Physical and mechanical properties of hybrid-reinforced decorative concrete

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Abstract. The article presents the results of studies of the influence of alkali-resistant glass fibers of different lengths on the functional properties of decorative concrete. It is based on the data of an experiment carried out according to the optimal unsaturated plan, which includes 27 different compositions of the material. The combinations of the decorative compositions had equal mobility of the mixture, with the minimum and maximum water-cement ratio of 0.36 and 0.55, respectively. Based on the results of the experiment, the primary experimental-statistical models describing the effect of composition factors on the properties of the material made it possible to reveal that an increase in the level of plasticization of the compositions allows to increase the utilization factor of the strength of glass fibers. The efficiency of hybrid reinforcement of decorative composites with glass monofilaments has been confirmed through the implementation of a number of computational experiments (CE). The analysis of the CE results showed that the introduction of hybrid highly dispersed fibers into the initial composition of polystructural decorative concrete, with their different quantitative combinations, makes it possible to improve a number of its functional characteristics and thereby ensure the preservation of the artistic and aesthetic expressiveness of products.

1. Introduction

In recent decades, the construction industry has seen a significant demand for decorative building materials. This is due to the fact that elements and products made from such materials can significantly improve the architectural expressiveness of buildings and structures, the landscape design of adjoining and garden and park areas, while creating a unique variety of the environment [1]. In particular, the use of high-tech decorative materials contributes to obtaining architectural details of various shapes with a high level of detailing and an improved design of the front surface of the material in a broad sense (color, texture, texture, etc.).

However, the effectiveness of using decorative building materials is largely determined by the ability of decorative elements and products to maintain the specified functional properties during the normalized period of operation. In this context, functional properties are understood as a complex of physical and mechanical properties that ensure the preservation of artistic and aesthetic expressiveness under conditions of continuous changes in temperature and humidity under continuous exposure of gaseous and liquid chemically active substances. Such external influences lead to the emergence and development of alternating thermal and moisture deformations, which, taking into account the aggressiveness of the external environment, provoke a decrease in functional properties. One of the
effective methods that cause a redistribution and change in the kinetics of the development of intrinsic and forced volumetric deformations is the use of highly dispersed reinforcement.

2. Analysis of scientific research, the purpose of the work

Decorative concrete, as a polystructural composite material, at all levels of structural inhomogeneities is characterized by the presence of a system of defects of different sizes (cracks, pores, voids, etc.). In the works of A.M. Brant, V.M. Vyrovoy, D.N. Korotkih and others [2-4] it is noted that the consequence of the defectiveness of composites is the localization of deformations and stresses with their concentration at the crack tips. It is known that cracks in the structure of cement composites spread due to the uneven distribution of volumetric deformations and stresses arising even under small internal and external influences, and due to a local excess of the tensile strength of concrete. In this regard, a rational solution to counteract and prevent the propagation of cracks of different sizes is the reinforcement of decorative concrete with hybrid discrete fibers at the micro and macro levels of its structure.

Analysis of scientific and technical literature shows that the type, quantity, geometric parameters and properties of hybrid discrete fibers, their orientation in relation to cracks, affect the change in the properties of building materials, products and structures. In particular, in the production of dispersed-reinforced decorative concretes, for which a high artistic and aesthetic expressiveness of the front surface of products is important, the basic principles of their technology should be taken into account [5]. For example, the type of concrete matrix, the type of dispersed reinforcement, methods of production of architectural products, giving the necessary texture to the front surface of products, etc.

The results of the researchers show that to control larger cracks, discrete fibers of greater length and high mechanical properties should be used, and to control small cracks - flexible and, accordingly, shorter lengths [6]. However, the research of scientists on hybrid concrete reinforcement at different levels of its structure is somewhat different. Thus, the article [7] shows the effect of hybrid steel fibers 50 and 25 mm long, taken in different proportions, on the mechanical properties of concrete. Mohammadi and others noted that the best effect on strength gain is obtained with a long to short fiber ratio of 65 + 35 %, respectively. In turn, the results presented in [8] on the hybridization of concrete with steel and polypropylene fibers demonstrate that steel fibers make the main contribution to the increase in strength, while polymer fibers do not have a significant effect. However, SU Jie and CHI Yin found a synergistic effect between the fibers in terms of deformability and resistance to external influences of the material. However, the experimental-statistical models (ES-model) obtained in our own research on the effect of a system of glass and polypropylene fibers on the strength and crack resistance of fine-grained concrete [9] made it possible to detect a negative synergy of two types of fibers. Therefore, the combination of high-modulus fibers of different lengths, but of the same type, can achieve the desired effect in strengthening the cement matrix of concrete. With regard to the fiber material, the most effective in improving the functional performance of decorative concrete are highly dispersed glass fibers of various lengths. At the same time, the tensile strength of glass monofilaments is slightly higher compared to the strength of hardened concrete. In particular, analysis of numerous works shows the advisability of reinforcing concrete at the micro level with fibers 10 ÷ 30 μm in diameter and less than 10 mm in length, and, accordingly, at the macroscale level – 10 ÷ 60 mm long.

Due to the fact that discrete reinforcing fibers are the initial components, it can be assumed that they are actively involved in organizing the structure of the material and through structural transformations affect the change in the properties of the material itself, as well as products, individual structural and decorative elements and structures. This predetermined the goal of research – increasing the functional properties of decorative items through the targeted use of the effects of multi-site structure formation by introducing hybrid dispersed fibers into the initial composition of polystructural materials.
3. Experimental conditions, functional properties of decorative concrete

Based on the conclusions of materials scientists in the field of research of fine-grained composites and regulatory requirements for the quality criteria of architectural details, when developing compositions of decorative concrete, recipe factors were selected and the ranges of their variation were determined [10].

The experiment was carried out according to the optimal symmetric plan, which includes 27 different compositions. Varying at three dosage levels of 5 components. Depending on the nature of their action on a fine-grained composite, the factors are combined into two groups.

The conditions for modifying the cement-sand system set the amount of finely ground zeolite \( X_1 \) at levels of 0, 4, 8 % (introduced instead of part of the cement from its mass), the proportion of fine quartz sand mixed with coarse \( X_2 \) at levels of 30, 50, 70 % and a polycarboxylate-based superplasticizer from the Melflux series \( X_3 \) at levels of 0.3, 0.5, 0.7% (based on the mass of cement).

The group of dispersed reinforcement factors consisted of alkali-resistant glass fibers with a length of 6 and 12 mm at the levels \( X_4 \) at levels of 0, 4, 8 % (introduced from the mass of the mixture).

The varied factors are normalized to the condition \(-1 \leq x_i \leq 1\) by typical formulas [11].

The fixed components of the decorative composite were the dosages of white Portland cement and quartz sand of natural granulometry, at a ratio of 1:3.4 by mass of the mixture. The compositions of the mortar compositions had equal mobility of the mixture (grade S4), with the minimum and maximum water-cement ratio of 0.36 and 0.55, respectively.

A number of functional indicators of decorative concrete were determined, in particular, the compressive strength \( f_{cm}, \text{MPa} \) and tensile strength in bending \( f_{ctfm}, \text{MPa} \) in equilibrium (index "n"), dry ("d") and water-saturated ("w") states of material, crack- \( K_{ic}, \text{MPa} \cdot \text{m}^{0.5} \) and frost resistance \( F, \text{cycles} \), water absorption by weight \( W_M, \% \). At the same time, to study the indicated properties of the material, in accordance with the experimental plan, samples were made and tested in accordance with the requirements of a number of regulatory documents.

According to the experimental data, a complex of ES-models of the form (1) was built, which describe the fields of functional characteristics \( Y_i \) of decorative concrete in the coordinates of 5 prescription factors \( x_1 + x_3 \) [12-15].

\[
Y_i = b_0 \pm b_1 x_1 \pm b_2 x_2 \pm b_3 x_3 \pm b_{12} x_1 x_2 \pm b_{13} x_1 x_3 \pm b_{23} x_2 x_3 \pm b_{123} x_1 x_2 x_3 \pm b_{4} x_4 \pm b_{5} x_5 \pm b_{45} x_4 x_5 \pm b_{34} x_3 x_4 \pm b_{35} x_3 x_5 \pm b_{54} x_4 x_5 \pm b_{45} x_4 x_5
\]

(1)

Nonlinear ES-model (1) is structured by groups of factors. Block (a) describes the effect of modifiers \( x_1, x_2 \) and \( x_3 \) on the analyzed property \( Y \) of the composite. Block (b) – influence on \( Y \) of dispersed fibers \( x_4 \) and \( x_5 \). Block (c) shows how the local fields of the analyzed property will be transformed due to the relationship between the two groups of composition factors.

In particular, on the basis of mathematical models (1) on the kinetics of strength gain in compression of a composite on days 1, 3, 7, 14 and 28, a number of useful results were obtained on the complex effect of prescription factors on \( f_{cm} \) of decorative concrete. At the same time, it was revealed that an increase in the level of plasticization of the composites to the maximum \( MF \) from 0.3 to 0.7% makes it possible to increase the utilization factor of the strength of glass fibers. This can be explained by the fact that the cement matrix of highly plasticized composites is characterized by apparently lower porosity in the zone of contact with the fiber. Consequently, the importance of the quality of the cement matrix is confirmed when using smaller fibers of two types [2]. Also, as noted in [16], with a properly designed composition with fine ingredients, when the size of the filler particle and the fiber cross-section is less than or equal to the size of the cement grain, it is possible to achieve high
adhesion of the matrix to the fiber and at the same time to obtain a denser microstructure of the material. It should be noted that in the design of decorative concrete compositions, the average particle size of cement and finely ground zeolite ($\bar{Q}_p \approx 15 \mu m$), as well as the cross section of glass fibers ($\bar{Q}_f \approx 14 \mu m$) were taken into account. Therefore, it seems appropriate to analyze the effect of highly dispersed hybrid fibers ($F6 + F12 \to 0.03 \pm 0.06 \%$) on the functional properties of concrete with the maximum level of plasticization ($MF \approx 0.7 \%$).

4. Results of computer modeling of functional properties of dispersed-reinforced decorative concrete

To determine the effectiveness of hybrid reinforcement of decorative composites with glass fibers of different lengths (6 mm and 12 mm), a number of computational experiments (CE) were performed. For the implementation of CE, structured ES-models (1) [17] of the functional properties of concrete ($f_{cm}, f_{ctfm}, K_{ic}, W_M$) were used in the coordinates of normalized factors $x_1 \pm x_5$. At the same time, for the characteristics of frost resistance, a "complete" model of compressive strength ($f_{cm,F}$, MPa), built on the basis of the test results of concrete specimens tested for the declared grade F400, was taken as a basis [14]. Since CE are carried out under the condition of high plasticization ($x_1 = +1$) of decorative composites and the content of hybrid glass fibers at different levels ($x_4 + x_5 \to 0$ and +1) from ES-models of the "full field" for each property [12-15] ($Y_i$), obtained 2-factor models of the form (2).

$$Y_i = b_0 \pm b_{1x_1} \pm b_{1x_1}^2 \pm b_{12x_1x_2}$$
$$\pm b_{2x_2} \pm b_{22x_2}^2$$

Models (2) describe local fields $Y_i$ (figure 1 and figure 2), formed by two factors $x_1 \{Z\}$ and $x_2 \{GS\}$, at $x_3 = \text{const}$, under the influence of dispersed reinforcement factors ($x_4 + x_5$). It should be noted that in order to compare the effect of hybrid reinforcement of a cement-sand system, a 2-factor model $Y_i$ was also taken into account, obtained with fixed dosages of fibers at low levels ($x_4 = x_5 = -1$), i.e. in their absence. Thus, in the diagram of each $Y_i$ property (figure 1 and figure 2), two surfaces are shown, which are formed by reinforced and unreinforced compounds of the composite. The change in the property $Y_i$ within the boundaries of the local field was estimated by its absolute and relative increments [17].

The obtained results of modeling the physical and mechanical properties of the decorative composite allow us to note the following.

The maximum compressive strength $f_{cm}$ is achieved exclusively in concretes on coarse sand ($x_2 = -1$ or $GS = 30 \%$), reinforced with high and medium dosages of short and long fibers ($F6 + F12 = 0.045 \%$). Moreover, to achieve the best effect, the introduction of finely dispersed zeolite ($x_1 = -1$ or $Z = 0 \%$) is not required. At the same time, the strength of composites in equilibrium $f_{cm,n}$ and dry $f_{cm,d}$ states, in comparison with unreinforced material compositions, increases by 14 % and 24 % (figure 1a).

The flexural tensile strength $f_{ctfm}$ of concretes is maximum when the content of hybrid fibers is at medium levels ($F6 + F12 = 0.03 \%$). Under these simulation conditions, $f_{ctfm}$ increases from 4.2 % to 7.9 % for composites in a water-saturated $f_{ctfm,w}$ and dry $f_{ctfm,d}$ state (figure 1b). However, to achieve this effect, finely ground pozzolan should be introduced instead of a part of the binder at least $Z \geq 4 \%$ (or $x_1 \geq 0$).

The introduction of hybrid fibers (at different ratios) into highly plasticized composites makes it possible to increase their crack and frost resistance by more than 6 % and 2.6 %, respectively. The increase in crack resistance is confirmed by the analysis of the data of the coefficient of technological influence $K_1 = K_{ic}^L/K_{ic}^S$ (proposed by V.N. Vyrovoy, [18]), and the ability of concrete resistance to frost fracture - the compressive strength $f_{cm,F}$ of the material samples that have passed the test (figure 1c and 1d).
Figure 1. Local fields of properties of dispersed-reinforced (top surface) and unreinforced (bottom surface) decorative concrete: (a) $f_{cm}$, (b) $f_{ctfm}$, (c) $K_T$ and (d) $f_{cm,F}$.
The positive effect of high-modulus and high-strength fiberglass is explained by the fact that they are capable, by means of tangential forces acting on the interface, to perceive the bulk of the applied stresses and redistribute volumetric deformations over the entire cross-section of the material. As a result, the cracking process is inhibited and the physical and mechanical characteristics of concrete are improved (Rabinovich F.N., Pashchenko A.A., Ramachandran V., Biryukovitch K.L. et al.) [19-20 et al].

In addition, positive dispersed reinforcement of concrete is observed in the study of water absorption at hydrostatic pressure. The content in the material of medium and high dosages of short and long fibers (0.9 kg per 1 m$^3$ of mixture) does not increase the saturation of concrete with water, and even reduces it by 10 % (figure 2). However, this result is achieved when plasticizing the compositions by adding polycarboxylate at the level of $MF = 0.54 \%$ (or $x_3 = +0.22$). Therefore, it can be concluded that the microfibers are efficiently packed between the cement grains. It is important to note that according to the fiber manufacturer, 1 kg contains approximately 200 million fibers.

5. Conclusion
The experimental-statistical "complete models" constructed on the basis of the results of the experiment, describing the influence of the composition factors on the properties of the material, revealed that an increase in the level of plasticization of the compositions rises the utilization factor of the strength of glass fibers. The effectiveness of hybrid reinforcement of decorative composites with glass monofilaments has been confirmed through the implementation of a number of computational experiments. The analysis of the experimental results showed that the introduction of hybrid highly dispersed fibers into the initial composition of polystructural decorative concrete, with their different quantitative combinations, makes it possible to improve a number of its functional characteristics and thereby to ensure the preservation of the artistic and aesthetic expressiveness of the product.
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