an increase in the curing time under normal storage conditions contributes to the strength compared to the reference composition. Therefore, the adhesion strength of the cement stone to the fibers of fly ash is enhanced. The compositions with 5 and 6% of fiber content lose their strength due to a significant increase in the water-to-cement ratio to 0.28 and 0.33, respectively.

The kinetics of hardening of a cement stone dispersed fiber-reinforced with a constant water-to-cement ratio showed that the composition with 3% of fiber content by weight of cement had the highest strength under such conditions of formation. The strength of the composition with 3% of fiber content was 59 MPa on the 3rd day, 71 MPa on the 7th day, and 85 MPa on the 28th day, which exceeds the reference composition without fiber by 8, 16, 19% at the corresponding hardening periods. Fiber began to clump in the compositions with 4 and 5% of fiber content with a constant water-to-cement ratio ($W/C = 0.25$), which led to worse molding capacity and decreased density. At the same time, the research results showed that the dispersed reinforcement of mixtures enhanced their

properties precisely at the level of the cement paste. The study of the effect of fiber as a dispersed reinforcing additive on the technological properties of fine-grained concrete is of great interest when used in road construction. Crucial indicators are rheological characteristics such as ultimate shear stress and structural viscosity of cement paste and the workability of fine-grained concrete dispersedly reinforced with the fibers of fly ash. The conducted studies showed that concrete obtained by mixing CSSMs, fly ash fiber, and a modifier requires initial and subsequent maintenance, which does not differ from the maintenance of a standard concrete mixture.

5 Conclusion

Given the geo-climatic conditions of Ukraine, a CSSM of fine-grained concrete is the most optimum variant for the construction and reconstruction of transport and airfield facilities. Therefore, it seems promising to develop its modified composition based on organic and mineral modifiers such as water-reducing superplasticizer and a fiber of fly ash and study its properties.

The introduction of modifiers into a CSSM and cement leads to the compaction of its structure, an increase in the water-holding capacity, and an enhancement of the cohesion, crack resistance, and tensile strength of concrete in bending. In addition, the developed composition reduces shrinkage of the material and leads to less abrasive wear of technological equipment compared to dispersed fibers from other materials.

Modifying additives introduced into a CSSM in optimal quantities provide a modified fine-grained concrete suitable for the construction and reconstruction of roads of all categories. Such concrete has a high-strength dense structure, low shrinkage, and the required water resistance, corrosion resistance, and durability. A review of the studies on the development of the composition and study of the properties of dispersed reinforced concrete mixtures (fiber-reinforced concrete) showed researchers' interest in this material all over the world. The above confirms the promising nature of this study dedicated to the fiber of fly ash used as a new reinforcing modifier.

The authors of this article examined the principles of the structure formation of modified CSSMs of fine-grained concrete. The authors have established that the introduction of a dispersed reinforcing additive such as fiber of fly ash increases the density of the structure of CSSMs, contributing to their strength, water resistance, performance reliability, and durability.

The developed, modified fine-grained concrete has a high structure density, compressive strength of 78.5 MPa, and tensile strength in bending of 7.17 MPa at the age of 28 days of normal hardening. Its water resistance is 1.6 MPa, water absorption and shrinkage are low, and corrosion resistance and adhesion to a previously laid layer are high. The compressive strength of specimens from the fine-grained modified concrete mixture of the developed compositions no. 2 and 3, micro-reinforced with a fiber of fly ash and water-reducing superplasticizer C3, increases by 10 and 14%, respectively. The tensile strength in bending of specimens made of modified concrete of compositions no. 2 and 3 slightly increases at the age of 28 days (by 10 and 15%, respectively). The above is due to the usage of fiber amount of 4% by cement weight. The portlandite content in cement stone of modified compositions decreases at the age of 28 days of normal hardening (by 3.0 and 2.18%, respectively) compared to the reference composition. It is due to the high pozzolanic activity of fiber of fly ash. This will increase the corrosion resistance of the fine-grained concrete.

According to the study results, the denser structure of the specimens from the CSSM of fine-grained fiber-reinforced concrete reduces its relative shrinkage by 1.6 times after 56 days tests compared to specimens of the reference fine-grained concrete. Consequently, the developed fine-grained concrete is sufficiently resistant to the formation of shrinkage cracks. The results of testing the developed fine-grained concrete for resistance to surface destruction under the action of water showed that pavement spalling of fiber-modified concrete specimens was almost 1.9 times less than that of reference fine-grained concrete.

Therefore, the developed composition of the CSSM of fine-grained concrete makes it possible to obtain a material with a modified structure that has physical-mechanical properties and performance indicators required for the construction and reconstruction of road and airfield structures.

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