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Increasing Impact Endurance of Fiber Concrete

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***Abstract*—The study covers the optimization of physical and mechanical properties and operational characteristics of fiber concrete that include complex influence of a binding agent on structure formation. The optimal composition of concrete ensuring the maximum static and dynamic strength was selected (impact endurance increases 6 times). It was revealed that the concrete with minor defects, high packing density, high filler-cement stone adhesion ratio, increased ratio of static tensile strength against static compression strength R_t/R_{com} and plasticity is characterized by the best resistance to dynamic loads. The penetration test on reinforced and fiber concrete plates showed that unreinforced concrete samples were completely destroyed while fiber concrete samples demonstrated their through penetration under the striker load.**

Keywords*—fiber concrete, composite binding agent, structure formation, cement stone, dynamic loads

I. Introduction

The protection of human life in the modern world with its natural and technogenic disasters shall be ensured through the optimization of the “person-material-habitat” system due to continuous improvement of construction materials for protective structures. With regard to the fact that large-tonnage cement production exerts a detrimental impact on human environment, there is a need to minimize its application. Thus, the concrete efficiency shall be improved due to composite binding agents (CBA).

There are several technological solutions to the increase of concrete impact endurance. One of them is increase of concrete static strength, which is used in many foreign countries. It is based on the use of high-grade cements, graded aggregates and superplasticizing agents. Another direction is the modification technology of concrete structure through the introduction of low hard porous disperse components (damping additives) into the concrete mix. This approach to the increase of concrete impact endurance was studied by R. Oyguc [1], M. Kristoffersen [2], A. Maazoun [3], Z.I. Syed [4], K. Makita [5], etc. However, such concretes ensure quite modest increase of impact endurance – up to 2-4 times, which is not sufficient for protective structures under the influence of destruction weapons creating high dynamic loads on enclosure facilities.

The use of fiber concrete with high shock resistance in the production of protective structures of enclosure facilities seems quite promising (V.S. Lesovik [6], A. Abrishambaf [7], D.-Y. Yoo [8-10], N. Ranjbar [11-12]). Dispersed reinforcement provides for considerable increase of all physical-mechanical characteristics of concrete, such as static strength, crack resistance, shock resistance [5].

However, not enough studies are devoted to the application of new types of nanodispersed mineral additives, as well as their compatibility to ensure the required operational characteristics of CBA. In particular, the impact endurance of various composites was almost not studied.

To ensure the widespread application of CBA in construction there is a need to study mixes containing portland cement and multicomponent fine-grained and organic additives that ensure the required properties of binding and composite agents for protective structures.

Thus, the purpose of the study was to create composite binding agents for concrete with high shock resistance.

For this purpose, composite binding agents obtained through joint mixing of the following components were created: 52-59% of cement, 30-32% of rice-husk ash (RHA), 5-7% of quartz sand, 6-8% of limestone crushing dust, 2-4% of superplasticizer (SP). Water was added in the amount necessary to ensure similar mobility, but at the rate of water binding ratio of not higher than 0.25. The cement stone was studied at the age of 1, 3, 7, 28 days.

II. Methods and materials

This section contains the description of materials and methods used in this paper. Standard methods were used to analyze the qualitative and quantitative structure and properties of initial materials, composite binding agents and concrete samples. Morphological features of a microstructure were studied via the Carl Zeiss CrossBeam 1540XB scanning electron microscope. The mineral content and structure were studied via the X-ray phase analysis using the D8 Advance X-ray powder diffractometer by Bruker AXS. Sample thermograms were obtained via the Shimadzu DTG-60H thermogravimetric analyzer.

The laser granulometry, which was used to determine the particle size distribution of powdery materials, allows defining the particle size and their content in the analyzed material. The laser light scattering particle size analyzer Analizette 22, NanoTek model (Germany) was used for these purposes.

The specific surface of binding agents and used mineral additives was measured according to GOST 310.2-76 via the PSH-11 device operating on the principle of air permeability through the layer of previously compacted material.

The compression strength under static loading (cube strength) was defined according to GOST 310.4-81. The prismatic strength and the modulus of elasticity were defined according to GOST 24452-80. The study was conducted on cubes with the edge of 150 mm and prisms with the basis of 100x100 mm and height of 400 mm.

The modulus of elasticity was defined for each sample at the loading level of 30% of the rupture load, according to the following formula:

$$E_\sigma = \frac{\sigma_1}{\varepsilon_{1y}}$$

where σ_1 – stress increment from the reference datum to external load of 30% of the rupture load; ε_{1y} – increment of elasto- instantaneous unit extension of a sample corresponding to load level $P_1=0.3P_t$ and measured at the beginning of each step of its application; P_t – rupture load measured by the press weighting device (machine); P_1 – corresponding increment of external load.

Two series of tests were carried out to study the impact endurance: on panels and on cylinders. The panels of 600x600x50 mm in size were taken from a mold in 24 h after casting and were kept in the laboratory until testing. The shock capacity of panels was tested on the 28th day.

$$E_{уд} = mghN$$

where $E_{уд}$ – impact energy, J; m – striker mass = 10 kg; g = 9.81 m/c^2; N – number of shocks.

The ratio of the number of shocks causing refusal (N_f) to the number of shocks causing the first crack (N_c) is the coefficient of impact strength $\mu_i = N_f / N_c$. The crack width of the entire fiber concrete panel was measured via the Dino-Lite AM3713TB microscope right after the first crack alongside with the study of crack growth.

III. Results

This section contains the results obtained in the study. At the first stage, the almost linear dependence of the required CBA mixing time to get various specific surface in the range from 280 to 900 m^2/kg was defined (Fig. 1, *a*). It is clear that these data may be used to forecast the required milling time to achieve a certain surface area. After milling of CBA components and measuring the surface area, water was added and the compression strength was measured after 28 days. The results are shown in Fig. 1, *b*. It is seen that the maximum compression strength was obtained at the surface area from 550 to 600 m^2/kg. The increase in surface area does not lead to further increase in strength, or to its reduction. It is caused by excessive number of fine particles since the limit of the superplasticizing agent was reached as was studied earlier [13]. Such behavior was also typical for the change of compound viscosity when the surface area of particles exceeded 600 m^2/kg. It is expected that the increase of the content of superplasticizing agent will lead to concrete with higher compression strength.

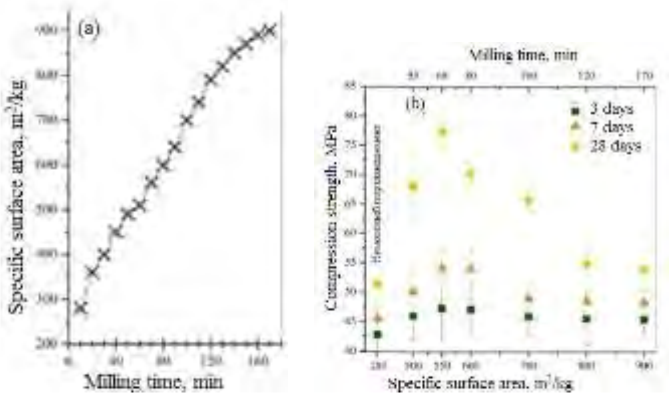

Fig. 1. Dependence between compression strength of cement stone samples and CBA specific surface area. Each point represents an average out of six measurements.

The microstructural analysis showed that the plain cement stone is characterized by the matrix with many voids and microcracks, the majority of which represent dyscrystalline and X-ray amorphous newgrowths, against the background of which one can see hexagonal portlandite plates (Fig. 2, *a, c*). The application of the developed composite binding agent allows compacting the microstructure, receiving clearly visible systems of needle- and plate-like newgrowths filling anisometric and isometric voids (Fig. 2, *b, d*). This leads to the formation of a hard matrix with reduced porosit, which, in turn, leads to hardening of a cement stone.

The XRF for diffractograms of CBA-based cement stone (Fig. 3) shows reduced intensity of peaks corresponding to clinker minerals: alite with d/n = 3.04; 2.97; 2.78; 2.74; 2.75; 2.61; 2.18; 1.77 Å and belite with d/n = 2.89; 2.67; 2.72; 2.76; 2.75; 2.78; 1.77 Å, which indicates the intensity of hydration when CBA is used. Besides, CBA reduces the intensity of portlandite peaks with d/n = 4.93; 2.63; 1.93 Å.

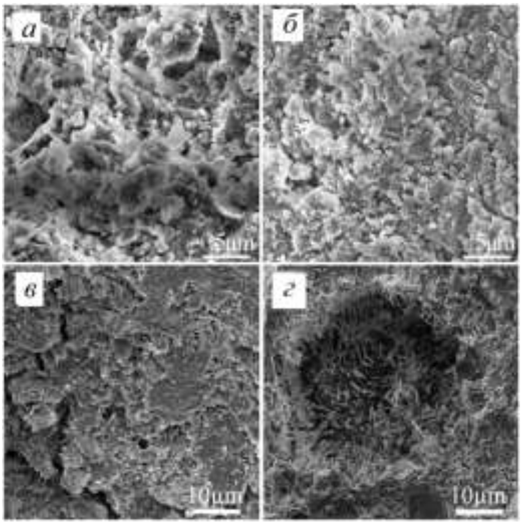

Fig. 2. Microstructure of new growths (28 days): plain cement stone (*a, c*) and CBA-based cement stone (*b, d*)

The differential thermal analysis of plain cement stone and CBA-based cement stone showed the existence of three main endothermic effects (Fig. 4). The first (at approximately 160ºC) is caused by the loss of adsorption water from gel-like hydration products. The decrease of the area of this effect withint the DTA of CBA-based cement stone shows the reduction of gel-like newgrowths due to their transition to crystal state.

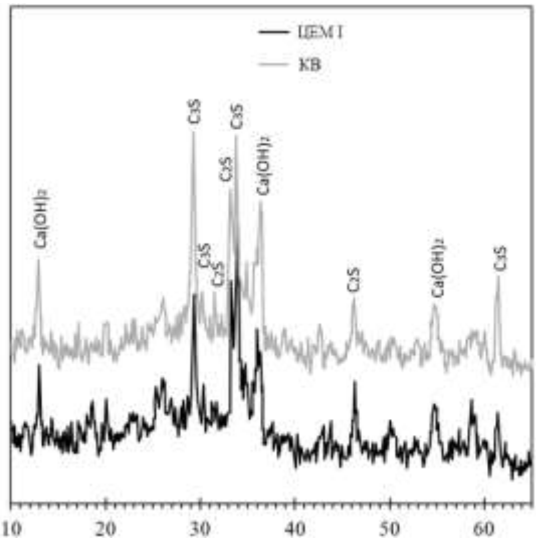

Fig. 3. XRF of newgrowths

The next endothermic effect (at approximately 475ºC) corresponds to calcium hydroxide dehydration. The increase of the area of this peak on a thermogram of a plain cement stone shows higher portlandite content in its structure.

The last endothermic effect (at approximately 525-650ºC) may be caused by the decomposition of calcium carbonate.

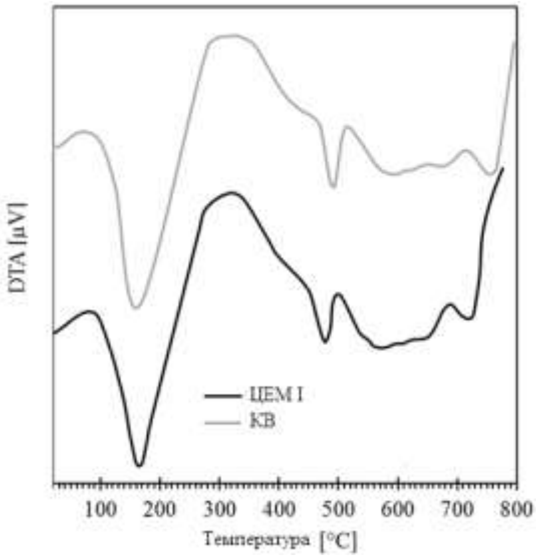

Fig. 4. DTA of plain clean cement stone and CBA-based cement stone

During the initial stage of curing due to the fact that crystalline hydrates occupy insignificant volume, chemical and mineralogical characteristics of additives and their pozzolanic activity almost do not impact the main properties of the binding agent system.

At the second stage of hydration of a composite binding agent the role of chemical processes, which modify the phase structure of a system, increases thus causing a balance shift from primary crystalline hydrates (calcium hydroxide and highly basic calcium silicate hydrates) towards steadier secondary fine-crystalline hydrates presented by low-basic CSH. First of all, the balance shift depends on chemical composition and activity of fine additives. The mandatory requirement of consolidation, and, hence, hardening of a cement stone is the balance shift towards the increase of low-basic CSH (I) calcium hydrosilicates. Apparently, this requirement will be sufficient until the excessive amount of a filler envelops a surface of new phases, thereby preventing the formation of contacts and the intergrowth of crystalline hydrates. Thus, it is possible to draw the conclusion on the optimum volume concentration of ultradispersed additive in the mixed system taking into account its pozzolanic activity. When the inert filler is used, its optimum dosage is defined according to the required for consolidation volume of capillary pores within the material structure.

Thus, it is possible to determine a few positive factors causing the optimization of physical-mechanical properties of cement stones with the application of the developed CBA:

– the rate of composite strength gain during the early period increases thus making the silica-containing components playing a role of the newgrowths crystallization;

– the increase of particle fineness and the concentration of a filler within the volume leads to the reduction of the total porosity of a composite;

– calcium hydrosilicates of the second generation appear as a result of amorphized rice peel ash reaction with $Ca(OH)_2$;

– “binding agent-filler” clusters are formed due to high superficial energy of binding agent particles.

The study of physical-mechanical properties of fine-grained concrete (Tab. I) showed that the composite binding agent provides for the improvement of technical characteristics of concrete in comparison with similar structures made with traditional binding agents. Physical-mechanical properties of fine-grained concrete depending on binding agent composition

TABLE I. PHYSICAL-MECHANICAL PROPERTIES OF FINE-GRAINED CONCRETE DEPENDING ON BINDING AGENT COMPOSITION

Composition	Consumption of materials per 1 m^3				Cubic strength, MPa	Prismatic strength, MPa	Modulus of elasticity, hPa
	Cement, kg	*CBA fillers, kg*	*Aggregate material, kg*	*Water, l*			
1-2	646	508	1020	223	73.6	54.0	41.0
2-2	606	548	1020	231	82.6	65.2	55.3
3-2	565	589	1020	236	75.3	50.3	41.3
CEM I 42.5 H	545	-	1634	218	62.9	41.8	35.2
PC+31% RHA*	376	169	1634	241	71.2	52.3	44.0
PC+3% SP	512	33	1634	182	65.3	49.2	41.2

*- rice-husk ash is crushed to 550 m^2/kg.

This is explained by denser structure of a cement stone based on developed composite binding agent, smaller porosity due to smaller water content in concrete. The 2-2 composition demonstrated the best physical-mechanical characteristics. It shall be noted that with the increase in ash content and the reduction of cement to ensure equal mobility of compositions, it is necessary to increase the amount of water in the concrete mix.

To receive high-density fiber concrete the influence of reinforcing fibers introduced into a concrete matrix was studied. According to Tab. 1, the 2-2 composition was chosen as a basis for concrete matrix.

To establish the optimum rate of fine-grained fiber concrete reinforcement the concrete samples having similar composition (2-2) with various steel and basalt fiber content were molded. Fig. 5 shows the results of the study of dependence of strength properties on reinforcement rate by various dispersed fiber types.

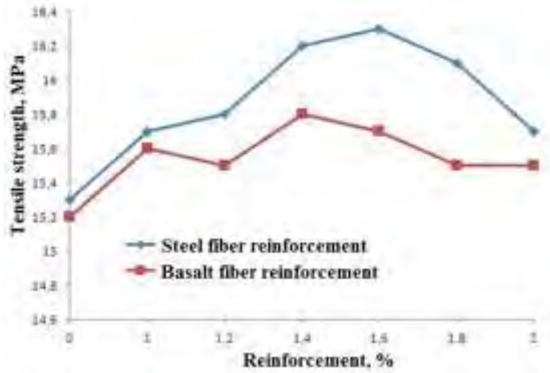

Fig. 5. Dependence of tensile strength of fiber concrete on reinforcement with different fiber types

The study of impact endurance of fiber concrete with different fiber types gave the following results (Fig. 6-7).

Fig. 6-7 show that when steel or basalt fiber is added the concrete strength increases (until the first crack is formed) up to 9 times in comparison with the corresponding mixes without fiber. Both steel and basalt fibers were efficient in preventing the growth of microcracks and reducing the distribution of these cracks until they were connected with further formation of macrocracks.

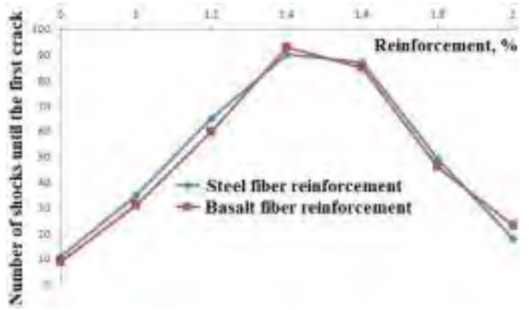

Fig. 6. Dependence of the shock number until the formation of the first crack on fiber volume concentration

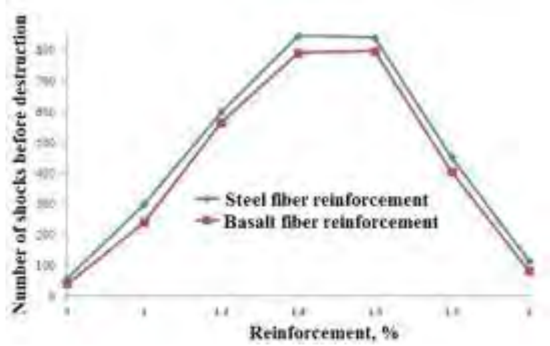

Fig. 7. Dependence of shock number before fiber concrete destruction on fiber volume concentration.

Fig. 8 shows the destructions of samples with and without a fiber. Unreinforced concrete panel was split into four parts after destruction (Fig. 8, *a*). The sample lost its structural integrity and geometry thus reaching the shock energy capacity. The destruction of a fiber concrete plate (Fig. 8, *b*) was caused by the perforation of panels with the falling striker, and the sample was not broken into pieces unlike simple concrete panels. Such behavior showed that fiber concrete panels remained structurally integrated and viscous. Fig. 8, *b* shows a considerable amount of secondary cracks.

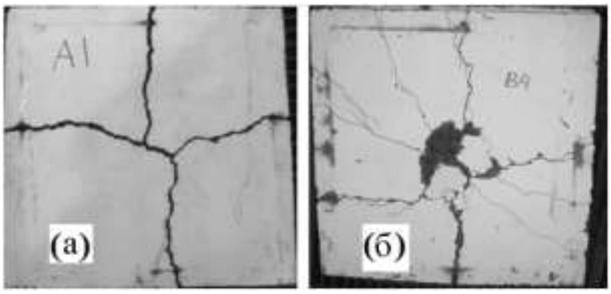

Fig. 8. Destruction of samples without (a) and with (b) fiber.

Dynamic loads are characterized by continuous change of parameters, high intensity and small duration. The impact or dynamic strength depends on initial defects in concrete structure more than the static strength due to impossibility of tension redistribution caused by the delay of microplastic deformations. When influencing the structure formation, the fiber ensures the decrease of internal tension and the reduction of centers of internal defects of concrete and their size thus preventing their further development. The study of various compositions of fiber concrete on impact endurance were further conducted. It is revealed that the 2-2 composition is able to withstand the greatest number of shocks. Despite the fact that the 1-2 sample showed the greatest impact strength, the given parameter cannot be considered ultimate in the design of protective structures since the number of shocks until the first crack and the number of shocks before sample destruction showed poor results (Tab. II).

TABLE II. IMPACT ENDURANCE OF FIBER CONCRETE DEPENDING ON BINDING AGENT COMPOSITION (REINFORCEMENT OF 1.4% STEEL FIBER)

Composition (marking according to Tab. 1)	Number of shocks until the first crack	Impact energy (first crack), J	Number of shocks before sample destruction	Impact energy (sample destruction), J	Impact viscosity coefficient, μ
1-2	6	354	198	11682	33
2-2	9	531	242	14278	27
3-2	8	472	191	11269	24
CEM I 42.5 H	1	59	6	354	5
PC+31% RHA*	1	59	15	885	15
PC+3% SP	3	177	51	3009	17

Tab. 3 shows the crack width and the number of secondary cracks before destruction of the panel. The initial crack width was used for comparison to define the efficiency of steel fiber in bridging microcracks within fiber concrete.

TABLE I. STUDY OF CRACK FORMATION DURING SAMPLE DESTRUCTION

Composition (marking according to Tab. 1)	Growth of the first crack, mm	Crack growth before sample destruction, mm	Number of secondary cracks
1-2	0.132	1.789	13
2-2	0.095	1.876	18
3-2	0.187	1.843	14
CEM I 42.5 H	0.234	1.112	7
PC+31% RHA*	0.187	1.160	10
PC+3% SP	0.197	1.324	12

The influence of a fiber bridge defines the impact energy absorption after the beginning of crack formation and, hence, the impact plasticity of concrete. Tab. 2 shows the impact viscosity coefficient μ_i expressed as the ratio between final and initial impact energies demonstrating good plasticity of concrete subject to impact loads. It is clear that the final impact energy (before destruction) is much higher than the energy used for the first crack. Even after the first cracks are formed a sample could withstand a large number of loads before its destruction. The final impact energy (before destruction) exceeded the published results for high-strength concrete [14-21]. It means that the developed fiber concretes have high impact strength and excellent potential for use as construction materials for protective structures.

IV. CONCLUSIONS

1. The paper suggests the principles of increasing the efficiency of fiber concrete that entails complex influence of the composite binding agent on structure formation of a cement stone. Besides, the strength with static compression of fiber concrete increases by 31% and impact endurance – up to 6 times.

2. It was revealed that the concrete with minor defects, high packing density, high filler-cement stone adhesion ratio, increased ratio of static tensile strength against static compression strength R_t/R_{com} and plasticity is characterized by the best resistance to dynamic loads. This ratio can be further improved if dispersed reinforcement of concrete is applied.

3. The complex analysis of "composition (raw material)-structure (raw material, material)-properties (material)" system serves the methodological framework of the study. The results of the study were obtained through modern research methods with the use of standard techniques to define the composition and properties of input products, binding agents and concretes via the certified and tested equipment of the Far Eastern Federal University and the Institute of Chemistry – FEB RAS.

4. It is established that the CBA consisting of 55.5% of cement, 31% of RHA, 10.5% of inert fillers and 3% of superplasticizer crushed to the relative surface of 550 m^2/kg ensures the optimization of cement stone structure and increase of its ultimate compression strength by more than 60%.

5. Compositions on the basis of certain natural technogenic resources of the Primorsky Krai, which have high adhesion to a cement matrix and similar strain properties, were made.

6. The comparison of fiber concrete test showed that the deformation gain growth results in the increase of both

compression and tension strength. Besides, the careful analysis of experimental data confirmed the compliance of applied methods with main research procedures, and the obtained dependences of the shock number on the deformation rate coincide well in terms of quality and quantity with the results of domestic and foreign studies.

7. The penetration test on reinforced and fiber concrete plates showed that unreinforced concrete samples were completely destroyed while fiber concrete samples demonstrated their through penetration under the striker load.

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