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The physical and mechanical properties of concrete with multifunctional additive

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ABSTRACT

Introduction. It is known that concrete is the main building material, despite the introduction of new technologies. The combination of strength and durability makes this material indispensable for the construction of civil and industrial infrastructure. However, the impact of aggressive external factors on concrete structures, such as an acidic or alkaline environment, temperature fluctuations, and the presence of water at low temperatures, can lead to a significant decrease in their strength characteristics. The introduction of various additives based on organic and inorganic compounds into the composition of concrete allows for the regulation of its performance properties and protect concrete structures from the negative impact of the environment. Therefore, research works aimed at improving physical and mechanical properties and quality of concrete structures are relevant. **Methods and materials.** The objects of our research were concrete samples, prepared with and without the use of a multifunctional additive called "Betomix-ITH Gel", which was developed by the researchers of the Institute of Theoretical and Applied Mechanics of the Ural Branch of the Russian Academy of Sciences (ITC UB RAS). The physical and chemical properties of the compared samples were studied in accordance with Russian and interstate regulatory documents in accredited laboratories of the Russian Federation and the Republic of Turkey. **Results and discussion.** As a result of the research, we have found that the introduction of the multifunctional additive "Betomix-ITH Gel" to the concrete mixture significantly increases the water resistance, frost resistance, and strength of concrete samples, compared to samples without the additive. It has been shown that Betomix-ITH Gel imparts the property of "self-healing" to concrete, with cracks up to 0.5 mm in size, and increases the resistance of steel reinforcement to corrosion. **Conclusion.** The research has proved experimentally the effectiveness of the Betomix-ITH Gel additive for improving the quality characteristics for concrete of various classes, which allows the use of this additive in concrete mixtures in the construction of reinforced concrete structures located in aggressive conditions.

KEYWORDS: concrete, concrete additive, waterproofness, self-healing, compressive strength.

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INTRODUCTION

Concrete is remained to be the main material of civil and industrial structures construction for today. However, the high concrete hydrophilic property negatively affects the strength characteristics and can lead to the destructive processes. The problem of concrete protection is especially acute during the direct contact with water or aggressive environments, including sulfate soils; in this cases water penetrates into the concrete body through the capillary-porous structure [1–8].

Achievement of concrete high performance characteristics is possible in the traditional way, by utilization of increased cement content in the concrete mixture alongside the surface types of waterproofing utilization, or by more effective way – introduction of active functional additives, which can increase the performance properties of the whole structure, into the concrete mixture at the stage of its preparation, [9–15].

The protective properties of such multifunctional additives are often based on the ability to react with concrete components even at the stages of mixing and hardening in the presence of an aqueous medium [16–21]. This interaction can cause the appearance of new spatial structures, such as crystallohydrates, which, during the growth process, bind surrounding water and increase in volume providing pore blocking and concrete voids clogging. As a rule, these compounds do not change their composition [20–24] and exhibit stability in acidic and alkaline environments, and most importantly, they are able to suppress the recrystallization of ettringite – the main cause of concrete sulfate corrosion. Thus, this type of waterproofing provides high protection of concrete for its entire service life. Investigation of such multifunctional additives effect on concrete samples is an urgent objective.

METHODS AND MATERIALS

Accredited Russian and foreign laboratories tested concrete mixture compositions with and without the "Betomix-ITH Gel" additive to determine the technological properties of the concrete mixture and concrete physical and mechanical characteristics.

The concrete additive "Betomix-ITH Gel" is manufactured in accordance with TS 5745-047-04740886-2013 and contains a mixture of water-soluble polymers and surfactants with a water-reducing effect. Consumption of the additive "Betomix-ITH Gel": 1.0% by weight of cement in the concrete mixture. "Betomix-ITH Gel" is compatible with antifreeze, plasticizing and other additives.

In Russian laboratories, the compressive strength of concrete was determined using cube samples with parameters 100×100×100 mm in accordance with GOST 10180-2012. The frost resistance of concrete was determined using cube samples with parameters 100×100×100 mm in accordance with GOST 10060-2012. Water resistance was determined according to GOST 12730.5-19 on cylindrical samples with a diameter of 150 mm and a height of 150 mm. Tests for the resistance of steel reinforcement to corrosion in aqueous environment was carried out in accordance with GOST 9.908-85. The objects of research were steel reinforcement samples 10 mm long: cold-drawn, low-carbon steel wire for reinforcement of RCS, diameter 4 mm according to GOST 6727-80; products 6-A240 st3sp according to GOST 5781-82; products 10-A500S according to GOST 52544-2006. The compositions of concrete samples are given in Table 1.

The DSI laboratory of the State Department of Technical Research and Quality Control of Hydraulic Structures of Turkey, Ankara, carried out compressive strength tests in accordance with the TS EN 12390-3 on cube-shaped samples with parameters 150×150×150 mm. The samples were cured in water at a temperature of 20±2 °C for 7, 28 and 56 days. The water resistance of the samples was determined by water depth penetration under pressure according to the TS EN 12390-8. Cube samples with parameters 150×150×150 mm were hardened in water at a temperature of 20±2 °C for 7, 28 and 56 days. Then the samples were dried at a temperature of 20±2 °C and humidity 50±5% for 7 days. The compositions of the samples are presented in Table 2.

RESULTS AND DISCUSSION

Tests by the Russian laboratories "ITC UB RAS" and LLC "IL Orgtekhstroy", Perm.

During the tests, concrete compositions with and without the addition of "Betomix-ITH Gel" additives were used. The properties of concrete mixtures are shown in Table 3.

Density growth and entrained air volume decrease is observed in samples with the "Betomix-ITH Gel" additive.

Table 4 presents the results of concrete samples strength tests.

A slight strength increase of samples with "Betomix-ITH Gel" additive is observed.

Addition of a well-known plasticizer Poliplast SP-4 (GC "Poliplast" Group of Companies, Russia) to the

Table 1
Composition of concrete per 1 m³ of concrete mixture (for dry aggregates)

Material	Material consumption per 1 m³, kg	
	Composition without additives	Composition with «Betomix-ITH Gel»
Cement CEM I 42.5 N	255	255
Natural sand	768	768
Crushed granite fraction 5–20 mm	1152	1152
Additive «Betomix-ITH Gel»	–	2.55
Supply water	178	178
Water-cement ratio	0.70	0.70
r (proportion of sand in aggregate mixture)	0.4	0.4

Table 2

Concrete compositions per 1 m³ of concrete mixture (for dry aggregates) for testing according to international standards

Material	Material consumption per 1 m³, kg					
Марка бетона	C16/20		C20/25		C25/30	
Portland cement CEM II/A-M (V-L) 42.5 R	240	240	330	330	375	375
Additive «Betomix-ITH Gel»		2.40		3.30		3.75
Water	221.2	206.8	241.8	224.6	245.4	227.7
Water-cement ratio	0.85	0.79	0.68	0.64	0.61	0.57
Sand 0–4 mm	995.5	1069.7	976.3	995.2	948.4	967.0
Crushed granite fraction 7–15 mm	419.6	387.9	354.1	360.9	343.9	350.7
Crushed granite fraction 16–22 mm	476.4	465.2	425.0	432.7	412.4	420.5

Table 3

Results of concrete mixture properties tests

Parameter	Parameter value	
	Composition without additives	Composition with «Betomix-ITH Gel»
Cone slump test, cm	15	15
Average density, kg/m³	2384	2398
Entrained air volume, %	1.7	1.5

concrete mixture together with "Betomix-ITH Gel", a synergistic effect is observed. The samples were hardened for 7 and 30 days under normal conditions at a temperature of (20±2) °C and relative air humidity (95±5)%, then in an aqueous environment for another 7 and 28 days. Table 5 presents the compressive strength results of testing samples after 7, 30, 37 and 58 days.

A significant strength increase of samples with the "Betomix-ITH Gel" additive is observed. A particularly impressive increase (32.8%) appears after the samples were cured in water for 28 days.

Concrete samples frost resistance results are presented in Table 6.

Table 4

Results of concrete samples compressive strength tests

Age, days	Curing conditions	Average compressive strength of samples, MPa		Strength growth, %
		Composition without additives	Composition with «Betomix-ITH Gel»	
3	Normal	14.3	14.4	0.7
7	Normal	19.2	19.3	0.5
28	Normal	25.9	26.2	1.16

Table 5

Samples tests for compressive strength results

Age, days	Curing conditions	Average compressive strength of samples, MPa		Strength growth, %
		«Poliplast SP-4» (1,7%)	«Poliplast SP-4» (1,5%) and «Betomix-ITH Gel» (1%)	
7	Normal	30.45	39.1	22.1
30	Normal e	39.0	46.1	15.4
37	30 days normal, 7 days in water	34.1	43.4	21.4
58	30 days normal, 28 days in water	33.8	50.3	32.8

Table 6
Concrete samples control tests results for frost resistance

«Betomix-ITH Gel» additive	Concrete reference samples		Main concrete samples after 3 freeze-thaw cycles at –50 °C (F1100)				
	X_{cp}' Average strength of concrete, MPa	X_{min}' Lower limit of the confidence span (with coefficient 0.9), MPa	Average weight of saturated samples, g		Change in sample weight, %	X_{cp}'' Average strength of concrete after testing, MPa	X_{min}'' Lower limit of the confidence interval, MPa
			Before testing	After testing			
Without additive	25.8	20.7	2416	2395	–0.87	25.7	22.5
	Standard deviation – 1.10; strength variation coefficient – 4.30%		Standard deviation – 1.30; strength variation coefficient – 4.90%				
With additive	26.6	21.2	2424	2417	–0.29	26.8	23.2
	Standard deviation – 1,20; strength variation coefficient – 4,60%		Standard deviation – 1.40; strength variation coefficient – 5.20%				

The lower limit of the confidence span for the concrete strength of the control samples, taking into account the coefficient of 0.9, is 20.7 MPa (without additive) and 21.2 MPa (with "Betomix-ITH Gel"). The lower limit of the confidence span for the concrete strength of the main samples is 22.5 MPa (without additive) and 23.2 MPa (with Betomix-ITH Gel). This observation corresponds to the ratio $X_{min}'' \geqslant 0.9\,X_{min}'$ (22.5 > 20.7 without additive; 23.2 > 21.2 with "Betomix-ITH Gel"). All samples were tested 3 cycles using the third (accelerated) method without cracks, chips or peeling of ribs, which corresponds to the design frost resistance grade F1100. Samples with "Betomix-ITH Gel" additive showed better results compared to samples without the additive.

The water resistance of concrete samples was also determined with the "wet spot" method. According to GOST 12730.5-2018, the water resistance of a samples series using this method is determined by the maximum water pressure at which no water percolation is observed on at least four out of six samples. The results are presented in Table 7.

The water resistance grade increase in the composition with the use of the "Betomix-ITH Gel" additive by 4 levels compared to the concrete composition

The resistance of steel reinforcement to corrosion in aqueous environments was carried out. Standard samples of reinforcement were kept for 10 days in aqueous media of the following composition:

1. Tap water, pH 7.
2. "Betomix-ITH Gel" additive, pH 9.9.
3. A mixture of Portland cement class 42.5, normal hardening CEM I 42.5 N GOST 31108-2016 with tap water in the ratio: 1/2.5, pH 11.5.
4. A mixture of Portland cement class 42.5, normal hardening CEM I 42.5 N GOST 31108-2016 with tap

Table 7
Water resistance tests results with the "wet spot" method

Water percolation through the sample		Concrete samples, pcs.	
Pressure, MPa	Stage	Composition without additive	Composition with «Betomix-ITH Gel» additive
0.2	I	0	0
0.4	II	0	0
0.6	III	0	0
0.8	IV	3	0
1.0	V	–	0
1.2	IV	–	0
1.4	IIV	–	1
1.6	IIIV	–	2
Water permeability grade		W6	W14

water in the ratio: 1/2.5 with the addition of 1% Betomix-ITH Gel additive by weight of cement, pH 11.4.

The research results revealed that in environment No. 1 corrosion is active on all reinforcement samples. In environments No. 2 - 4, no corrosion of the reinforcement was detected. At a pH = 9—12, steel passivation occurs. Thus, the introduction of the Betomix-ITH Gel additive into the concrete solution preserves the stable-passive corrosion state of steel reinforcement.

Tests by DSI laboratory, Ankara, Turkey.

Concrete testing laboratory researchers of the State Department of Technical Research and Quality Control of Hydraulic Structures of Turkey also carried out series of tests of the Betomix-ITH Gel additive according to interstate standards. In this system, the strength class of concrete is designated as ... C16/20, C20/25, C25/30... and corresponds to the concrete class ... B20, B25, B30..., according to the Belarusian regulatory document CSRB 5.03.01-02 “Concrete and reinforced concrete structures” (National complex of normative and technical documents in construction. Construction Standards of the Republic of Belarus). Application of such designations is connected with the fact that several European countries use a cylinder with a height twice bigger than the diameter to test the compressive strength of concrete. The performance of cylinder samples will differ from cube-shaped specimens.

Samples were prepared with the compositions presented in Table 2. Investigation results of concrete mixtures technological parameters are presented in Table 8.

In with the Betomix-ITH Gel additive, an in

Density growth and mobility decrease of concrete mixture samples with the “Betomix-ITH Gel” additive were observed compared to samples without the additive. Compressive strength tests are presented in Table 9.

Strength increase of samples using the “Betomix-ITH Gel” additive is observed. Results of strength increase during the samples hardening in water are much higher than during hardening in air since conditions play a significant role on the strength of concrete structures. Class C25/30 (B30) strength gain decrease is probably associated with the initial high strength of this class; the higher class of concrete is, the more difficult is to improve its strength by additives.

The water resistance of the samples was also determined by the depth of of water under pressure penetration. The test results are presented in Table 10.

Waterproof grade W was classified according to GOST 12730.5-2018. Since the correlation of different methods is not accurate in terms of particularly low water resistance, it is difficult to judge the number of steps by which the grade of concrete has been increased, especially for classes C20/25, C25/30. Water resistance increase of class C16/20 concrete with the “Betomix-ITH Gel” additive for at least 2 levels was observed.

In article [25], an attempt was made was performed to independently establish the assignment of water resistance grade according to GOST 12730.5-2018 and according to EN 12390-8. The mentioned data showed that waterproof

Table 8
Technological properties of the concrete mixture tests results

Parameter	Parameter value					
	Composition without additive			Composition with «Betomix-ITH Gel» additive		
Concrete grade	C16/20	C20/25	C25/30	C16/20	C20/25	C25/30
Average density, kg/m^3	2352.7	2373.2	2326.7	2348.4	2325.0	2346.4
Entrained air volume, %	2~3	2~3	2~3	2~3	2~3	2~3
Cone slump test, cm	8	6	14	8	13	9

Table 9
Test results of compressive strength according to TS EN 12390-3

Age, days	Concrete grade	Average compressive strength of samples, MPa		Strength growth, %
		Composition without additive	Composition with «Betomix-ITH Gel» additive	
7	C16/20	12.2	14.1	15.57
28	C16/20	17.8	20.1	12.92
56	C16/20	20.1	23.4	16.42
56	C20/25	27.2	34.6	27.20
56	C25/30	32.3	36.1	11.76

Table 10

Results of water resistance tests by the depth of water under pressure penetration according to the TS EN 12390-8

Concrete grade	Age, days	«Betomix-ITH Gel» additive presence	Average maximum water penetration depth, mm	Waterproof grade W
C16/20	7	–	126	6
		With additive	109	6
	28	–	87	6
		With additive	32	10–14
	56	–	72	6
		With additive	29	10–14
C20/25	56	–	27	10–14
		With additive	20	16–20
C25/30	56	–	32	10–14
		With additive	19	16–20

grade for concrete with the "Betomix-ITH Gel" additive also increased by at least two levels.

Taking in account the research data from Russian laboratories, compositions using the "Betomix-ITH Gel" additive unconditionally show a significant water resistance increase. This water resistance increase allows the use of weakly sulfate-resistant Portland cements group with the "Betomix-ITH Gel" additive in aggressive soils containing sulfates, according to SP 28.13330.2017.

In addition to physical and mechanical tests, a visual assessment of the regeneration of previously destroyed concrete samples of various classes containing the "Betomix-ITH Gel" additive was carried out by optical microscopy method. Hardening of the samples occurred in water at a temperature of 20±2 °C for 7 and 56 days and then the samples were dried at a temperature of 20±2 °C, humidity 50±5% for 7 days. After that the samples were mechanically destroyed and stored in water for 26–31 days. Microphotographs of the samples were taken before immersion in water and after 26–31 days in water (Figures 1–4).

The microphotographs (Figures 1–4) reveal that after a storage of previously destroyed concrete samples with "Betomix-ITH Gel" additive in water during the month, the cracks self-healed and became clogged with needle-shaped crystals. This property of concrete allows increasing concrete products service life, since needle-shaped crystals can prevent the diffusion of water drops through pores and microcracks inside the concrete, thereby improving the characteristics of concrete in terms of water resistance and frost resistance. After the concrete dries, unreacted functional chemical additives remain in the pores of the concrete. In cases where a new source of water appears, additives are able to pass into a saturated brine solution and form additional needle-like structures (Fig. 5), giving the concrete a "self-healing" property.

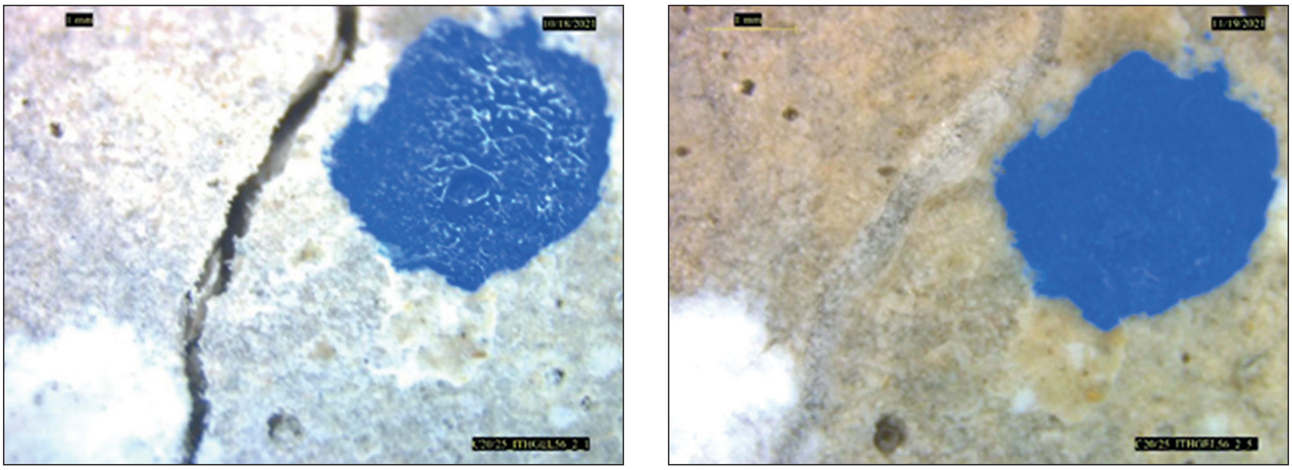

Fig. 1. **Concrete sample microphotograph of C20/25BG (additive "Betomix-ITH Gel", 56 days of hardening) after mechanical destruction and exposure to water for 31 days**

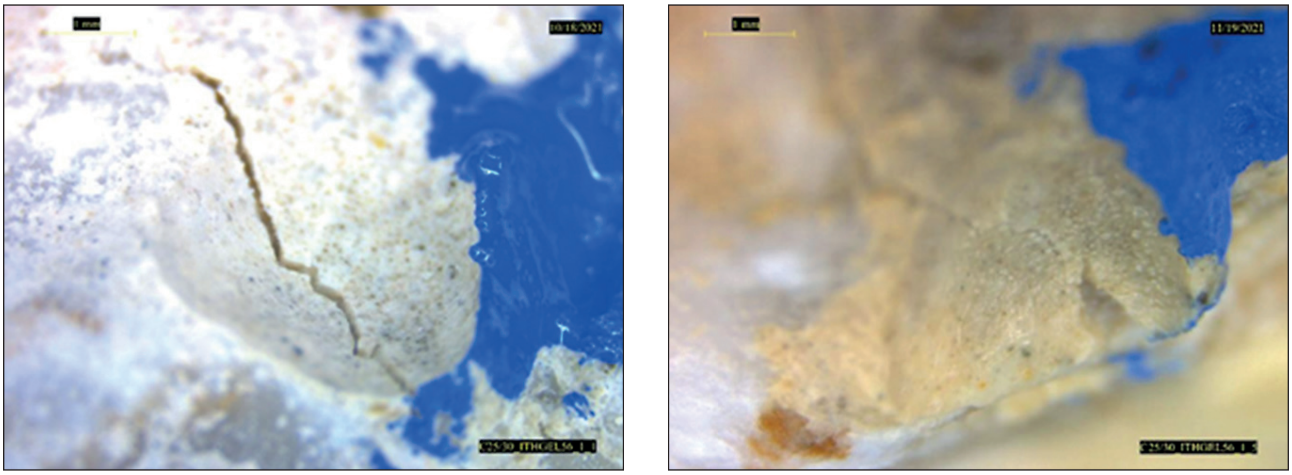

Fig. 2. **Concrete sample microphotograph of C25/30BG (additive "Betomix-ITH Gel", 56 days of hardening) after mechanical destruction and exposure to water for 31 days**

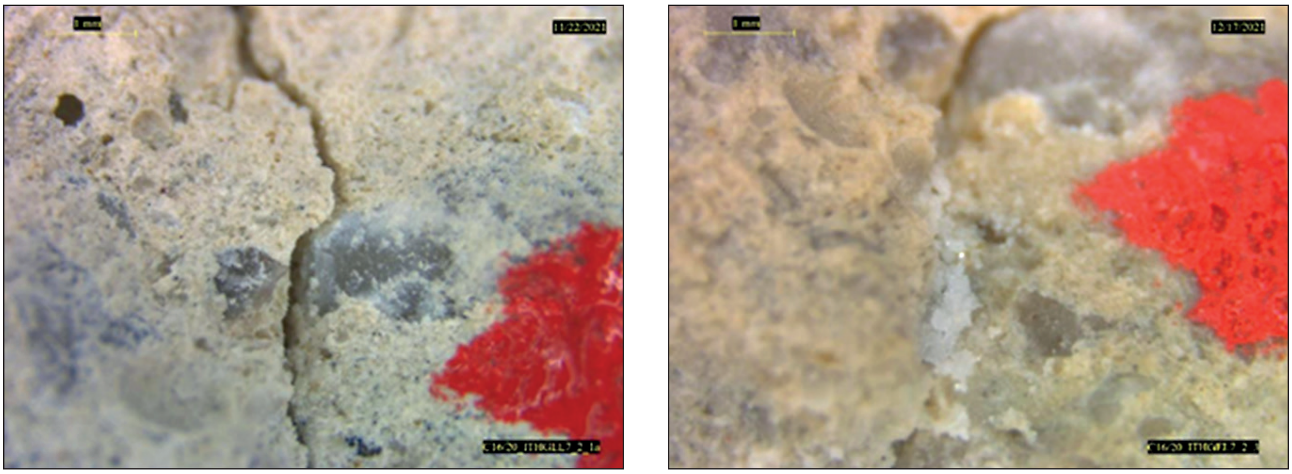

Fig. 3. **Concrete sample microphotograph of C16/20BG (additive "Betomix-ITH Gel", 7 days of hardening) after mechanical destruction and exposure to water for 26 days**

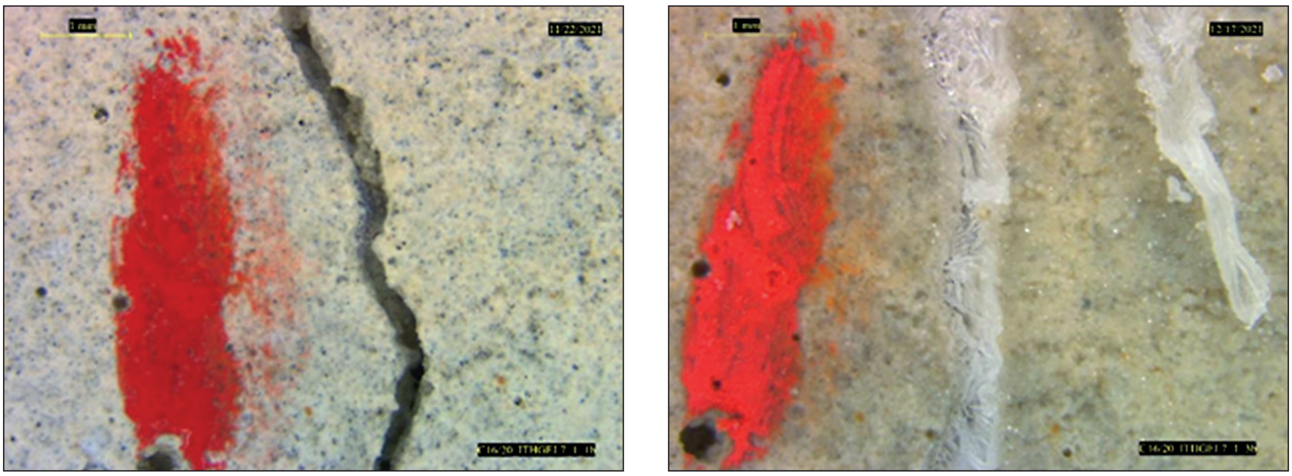

Fig. 4. **Concrete sample microphotograph of C16/20BG (additive "Betomix-ITH Gel", 7 days of hardening) after mechanical destruction and exposure to water for 26 days**

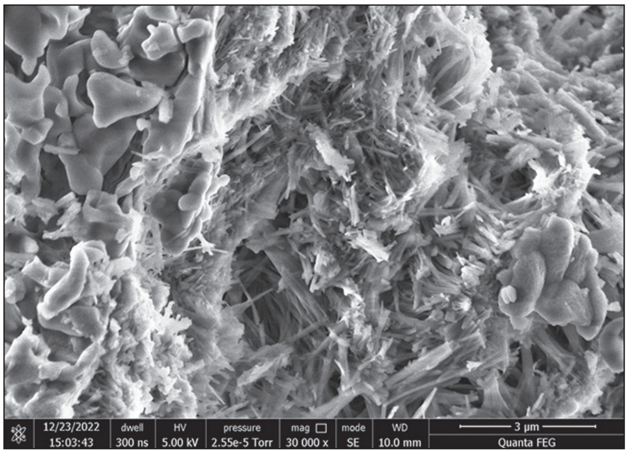

Fig. 5. **Formation of a needle-like structure of the multifunctional additive "Betomix-ITH Gel", magnification ×30000**

CONCLUSION

Current research established:

1. Introduction of the "Betomix-ITH Gel" additive provided density increase and a mobility decrease of the concrete mixture.

2. The addition of "Betomix-ITH Gel" leads to the strength of concrete increase, especially in water environment.

3. The introduction of the "Betomix-ITH Gel" into the concrete solution preserves the stable-passive corrosion state of steel reinforcement.

4. The water resistance of concrete with the "Betomix-ITH Gel" additive increases by 2–4 levels, which allows the use of weakly sulfate-resistant Portland cements group in aggressive soils containing sulfates.

5. "Betomix-ITH Gel" additive gives concrete the "self-healing" property.

Thus, concretes with the "Betomix-ITH Gel" additive showed, among other improved qualities, a noticeable water resistance growth by at least 2 grades. For some classes of concrete the water resistance increase occurred by 4 grades. Such results make it possible to utilize the additive in the construction of a wide range of civil and industrial facilities, as well as to use a group of weakly sulfate-resistant Portland cements in soils containing sulfates. An exceptional property of "Betomix-ITH Gel" was also discovered - the ability of cracks to "self-heal". This means that this additive can also be used to obtain leak-proof "cold" joints in concrete. In addition, the introduction of a plasticizing additive based on naphthalene sulfonic acid into the concrete mixture together with "Betomix-ITH Gel" promotes a synergistic effect and a significant compressive strength increase of concrete samples revealing wide opportunities for "Betomix-ITH Gel" additive with other plasticizing additives combination.

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N. B. Kondrashova – original text writing; drawing up final conclusions; article text correction.

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