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HEAVY CONCRETE BASED ON A POLYDISPERSE BINDER INCORPORATING A COMPLEX MODIFIER

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ABSTRACT: Efficient use of reclaimed lands requires durable and reliable concrete materials for irrigation structures. This study addresses methods for improving the performance characteristics of heavy concrete intended for hydraulic reclamation applications. The aim of the research is to develop a scientifically substantiated technological solution for producing heavy concrete based on a polydisperse binder with a controlled particle size distribution, combined with a complex chemical–mineral modifier (superplasticizer, polymer, and microsilica) and micro-reinforced with basalt fiber. The research methodology is based on the system–structure–property approach and employs the Drop & Roll algorithm to optimize dense particle packing. Experimental investigations included laser particle size analysis, X-ray diffraction, scanning electron microscopy, and standard methods for determining the physical, mechanical, and performance properties of cement stone and concrete. It was established that the optimized binder composition (15% with a specific surface area of 150 m²/kg, 75% with 300 m²/kg, and 10% with 450 m²/kg), in combination with 0.3% superplasticizer, 0.2% polymer admixture, and 15% microsilica, ensures the formation of a dense fine-crystalline cement stone structure with crystal sizes of 60–75 nm. The developed concrete demonstrates high performance, with a compressive strength of 77.3 MPa, flexural strength of 8.62 MPa, water absorption of 1.9%, water impermeability grade W14, and frost resistance up to F600, confirming the feasibility of its application in hydraulic reclamation structures.
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Keywords: Water Reclamation Construction, Polydisperse Binder, Complex Modifier, Corrosive

1. INTRODUCTION

The heavy concretes used in water reclamation construction must meet high durability requirements, primarily evaluated in terms of their strength, freezing resistance, and resistance to the leaching of calcium hydroxide from the cement stone. Thin-walled water reclamation structures (thickness to 15 cm), particularly trays, are constantly impacted by aggressive factors: impact of highly mineralized water, including ground waters, cavitation impact of continuously moving water flows. Therefore the number of defects increases progressively, that brings to significant water losses during transportation. To increase durability and operational reliability of reclamation facilities is possible due to using special protective anti-filtration linings, which allow reducing transportation water losses at the level of 15-20%. The integrity of thin coverings (thickness 0.2 mm) can be damaged even by insignificant mechanical influences that is the main problem when using them. For that reason there is an ongoing search of effective materials, for example polymeric compositions [1] capable to withstand both mechanical impacts and aggressive environmental conditions. Unfortunately, frequently offered polymeric compositions require the use of expensive chemical components that makes their large-scale implementation difficult. Therefore concrete using binders based on Portland cement clinker still remain the foundation of reclamation construction. In modern hydrotechnical and water reclamation construction the modified concrete [2-5] ensuring the required quality is mostly used.

The analysis of scientific research has shown that the main positive functions of adding modifiers into cement-based systems are: reducing the cement-based system viscosity to improve technological properties of concrete mixes, therefore the workability of concrete mixes can be increased to a 'flowable', self-compacting consistency without exceeding the normal consumption of the initial materials [6-8]; reducing the gauged water consumption for more than 20% and receiving high-strength concrete (B40 and more) from workable concrete mixes based on typical Portland cements [9-14]; changing the structure of cement stone and concrete in order to increase their strength to 40% and resistance to repeated alternating physical impacts [15-18]; regulating the speed of cement hydration and concrete hardening [19-20]; reducing the cement consumption to 25% while maintaining the required workability of the concrete mix and concrete strength [21]; combining the above effects to produce a concrete mix and concrete with the specified properties [22-24].

This means that increasing the concrete quality for hydrotechnical construction, partially water reclaiming, is an area of concern and requires further development in accordance with the current technological paradigm, aimed at creating a high-density concrete structure that effectively combines the required technological and operational properties through the use of high-strength binders, providing high density of packaging initial particles in each material microvolume jointly with complex modifier.

2. RESEARCH SIGNIFICANCE

The scientific significance of this study lies in the further development of the system–structure–property approach applied to heavy concretes with predefined performance characteristics. For the first time, heavy concrete for hydraulic reclamation applications is considered as a multilevel dispersed system based on a polydisperse binder with a controlled particle size distribution, a complex chemical–mineral modifier, and basalt fiber micro-reinforcement.

The proposed approach enables targeted control of the cement stone and concrete microstructure, leading to enhanced strength, density, and durability. The use of standardized testing methods and statistical data processing ensures the reliability and reproducibility of the results, thereby confirming both the scientific and practical relevance of the developed technological solution.

3. MATERIALS AND METHODS

In the study the initial materials with the following characteristics were used: mineral binder – Portland cement TsEM I 42.5H, «Holsim (Rus) SM» LLP (GOST 31108-2020); natural sand with a fineness modulus of 2.5, Khromtsovsky quarry LLP (GOST 8736-2014); granite crushed stone, fraction from 5 to 15 mm, Bogaevsky quarry LLP (GOST 8267-93); Melflux 5581F superplasticizing additive (GOST 24211-2008), POLIDON-A polymeric additive, Orgpolimersyntez LLP (TU 9365-002-46270704-2001); microsilica of MKU-95 class, EVEREST STC LLP (GOST P 58894-2020); chopped basalt fiber (BF), InReS LLP (TU 5952-002-13307094-08).

For the fine grinding of the clinker component a planetary ball mill Fritsch Pulverisette 7 was used. Consiquently there were received three series of finely ground binder samples with a specific surface area of 150, 300 and 450 m^2/kg respectively. The fineness of the binder grinding was controlled by sifting the sample through a standard set of sieves. Measurement of the resulting specific surface area and subsequent calculation of the particle size of the finely ground binder was done by means of PSH-11M device. The device operates using the Kozeny-Karman gas permeability method, based on determining the time of passage of a fixed air volume through the sample layer, after which the specific surface area is calculated taking into account air viscosity and its temperature. To carry out the X-ray phase analysis of cement stone a powder X-ray diffractometer DRON-3M was applied. The physical and mechanical study of the received concrete stones and concrete properties was controlled by means of automatic test press system Controls MCC8. To define freezing resistance the first base method was applied. The test samples consisted of a series of concrete cubes with an edge length of 100 mm. The specimens were cured for 24 hours when immersed to one-third of the sample height, 24 hours when immersed to two-thirds of the sample height and 48 hours when fully immersed. The testing was going on until sample structural defects appeared, such as cracks, chipping and scaling, mass loss, and loss of specimen strength by more than 5% of the required value. Determination of water resistance was carried out via concrete samples water permeability testing device by “wet spot” method Form+Test WE 6 MMZ.

The reliability of the research results is ensured by the use of regulatory documents, a wide range of research methods with certified and calibrated scientific equipment, the consistency between theoretical and experimental studies, and the reproducibility of the results with a probability of 0.95 for a large volume of experiments; as well as by the positive outcomes of pilot-industrial implementation and practical testing of the developed high-performance concrete based on a polydisperse binder with a complex modifier, reinforced with basalt fiber, intended for water reclamation construction. To receive the optimal composition of the polydisperse binder there were applied some topological properties of the received cement compositions using a software-computational package based on Drop and Roll algorithm. The analysis of scientific literature sources showed [23, 24], that to decrease the impact of “wall effect” the ratio of particle diameter to package size should be > 20. Due to the fact that the packaging calculation of 20 diameters of the largest sphere will take a very long time it was decided to study a unit cell, defined by the ratio of the largest sphere diameter to the side length 1 to 14. In our case the largest diameter is equal to 12 μm that is consistent with the particle size distribution data of the powders used, therefore the cell size will be 168x168x168 μm. The initial data for calculating the topological characteristics and the influence of the grain composition of the binder on packing density are shown in table 1.

Table 1. Initial data to calculate the topological characteristics

№	Disperse compositions of cement particles						Compressive strength of cement stone, MPa, at the age of, days.	
	Specific surface area of the compositions, m^2/kg			Composition, %			7	28
1	CEM 42,5 H control						28.4	43.5
2	150	0	0	100	0	0	20.3	25.2
3	0	300	0	0	100	0	26.2	39.4
4	0	0	450	0	0	100	38.6	49.7
5	150	300	0	20	80	0	24.1	39.6
6	150	300	0	25	75	0	20.7	31.3
7	150	300	0	30	70	0	19.0	28.6
8	0	300	450	0	80	20	41.2	58.5
9	0	300	450	0	75	25	47.4	60.7
10	0	300	450	0	70	30	50.6	63.2
11	150	300	450	15	80	5	40.2	52.0
12	150	300	450	15	75	10	44.6	56.4
13	150	300	450	15	70	15	48.5	57.8

To ensure reliable results, three test batches were prepared for each composition, with five specimens in each batch. The values reported in the table represent averaged results.

Considering the fact of increased energy consumption in the production of fine-dispersed powder with a specific surface area 450 m^2/kg, it was decided to assume as the optimal package composition 12 (table 1) with ration of cement particles in %: 15 – with average diameter d_{av}=12 µm and specific surface area S_{sp} =150 m^2/kg; 75 – d_{av} = 6,6 µm, S_{sp} = 300 m^2/kg; 10 – d_{av}= 4,9 µm, S_{sp} = 450 m^2/kg. Using the design of experiments method, the dependencies of the influence of controlling factors on the selected quality parameters of concrete were established.

Second-order regression equations were obtained. These equations adequately describe the dependence of compressive strength and the conditional stress intensity factor at the age of 28 days of normal curing, as well as the water absorption of modified heavy concrete at the same curing age.

Table 2. Ranges and levels of variation of the input factors for the design of a second-order experimental plan

Varying factors		Basic levels	Variation ranges
X_1	Composition of Polydon-A polymer additive	0.2	0.1
X_2	Composition of fiber	0.7	0.15

The relationships were established as functions of the variables X_1, representing the content of the Polydon-A polymer admixture, and X_2, representing the basalt fiber content expressed as a percentage of binder weight.

The following parameters were selected as the controlling factors of the objective functions of the experimental model: Y_1 – compressive strength (Rc, MPa), Y_2 – conditional stress intensity factor (K_c^*, MPa ×м^{0,5}), and Y_3 – water absorption (W_m, %). The input factors influencing the investigated characteristics are presented in Table 2.

The regression equations describing the modified heavy concrete are as follows:

$$Y_1 = 77.3 + 1.62X_1 + 1.13X_2 + 2.15X_1X_2 - 7.37X_1^2 - 6.44X_2^2 \quad (1)$$

$$Y_2 = 0.074 + 0.002X_1 + 0.001X_2 + 0.003X_1 \bullet X_2 - 0.005X_1^2 - 0.004X_2^2 \quad (2)$$

$$Y_3 = 1.9 - 0.2X_1 - 0.11X_2 - 0.25X_1X_2 + 0.65 \bullet X_1^2 + 0.45X_2^2 \quad (3)$$

The regression equations were automatically tested for adequacy using the following Student and Fisher criteria. The approximation error did not exceed 1–2%. Using Matlab R2015b, the maximum of the objective function of the second-order regression equation was identified: MAX Y_1^{max} = 77.3538 when X_1 = 0.0244, X_2 = 0.0918, that in natural values are 0.202% and 0.714%, relatively. MAX Y_2^{max} = 0.0744 when X_1 = 0.2676, X_2 = 0.2254, that in natural values are 0.227% and 0.734%, relatively. MIN Y_3^{min} = 2.352 when X_1 = 0.380, X_2 = 0.120, that in natural values are 0.238% and 0.718%, relatively. The optimal values were determined X_1^{opt} = 0.2; X_2^{opt} = 0.7 in natural, when the function Y_1 – compressive strength (R_c) has minimum value, and Y_3 (water consumption, Wm) – minimal. After substituting the obtained values into equations 2–4, the compressive strength was determined R_c = 77.3 MPa, = 0.074169 MPa ×$m^{0,5}$; water consumption Wm = 1.9 %.

4. RESULTS AND DISCUSSION

In order to assess the influence of the combined modifier (Melflux 5581F + Polydon-A + microsilica) on the properties of the modified cement stone, samples with different compositions were prepared using a paste of normal consistency (table 3).

Analysis of the data in Table 3 showed that in composition 2 there was a decrease W/C for 13.3% and also curing time; compressive strength at the age of 3 and 28 days increased for 26.1 and 20.5% in comparison with composition 1. When adding Melflux 5581F (composition 3) to polydisperse binder W/C decreased for 30.8%; at the same time, the curing time increased, and strength at the age of 3 and 28 days increased for 6.9 and 16% in comparison with composition 2. In composition 4 PB+Polydon-A W/C increased for 16.7% and curing time increased; strength at the age of 3 and 28 days decreased slightly from 24.8 to 24.0 and 60.8 to 59.2 MPa in comparison with composition 3. Joint introduction into PB (superplasticizer Melflux 5581F + Polydon-A) positively affected on water consumption and strength: W/C decreased for 34.6%, strength at the age of 3 and 28 days increased for 11.2 and 25% in comparison with contr. (composition 2). Maximum strength 82.5 MPa showed composition 6, containing active mineral additive microsilica grade MKU-95, the availability of which will allow solving the problem of corrosion resistance.

Grinding was carried out using a planetary ball mill Pulverisette 7, producing three successive series with specific surface areas of 150, 300, and 450 m^2/kg. The grinding fineness was monitored using a PSKh-11A instrument. Particle size distribution of the binder was verified using a Fritsch ANALYSETTE 22 NanoTec ultrasonic particle size analyzer.The phase composition of cement stone samples, calculated basing on the obtained XRF data is shown in Figs. 1-2.

The results of X-ray phase analysis showed, that in composition 2 (PB) presence of C3S and C2S increased in comparison with composition 1, and the degree of hydration decreased from 70 to 52% relatively. The decrease in the degree of hydration is explained by the presence of large unhydrated grains of binder in the composition 2 (fraction 150 m2/kg), which form the clinker stock reserve. When adding to PB Melflux and Polydon-A separately (compositions 3 and 4, table 3) there was a slight decrease of C3S and C2S for 2-3% in comparison with the control one (composition 2). Their joint introduction into PB (composition 5, table 3) showed a slight decrease in the main clinker minerals, while the degree of hydration increased to 57% in comparison with compositions 3 and 4. To increase the resistance of cement stone to leaching corrosion 15% of MKU-95 was added to composition 6. At the same time, the content of residual clinker minerals decreased slightly, and the amount of Ca(OH)2 decreased for more than 26.6% in comparison with the control one

Table 3. Compositions of cement stone at the age of 28 days of normal curing, made of cement paste of normal consistency.

Materials	Consumption of materials to receive cement paste of normal consistency, g					
	1	2	3	4	5	6
CEM I 42,5 H (factory)	400	-	-	-	-	-
Polydisperse binder PB (contr.) fr. m^2/kg: 150 (15%) + 300 (75%) + 450 (10%) contr.	-	400	400	400	400	340
MS (15%)	-	-	-	-	-	60
Gypsum stone (3%)	-	12	12	12	12	12
Melflux 5581 F (0.3%)	-	-	1,2	-	1,2	1,2
Polydon-A (0.2%)	-	-	-	0,8	0,8	0,8
W/C (water/cement)	0.3	0.26	0.18	0.21	0.17	0.20
Time of cement paste curing, h-min start/finish	2-55 8-20	1-32 6-15	2-05 7-10	2-15 7-25	2-10 7-20	2-20 7-30
R_c 3 days, MPa	18,4	23,2	24,8	24,0	25,8	26,5
R_{tb} 28 days, MPa	43,5	52,4	60,8	59,2	65,5	82,5

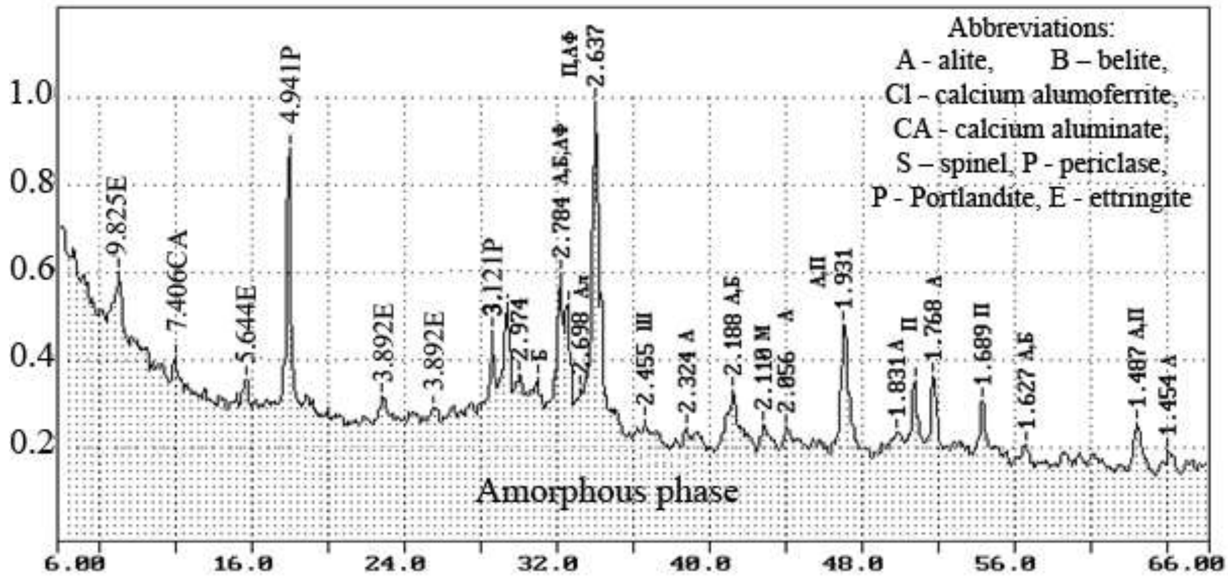


Fig. 1 X-ray phase analysis of hydrated cement stone samples at the age of 28 days of curing composition CEM I 42.5H

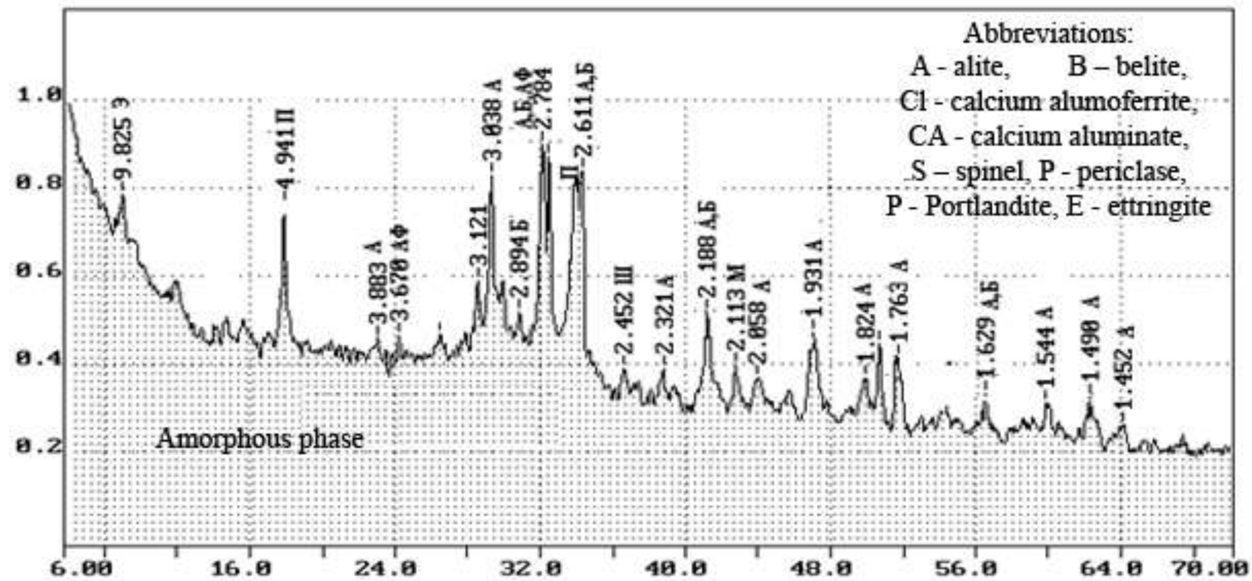
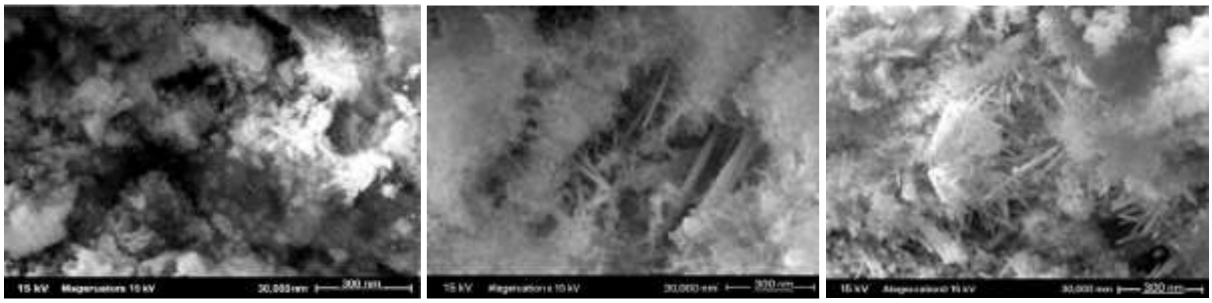


Fig. 2 X-ray phase analysis of hydrated cement stone samples at the age of 28 days of curing: PB+$CaSO_4 \cdot 2H_2O$+Melflux+Polydon-A+MS



a) b) c)

Fig. 3 Microstructure of cement stone at the age of 28 days for normal curing. Accelerating voltage: 15 kV; magnification: 30,000×; scale bar: 300 nm.: a) polydisperse binder - PB (control); b) PB +(0.3%Melflux+0.2% Polydon-A); c) PB +(0.3% Melflux+ 0.2% Polydon -A+15% MS)

This fact is evidence of the occurrence of a pozzolanic reaction, accompanied by the binding of $Ca(OH)_2$ with microsilica into less soluble and more chemically stable low-basic calcium hydrosilicates. Studies of the cement stone microstructure showed (fig.3), that presence of a complex modifier in the composition (fig. 3, c) allowed to receive the dense cement stone of ordered structure with uniformly distributed pores throughout the volume with accumulation of needle-shaped ettringite crystals in the micropores formation area. It was established that in composition 5 (table 3) the crystall sizes decrease from 70 to 90 nm (figure 3, b), and in composition 6 (table 3) – from 60 to 75 nm (figure 3, c), that is significantly lower than in the control 2 (table 4) – from 100 to 120 nm (fig. 3, a).

Table 4 Properties of modified concrete mixes and concretes

Values	Compositions					
	PC+ 0.3%Melflux	PB +0.3% Melflux	PB +0.2% Polydon-A	PB + 0.3% Melflux+ 0.2% Polydon-A	PB + (0.3% Melflux+ 0.2% Polydon-A +15%MS)	PB +(0.3% Melflux+ 0.2% Polydon-A+15%MS)+0.7%BF
Workability Grade /Conus draft, cm	W2/5	W2/6	W2/5	W2/6	W2/7	W2/5
Water separation of concrete mix, %	0.45	0.31	0.24	0.20	0.19	0.22
Solution separation, %	2.8	1.44	1.37	1.34	1.32	1.28
Average density of concrete kg/m^3	2401	2408	2406	2411	2420	2417
Porosity, %	14.52	11.67	10.54	10.12	9.2	8.6
Water impermeability, W	6	8	10	12	14	14
R_{tb} (av.), MPa,	5.78	6.54	6.27	6.93	7.73	8.62

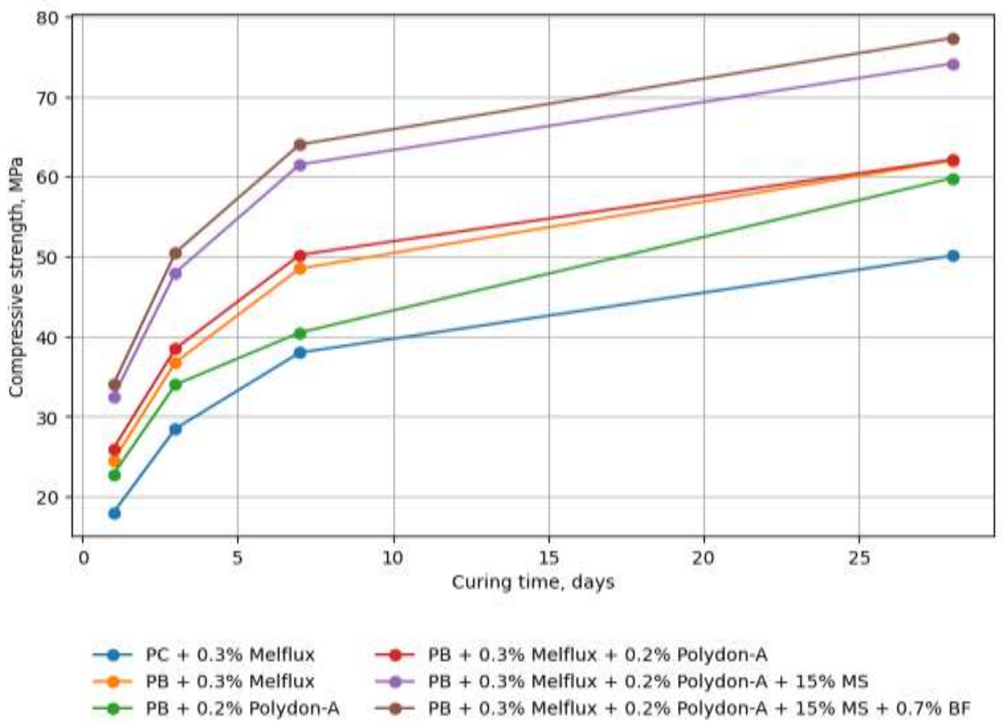


Fig. 4 Compressive strength development of modified heavy concrete at different curing ages.

Modified cement stone (composition 6, table 3) has a denser and more uniform fine-pored structure where micropore size is from 0.1 to 0.6 mkm (fig. 2, c); in composition 5 the main range is from 0,5 mkm to 2 mkm (fig.3, b); in the control sample composition 2 (table 3) from 1 to 5 mkm (fig.3, a), with pore presence up to 50 mkm. Positive changes in the proposed composition 6 are due to the combined effect of complex modification (0,3% Melflux+ 0,2% Polydon-A+15%MS), accompanied by a water-reducing effect and the formation of an additional amount of low-basic calcium hydrosilicates. The results of modified cement stone research formed the development basis of the heavy concrete composition with a given set of operational properties.

The positive changes observed in the proposed composition No. 6 are attributed to the combined effect of complex modification (0.3% Melflux + 0.2% Polydon-A + 15% microsilica), which is accompanied by a pronounced water-reducing effect and the formation of an additional amount of low-basic calcium silicate hydrates. The results of studies on the modified cement stone formed the basis for the development of a heavy concrete composition with a predefined set of performance properties.

Table 4 presents the heavy concrete compositions used for subsequent investigations. The research analysis (table 4, fig. 4) of concrete mixes properties showed, that proposed composition reduced the water separation and solution separation rates by 2.1 and 2.2 times compared to the control one. This fact has a positive effect in reducing negative consequences: stratification of concrete mix, settling of large aggregate and reduction of concrete inhomogeneity. The results of modified cement stone research showed the value increase: for compression in composition PB +(0,3% Melflux + 0,2% Polydon-A + 15% MS) by 47.9% relative to the control value (PC + 0,3% Melflux) and by 19.5% relative to the composition (PB +0,3% Melflux), that in absolute terms amounts by 24 and 12 MPa, respectively.

Concrete with basalt fiber has the maximum increase in R_{tb} strength (composition 6). Value R_{tb} increased by 49.1% compared with the control one and by 11.5% compared with composition 5 (without fiber). Based on the results of hydrophysical tests of modified concrete (composition 6, table 5) it is clear that: water consumption decreased by 57.8%; water resistance grade increased by 4 stages of emerging compared with the control one. The results of freezing resistance tests showed: maximum weight reduction to 6.32% and cubic strength by 26% in the control composition 1 after 400 test cycles, that exceeds the established indicators of GOST 10060-2012 requirements; high freezing resistance of compositions, containing a complex modifier. After 600 test cycles the weight loss in compositions 5 and 6 was 1.8% and 1.5% when strength decreases by 10.2% and 9.1% respectively, that confirms a sufficient margin of safety and freezing resistance.

5. CONCLUSION

1. The enhanced strength and performance characteristics of the developed heavy concrete are attributed to the synergistic action of the polydisperse binder, the complex chemical–mineral modifier, and basalt fiber, which collectively ensure densification of the cement stone structure and an increase in its durability. The polydisperse binder composition promotes dense particle packing, reducing capillary porosity and providing a uniform distribution of hydration products. It exhibits a water-reducing effect, decreases segregation of the concrete mixture, reduces permeability, increases strength, and lowers shrinkage and creep of the hardened concrete. Microsilica, acting as both a microfiller and a pozzolanic component, contributes to an increase in the density and strength of the cement stone and the concrete based on it, as well as to improved resistance to corrosion of type I (leaching) by binding portlandite $Ca(OH)_2$ into water-insoluble low-basic calcium silicate hydrates. The water-soluble polymer admixture Polydon-A is used to modify the pore structure of the cement stone, thereby enhancing its impermeability and corrosion resistance.

2. The creation of a high-density heavy concrete structure that rationally combines the necessary technological and operational characteristics was substantiated and experimentally proved by optimizing the composition of cement binders of various dispersion with a complex modifier (superplasticizer + polymer + microsilica) = basalt fiber. Modified concrete has the following properties: compressive strength – 77.3 MPa; ultimate tensile strength in bending – 8.62 MPa; water consumption – 1.9%; water resistance class – W14; freezing resistance $F_1 = 600$, increased resistance to aggressive environment.

3. Prospects and recommendations for further research development consist of improving the composition of modified heavy concrete based on a polydisperse binder with a complex modifier by searching for new types of modifiers and micro-reinforcing fillers in order to reduce production costs as well as the study of its potential application in hydraulic structures located in the variable water level zone.

The prospects and recommendations for further development involve improving the composition of the modified heavy concrete based on a polydisperse binder with a complex modifier by exploring new types of modifiers and micro-reinforcing fillers aimed at reducing production costs, as well as investigating the potential for its application in hydraulic structures exposed to variable water levels.

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