Crack resistance of decorative composites

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Abstract. The results of a study of crack resistance obtained during the development of fine-aggregate concrete for architectural elements are presented. The crack resistance study of 27 different proportions of compositions was carried out in accordance with DSTU B V.2.7-227: 2009 using experimental statistical modeling methods. Due to the fact that the method of initiating the initial crack in the samples changes the distribution of the technological fields of strain, the tests were carried out on two series of samples. The data obtained show that the crack sealing method changes the deinformative-stressed state of the composite. So, crack resistance for one concrete composition can vary, from the conditions of the experiments, from 3 to 40 \%. Based on the obtained values of the characteristics of the material, in particular, for the coefficient of technological impact on crack resistance, which describe the fields of these criteria in the coordinates of the factors of concrete composition, models were built. The results of the model are presented on 5 factor diagrams of the form “cubes squared”. An analysis of the constructed diagrams showed that the initial conditions for the organization of the structure of concrete determine its ability to resist the development of various types of cracks. During the introduction of finely dispersed fibers at an optimal dosage of fine sand grains (50 \% in a sand mixture) and a slight replacement of cement with zeolite (from 2 to 3.4 \%), it is possible to reduce the technological damage to the decorative composite, thereby improving crack resistance.

1. Introduction
In recent decades, decorative concrete has been widely used in various fields of construction [1-3]. Due to the high technological properties of fine-grained and fine-aggregate concrete, based on them, it is possible to produce architectural details of various nomenclatures (for example, facade elements, plates for wall cladding of buildings, small architectural forms, etc.) that are not inferior to products from the front surface (from an aesthetic point of view) made from natural stones. The effectiveness of such concrete is also associated with the ability to more easily achieve the necessary texture and complex shape for decorative elements, while using inexpensive local sands with natural granulometry and industrial waste, which significantly reduces the cost of facial products. In turn, the durability of architectural elements directly depends on the ability of fine-grained (sand) composites to withstand without destruction the entire complex of alternating alternating volume changes caused by climatic influences. At the same time, an important characteristic of these composite materials, which determines their reliability in architectural elements, is crack resistance, namely, resistance to crack formation and development.
Within the multistructure approach [4], decorative fine-aggregate concrete is organized as a “structure in structure” into an independent structural heterogeneity in which it stands out at the micro and macro levels. According to the authors of [5], cracks are present at each structural level of concrete, which are dangerous for some “structures”, but safe for others. In the general case, it is necessary to ensure that cracks from lower levels do not pass into higher ones. Since this negatively affects the durability, bearing capacity and appearance of architectural elements.

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

The structure of the composite material is characterized, in particular, by a large number of technological defects (cracks, pores, etc.), which under the influence of various external factors and internal deformation processes are concentrators of internal stresses, and, in turn, lead to the appearance and development of existing cracks. A study of the interconnections of structure between crack resistance of cement composites is described in the works of Yu.V. Zaitsev, K.A. Piradova, P.G. Komokhov, V.M. Vyrovoy, S.I. Solodkiy, A.M. Kharitonova, V.I. Kondrashchenko and others.

In the works of V.M. Vyrovoy [4, 5] showed that the appearance and development of cracks at the micro level during the period of material structure formation depend on the volumetric deformations of individual cluster structures of the system. With large deformations of the microstructure of the hardened material, the development of cracks depends on the demonstration on their banks of deformation processes associated with changes in humidity, temperature, etc.

The nature of cracking at the macro level of concrete is determined by the interaction of the hardening binder with the aggregate. In the work by Yu.V. Zaitseva [6] it is stated that cracks in concrete, depending on the ratio of the properties of the components and the contact characteristics of these components, can develop in its various zones. Since cracks tend to easily penetrate from stiffer to less stiff material. The research results presented in [4] also confirm that, depending on the ratio of the cohesive and adhesive strengths of the matrix, cracks can occur in the macrostructure of concrete, not only at the boundary with the surface of the aggregates, but also in the cementitious part. The type and orientation of cracks in the matrix, in addition to the level of interaction with the surface of the aggregates, is determined, in particular, by the geometric characteristics of the structural cell of concrete. Moreover, as noted by A.M. Kharitonov in [7], a significant difference between the elastic moduli of cement stone and aggregate also leads to heterogeneity of the stress distribution in the bulk of the material. As a result, cracks appear actively around the hard aggregate grains in the cement matrix, violating the integrity of the concrete under load or with an increase in shrinkage deformation. According to E.A. Piradov, crack formation during fracture and deformation occurs due to the accumulation of defects in the concrete structure in the form of pores, capillaries and cracks in their critical concentration. Also, the authors of [8] believe that the cause of cracks, especially in the early stages of concrete hardening, is the period from 10 to 17 hours, when the maximum temperature gradient appears on the surface and in the material mass. Thus, the objective existence of technological defects in the structure of cement composites suggests their further influence on the construction and technical characteristics of products and structures during their operation. Given the above, in order to minimize stress concentration and ensure conditions for the joint deformation of structural elements, it is necessary to maximize the organization of the optimal initial conditions for the structure formation of the matrix material.

In the scientific works by V.I. Solomatova, V.M. Vyrovoy et al. [5] demonstrated that an effective method for controlling the initial number of cracks is the targeted use of fillers, where, depending on the ratios of the surface activity of the filler and cement binder particles and their sizes, it allows to reduce bulk deformations and helps to slow down crack growth. In the book by A.E. Sheikin indicated that the development and growth of cracks can be effectively slowed down by the presence of small pores in the material that are evenly distributed over the volume of the cement stone, including inclusions with lower strength and elastic modulus [9]. Also, according to P.G. Komokhov, a decrease in the rate of crack propagation in concrete can be achieved by introducing low-brittle inclusions into its composition, since they are structural stress dampers that change the nature of crack branching [10].
Therefore, taking into account the above, the durability of architectural elements largely depends on the fracture toughness of the matrix material, and the stated goal of the study is to increase the fracture toughness by regulating the structure of decorative composites through the use of discrete fibers, finely dispersed filler and rational granulometry of sand.

3. Description of the conditions and procedure for performing the experiment
The crack resistance study of 27 different compositions of fine-aggregate concrete, modified and dispersively reinforced by the fifth $X_{f}$ component, was carried out in accordance with DSTU B V.2.7-227:2009 using experimental statistical modeling methods (V.A. Voznesensky). Quantitative values of the characteristic were determined by the methods of linear fracture mechanics due to the critical stress intensity factor ($K_{ic}$, MPa-m$^{0.5}$).

Due to the fact that the distribution of technological strain fields changes from the method of initiating the initial crack in the samples [6], the tests were carried out on two series of samples. Initial cracks obtained during the formation of samples by laying a steel plate in the mold and using a cutting tool.

Depending on the nature of the influence of prescription factors on the decorative composite [11], while taking into account three-level dosages $X_i \pm \Delta X_i$ [12] of the varied components, composition factors are combined in two groups.

The first group includes factors for the modification of the cement-sand system:
- fin-grained zeolite (Zeolite Bio, Ukraine) in the amount of $X_1(Z) = 4 \pm 4$ %, was introduced instead of part of the cement (the lower allowable binder border is 92 parts by weight). The mineral composition of natural zeolite is mainly represented by clinoptilolite in the amount of 83-96 %, and the chemical composition is represented by active oxides with respect to cement portlandite, SiO$_2$ and Al$_2$O$_3$, respectively 72.5 and 13.1 %;
- the fraction of fine-grained sand (with an average diameter of $d = 0.22$ mm) in the mixture with coarse-grained ($d = 0.37$ mm) is $X_2(GS) = 50 \pm 20$ %. Sands with natural granulometry (without fractionation) were used – river and quarry;
- a superplasticizer of complex action was given in an amount of $X_3(MF) = 0.5 \pm 0.2$ % by weight of the binder. The Melflux 2651F additive (BASF Construction Polimers, Germany) is a water-soluble powder of a modified polyether carboxylate, whose action is based on a combination of electrostatic and steric effects. The plasticizer reduces the water-cement ratio W/C, thereby reducing the shrinkage of cement compositions, providing high early strength of concrete, in particular high-viscosity mixes.

Parameters disperse reinforcement of cement-sand composite include the second group:
- alkali-resistant glass fibers (Owens Corning, USA) with lengths of 6 and 12 mm, the dosage of which corresponded to the levels $X_4(F6) = X_4(F12) = 0.015 \pm 0.015$ % (by weight of the mixture). Finely dispersed fibers have the property of breaking into the smallest elementary fibers, the diameter of which is 14 microns, when they get into the mixer, creates disperse reinforcement of the entire volume of the soluble matrix, and also exclude the device of the protective layer on the surface of architectural elements.

The transition of variable factors in the normalized variables $1 \leq \chi_i \leq +1$ was performed according to standard formulas [12].

In a full-scale experiment, a cement-sand ratio of 1:3.4 by weight of the mixture was recorded. White Portland cement (100 m.h.) of the CEM I 52.5R grade was used as a binder.

4. Fracture resistance: field data, correlation with characteristics, modeling
An analysis of the research results shows that the fracture toughness in 24 warehouses of a sand composite on samples with a sprayed (artificial) $K_{ic}$ crack is bigger than $K_{ic}$ on samples with a laid (natural) crack, while the deviations of the property values are more than 3 %, and in composition # 7 even 40 %. The reason for the difference in the values between $K_{ic}$ and $K_{ic}$ may be, as is noted in [6], the presence of a system of microcracks surrounding the initial artificial incision, and which require an increased influx of external energy at the initial stages of crack development.
As the fracture resistance of concrete depends on various technological defects present in its structure (capillaries, pores, cracks), therefore, the dependence of $K_{ic}$ on the water absorption by volume ($W_\text{or}$, %) of the sample cubes at fixed points of time was considered: in 0.25 h, from 1 hour up to 6 hours inclusive, and further a day for 28 days. The highest correlation between $K_{ic}$ and $W_\text{or}$ was detected after keeping the samples in water for 15 minutes (Figure 1). Over time, the interdependence between the properties ($K_{ic}^s$ i $W_\text{or}$, $K_{ic}^l$ i $W_\text{or}$) is lost. No correlation was found between $K_{ic}$ and water-cement ratio W/C, as well as mechanical characteristics ($f_\text{lim}$, $f_\text{em}$, $E_c$) of the composite. In the work of Yu.V. Zaitsev is shown [6], that with the decrease in W/C decreases the content of air pores in concrete, strengthens its structure and increases the strength and resistance to crack development.

![Figure 1](image1.jpg)

**Figure 1.** The effect of water absorption by volume on the crack resistance of composite samples with artificial (a) and natural notch (b).

To analyze the effect of composition factors on the value of the stress intensity factor $K_{ic}$ depending on the method of initiation of cracks in the composite, COMPEX experimental-statistical models (EC-models [13]) whose results are interpreted in the diagrams “cubes on a square” for $K_{ic}^s$ and $K_{ic}^l$ (Figure 2a and b). As the carrier, a square with the coordinates of discrete hybrid fibers $F6$ and $F12$ is selected. The values of fracture toughness are reflected in the isosurface inside 5 cubes, in the coordinates of the modification factors of the cement-sand system of zeolite $Z$, silica sand $SG$ and superplasticizers $MF$. The results of two pairs of diagrams (Figure 2a and b) allow us to note the following.

The greatest influence on the level of decrease in crack resistance ($K_{ic,min}$) is provided by the finely dispersed zeolite and the significant presence of finer grains of sand in the compositions of the material. So, when replacing cement pozzolanic in the amount of Z = 8 % and the maximum content of fine sand grains ($SG = 70$ %), the fracture toughness of the unreinforced composite ($F6 = F12 = 0$ %) is minimal and amounts to $K_{ic}^L = 0.225$ and $K_{ic}^S = 0.301$ MPa·m$^{0.5}$. In this case, the maximum levels of the coefficients $K_{ic}^L = 0.373$ and $K_{ic}^S = 0.413$ MPa·m$^{0.5}$ are achieved in composites without zeolite, respectively, with approximately the same ratio of grains of fine and coarse sand ($SG \approx 50$ %) and at a dosage superplasticizers below average $MF$ level < 0.5 %.

The effect of glass fibers of different lengths on the $K_{ic}$ of concrete samples with natural and artificial cuts is somewhat different, but in all cases the introduction of superfine fiber contributes to the material’s resistance to crack opening. The maximum levels of $K_{ic}^L$ material when content is only long ($F12 = 0.03$ % and $F6 = 0$ %) or short ($F6 = 0.03$ % and $F12 = 0$ %) fibers or mixtures there of ($F6 + F12 = 1.2$ kg/m$^3$), compared to the unreinforced composite, increased by 8 % (Figure 2a). It should also be noted that a separate maximum content of fine fibers with a length of 6 mm or 12 mm can increase the resistance of the material to the development of cracks in products that are influenced by external factors by about 5 % (Figure 2b, lower right cube $F6 = 0.03$ % or top left cube $F12 = 0.03$ %).
Figure 2. Analysis of the influence of prescription factors on the crack strength of concrete in the dry state: (a) $K_{\text{IC}}^L$, MPa·m$^{0.5}$; (b) $K_{\text{IC}}^S$, MPa·m$^{0.5}$. 
The positive effect of discrete fiberglass on the fracture toughness of a cement composite is due to the fact that [14], because they are uniformly distributed in the cement matrix, they cause the redistribution of stresses that cause cracks and reduce, in fact, the average the length of the crack.

When comparing the dimensionless generalization index - the relative increase in $\delta \{K_{ic,max}/K_{ic,min}\}$, obtained in different formulation fields for $K_{ic}$ and $K_{ic}^3$ (Figure 2a and b), it is seen that in general, the same effect of fine and fibrous fillers is observed $K_{ic}$. The greatest increase is observed in the compositions of fine-grained composite of unreinforced fiber.

5. The effect of technological damage on the fracture resistance of the decorative composite

In scientific works [5, 6, 15], devoted to the mechanism of structure formation of composite building materials at different scale levels, it is shown that a certain set of technological imperfections - technological cracks (TC), internal surfaces is laid in the structure of the material during its fabrication section (FS). The type and nature of the distribution of TC and FS are determined by the qualitative composition and concentration of the particles of the dispersed phase, the ratio of surface activity between solids and the dispersion medium, as well as technological features of processing the matrix material into the product. According to [4], the presence of internal boundary sections in the form of TC shores and FS shores implies the ability to perceive and redistribute internal deformations and deformations caused by different operational loads. In [5, 6] it was demonstrated that the fracture toughness of cement composites with mineral fillers depends on the method of initiation of the initial cracks. This is because the distribution of residual deformations is determined by the geometric characteristics of the specimen, and the magnitude of the deformations depends on the initial composition of the material. In view of the above, it is of interest to study the influence of technological features of obtaining a decorative composite on its crack resistance.

At the technological formulation of the problem, from the development of compositions of plasticized concrete, it was assumed that the joint introduction of glass hybrid fiber and fine zeolite (characterized by a smaller modulus of elasticity than cement stone) with rational natural particle size distribution of sand (without fractional fracturing). In turn, the positive effect of pozzolan on the formation of the structure of the decorative composite was found when conducting a computational experiment on two-factor fields of “full” EC-model of compressive strength, the results of the study presented in [16]. The influence of the initial composition of the material and the technological features of its processing into the product was estimated through a dimensionless coefficient ($K_T$), the numerical values of which were determined by the ratio of the values of the critical stress intensity coefficients of the specimens-beams with the laid and sprayed crack $K_T = K_{ic}^L / K_{ic}^S$.

The obtained values of the coefficient of technological impact on the fracture resistance of $K_T$ are in the range from 0.7 to 1.1. As the results of the $K_{ic}$ study showed, under the conditions of the experiments, the criterion for one composition of the composite can range from 3 to 40 %. To analyze the influence of prescription factors on $K_T$, a “full” experimental-statistical model (EC-model) was used [12]. The maximum level of the model ($K_{T,max} = 1.09$) is achieved in the composition of the composite with the fiber content of 6 and 12 mm at high and above average levels, as well as zeolite and fine sand particles at below average levels.

For a more complete analysis of the results of modeling on the EC-model, a diagram of the form of “cubes squared” was constructed. The analysis of the diagram revealed three features:

- comparison of the maximum values of the $K_T$ criterion in three-factor fields confirms the feasibility of joint introduction of hybrid fibers into composites made on coarse-grained sand with partial replacement of cement by zeolite filler from 2 to 2.6 %;
- in the absence of glass fibers 6 mm in length, the partial replacement efficiency of cement by zeolite increases to 3.4 %, but for concrete with a grain content of fine sand fraction in the sand mixture not more than 38 %;
- to reduce the technological damage of decorative composites reinforced with only short fiber, 1.5 times possible with the content of fine sand at a below average level (< 50 %) and with a small replacement of the binder zeolite no more than 0.6 %.
For the three above mentioned features, it is worth noting the important fact of the positive effect of the superplasticizing additive on a polycarboxylate basis on the formation of the structure of a composite with highly dispersed fillers.

6. Conclusion
The fracture resistance of the decorative composite depends largely on the structural design, which is determined by the type and content of highly dispersed mineral fillers, as well as the ratio of quartz grains of fine and coarse sand. The analysis of the constructed 5-factor “cubes squared” diagrams by experimental-statistical $K_{IC}$ models showed that the initial conditions of organization of the concrete structure determine its ability to resist the development of different types of cracks. Since the introduction of fine fibers with optimal dosing of fine sand grains ($<50\%$ in the sand mixture) and a slight replacement of cement by zeolite (from 2 to 3.4\%) allows to reduce the technological damage of the decorative composite, thereby improving its fracture toughness.

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