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FIBRE-REINFORCED DECORATIVE COMPOSITE: THE EFFECTS OF COMPOSITION ON THE STRENGTH

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Abstract. The paper continues to present the results of the study aimed at getting high performance decorative concrete. To the previously presented analysis of the influence of the composition on the growth process of the plastic strength of concrete mix, the results of consideration of the compressive and flexural strength of the concretes in the dried and water-saturated states have been added. The effects of fine zeolite (active mineral additive), quantity of fine sand in mixture with more coarse one, dosages of superplasticiser and alkali resistant glass fibres of 6 and 12 mm length on the strength have been evaluated with the 2-order experimental-statistical models. The models have been built on the data obtained for 27 compositions, in accordance with 5-factor design of experiment. The visualisation of the local fields of concrete strength in coordinates of the part of factors, changing when the values of other factors change, helps to analyse the individual and synergetic effects of the components and to outline the next research tasks.

Keywords: fine-grained concrete, glass fibre, zeolite, compression strength, flexural strength, design of experiment, experimental-statistical model.

Introduction. Decorative concrete has been and remains a demanded building material [1-3], since people want to live and work in beautiful and comfortable environment. Fine-grained concrete can be good for decorative elements, if it has the wide spectrum of appropriate properties, of both process mix and hardened composite. The possibility to produce various curved shapes with a smooth interface and high-quality texture of surfaces must be provided, as well as weather and frost resistance (i.e., durability), sufficient strength and crack resistance.

To reinforce cement matrices various kinds of fibre are used [4]. When developing specific high performance materials (the most appropriate for what they are intended for [5, 6, p. 11]) the possibilities to use «hybrid» fibres (poly-reinforcement), combining individual merits of various fibre, are investigated [7-14]. As many authors confirm [7, 9], relatively short low-modulus fibres, can prevent the emergence and development of shrinkage cracks only. They can bridge microcracks more efficiently then the long ones. «As the microcracks grow and join into larger macrocracks», the long highly elastic fibres «become more active in crack bridging» [9].

With account for results of previous experimental study [10, 15] purposed to get high performance decorative compositions, the new study has been launched [16]. It has been decided: ⬩ to use hybrid reinforcing system consisting of the glass fibre of two lengths; ⬩ to try fine zeolite as active mineral additive (such as metakaolin or microsilica), which should be introduced to provide sufficient density of the matrix around glass fibre (as it was shown in [7, 17] and was confirmed in [15]). To obtain workable mixes and appropriate thickness of the layers of cement paste around aggregate grains and around fibres it was necessary, of course, to determine an appropriate quantity and type of cement, quantity and fractions of sand.

The fixed quantities of the basic components and dosages of the others, varied according to design of the experiment, have been given (as well as the design itself) in the previous paper [16]. The first results have been presented there: the data on the process of initial structure formation for

27 compositions, the curves and the models of plastic strength growth, some numeric generalising indices of the process and the means to evaluate their dependencies on mix proportions.

This paper continues to present the results of the study, namely, related to the effect of the composition on the strength of the hardened decorative composite.

Conditions of the experiment. With constant contents of the binder, «white cement (produced by CIMSA) + zeolite (fine clinoptilolite)», and of the aggregate (3.4 of cement mass, 2 fractions of sand) 5 composition factors (X_i) were varied. In the system of factors, the first three define the «cement-sand matrix» subsystem, the other two make up the «hybrid fibre» subsystem.

X_1 – content of zeolite introduced instead of a part of cement, ***Z*** (4 ± 4 % of binder mass);
X_2 – mass part of fine sand (average diameter d = 0.22 mm) in mixture with more coarse sand (d = 0.37 mm), ***SG*** (*Sand Granulometry*, from 30 to 70 %);
X_3 – dosage of polycarboxylate based superplasticiser «*Melfux*», ***MF*** (0.5 ± 0.2 % of binder mass);
X_4 – amount of alkali-resistant glass fiber, 6 mm long (*Owens Corninng,* 14 μ in diameter), ***F*6** (0.015 ± 0.015 % of concrete mix mass);
X_5 – quantity of alkali-resistant glass fibre,12 mm long (the same manufacturer and diameter), ***F*12** (0.015 ± 0.015 % of the mix mass).

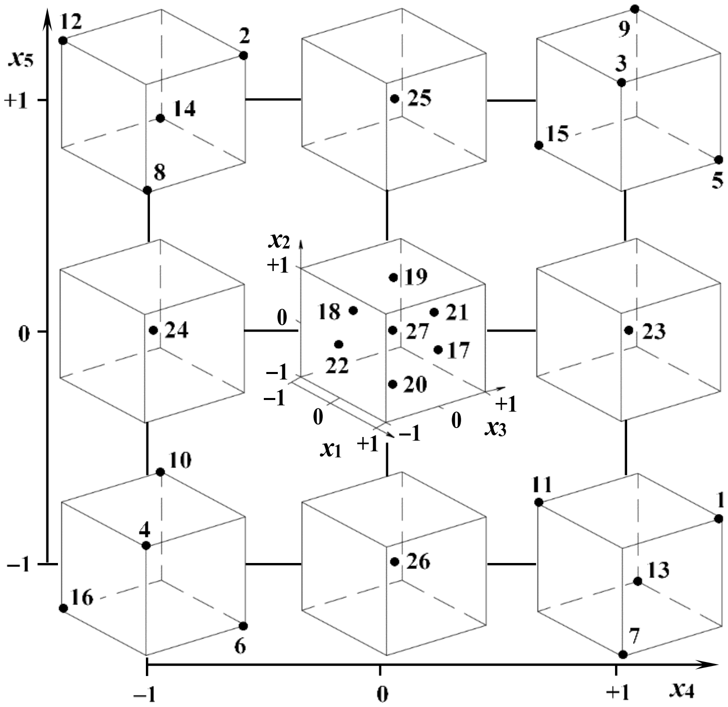

Fig. 1. 27 points of the design of experiment on the diagram «cubes on square»

The values of X_i in 27 compositions correspond to 27 points of the experiment design on 5-dimensional hypercube (shown as cubes on the square, Fig. 1) of normalised factors $|x_i|\le 1$ [18].

To the data on plastic strength (P_m) for 27 concrete mixes [16] the data on mechanical strength for 27 composites after 1, 3, 7, 14, and 28 days of hardening are added. Strength values were determined on prism specimens of the size 40 × 40 × 160 mm, in accordance with Ukrainian standard [19]. After 28 days flexural strength (f_{ctfm}, MPa) and compression strength (f_{cm}, MPa) have been determined by testing the specimens in normal state, after drying for 24 h at 105±5°C, and after saturating dried specimens with water during 24 h.

Curves of structure formation: from first minutes to 28 days. The obtained data have made it possible to display and in some way to describe the process of structure formation in the compositions under study. Shown in Fig. 2 are so called «whole curves» of structure formation processes [20, pp. 35-37] for 3 compositions. The first section of such curve, for the plastic state of material, can be described by exponential model with polynomial exponent, as it was shown in [16]. The state of hardening, from 1 to 28 days, might be also described by some function of time. More over, the appropriate growth model can be selected for the whole curve of gaining strength. Such a description can only be formally, conditionally correct, since it would represent different states of mixture system, characterised with different methods. Nevertheless, Morgan–Mercer–Flodin (MMF) model (with interpretable parameters [21]) can fit the data on the growth of strength for all 27 compositions, in particular, the model (1) for #13 (got with *CurveExpert*, standard deviation 0.54, coefficient of correlation 0.992,), with corresponding curve #13*M* in Fig. 2.

$$\ln R = (0.124\times3.42\cdot10^4 + 11.2\times\ln\tau^{6.43}) / (3.42\cdot10^4 + \ln\tau^{6.43}), \qquad (1)$$

where R – common symbol for both P_m and f_{cm} (in kilopascals), τ – time in minutes.

On the used Experimental-Statistical (ES) models. Since the data on 27 compositions have been obtained in the designed experiment, ES-models [6, 18, 22, 23] can be built for the strength (P_m or f_{cm} or other criteria Y) at any time in the interval under study, as well as for any numerical characteristics of the structure formation process (including parameters of process model), as this was shown in [16]. Thus ES-models make it possible to describe the specific features of the process in dependence on composition.

Such model in structured form can look like (2), where b_0 equals the level of Y in a centre of experiment (at central values of all x), block (**a**) evaluates the effect of cement-sand matrix factors on Y, at the median dosages of fibres, (**b**) evaluates the effect of hybrid fibre at median values of matrix factors, (**c**) characterises synergetic effects of factors from 2 subsystems. Here given is such model (3) for compression strength at 28 days, after drying (without insignificant coefficients).

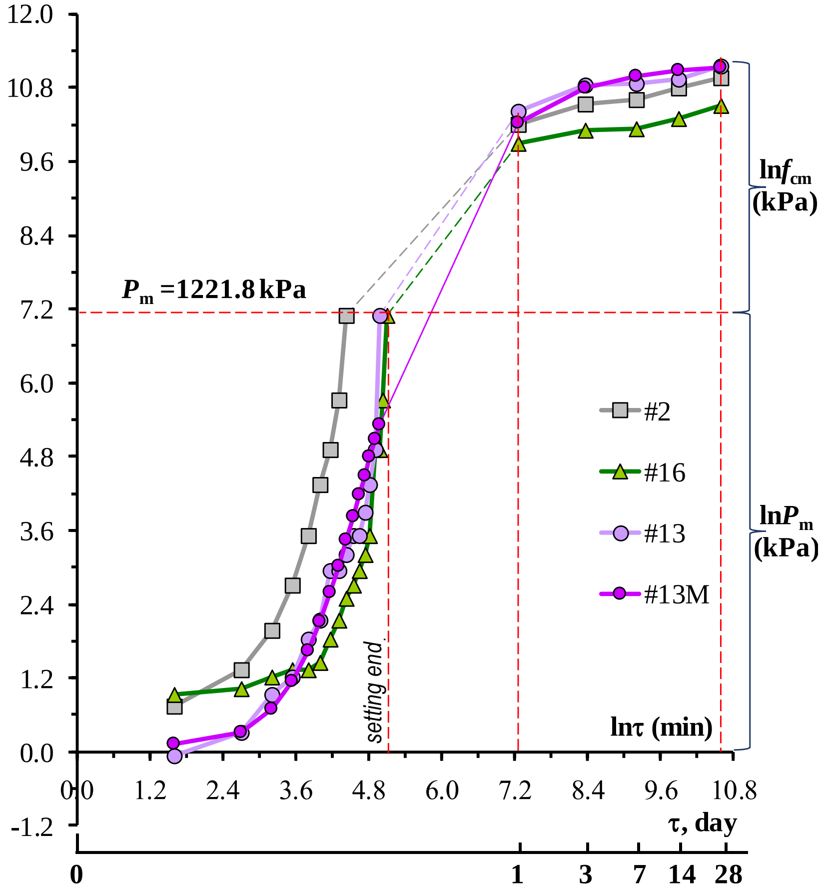

Fig. 2. The curves of strength growth with time (P_m then f_{cm}) for compositions **#2** (x_1=x_2=x_3=x_5=+1, x_4=–1, no short fibre, upper values of other factors), **#13** (x_1=x_2=x_5=–1 и x_3=x_4=+1, upper content of both fibres, low values of other factors), **#16** (x_1=x_2=x_3=x_4=x_5=–1, without zeolite and fibre, lower contents of superplasticiser and fine sand)

$$Y = b_0 \boxed{\begin{array}{lll} +b_1x_1 & +b_{11}x_1^2 & +b_{12}x_1x_2 \\ +b_2x_2 & +b_{22}x_2^2 & +b_{13}x_1x_3 \\ +b_3x_3 & +b_{33}x_3^2 & +b_{23}x_2x_3\ \mathbf{(a)} \end{array}} \boxed{\begin{array}{ll} +b_{14}x_1x_4 & +b_{15}x_1x_5 \\ +b_{24}x_2x_4 & +b_{25}x_2x_5 \\ +b_{34}x_3x_4 & +b_{35}x_3x_5\ \mathbf{(c)} \end{array}}$$

$$\boxed{\begin{array}{lll} +b_4x_4 & +b_{44}x_4^2 & +b_{45}x_4x_5 \\ +b_5x_5 & +b_{55}x_5^2 & \mathbf{(b)} \end{array}} \qquad (2)$$

$$f_{cm.d} = 49.42 \boxed{\begin{array}{lll} \pm\ 0\ x_1 & \pm\ 0\ x_1^2 & \pm\ 0\ x_1x_2 \\ -3.27x_2 & +9.16x_2^2 & \pm\ 0\ x_1x_3 \\ +12.6x_3 & \pm\ 0\ x_3^2 & +1.24x_2x_3 \end{array}} \boxed{\begin{array}{ll} -3.74x_1x_4 & \pm\ 0\ x_1x_5 \\ -3.36x_2x_4 & +1.54x_2x_5 \\ +1.27x_3x_4 & \pm\ 0\ x_3x_5 \end{array}}$$

$$\boxed{\begin{array}{lll} \pm\ 0\ x_4 & \pm\ 0\ x_4^2 & +1.49x_4x_5 \\ \pm\ 0\ x_5 & -9.55x_5^2 & \end{array}} \qquad (3)$$

The joint use of the process model, the one like (1), and ES-model, like (2) in this particular case, can be formally expressed by multiplicative model (4), where **x** is the vector of composition factors (and possibly of other technology factors). The model can be written as model of the process with its parameters being the functions of $\boldsymbol{x}$, or it could be ES-model with coefficients b depending on τ.

$$Y(\tau, \boldsymbol{x}) = Y(\tau) \times Y(\boldsymbol{x}) \tag{4}$$

Discussion of modelling results. ES-model (3) describes the whole field [6, 22] of the **compression strength** $f_{cm.d}$, of the dried concrete, in coordinates of all 5 composition factors. The maximal level of the field equals 81.6 MPa (at $x_1 = x_2 = -1$, $x_3 = x_4 = +1$, $x_5 = 0$). The minimal one is 18.4 MPa (at $x_1 = x_4 = +1$, $x_2 = +0.52$, $x_3 = x_5 = -1$). Since the positive effect of superplasticiser is observed at its high dosage ($MF = 0.7$ %), fixed in (3) has been $x_3 = +1$. This has enabled the effects of other factors to be visualised using the diagram «squares on square» (Fig. 3).

Shown in Fig. 3 are 5 local fields of $f_{cm.d}$ in coordinates of fibre factors, located in the vertices and the centre of the square $\{x_1, x_2\}$, changing with quantities of zeolite and fine sand. Similar images, obtained due the model analogous to (3), are shown (Fig. 4) for the strength of the decorative concrete in a water-saturated state, $f_{cm.w}$ (MPa). When analysing the diagrams in Fig. 3 and 4 the following can be noted.

Concretes with low content of fine sand ($SG = 30$, $x_2 = -1$) get the greatest increase in compressive strength due to fibers, maximal levels of the strength being achieved at upper and median dosages of short and long fibre respectively ($x_4 = +1$, $x_5 = 0$). Maximal relative increase of 56 % for $f_{cm.d}$ and 18 % for $f_{cm.w}$ could be obtained when there is no zeolite in such composition.

The increase could be explained by the fact that highly dispersed fibres of high modulus of elasticity, evenly chaotically distributed in the cement-sand matrix, form a certain framework capable of taking most of the tangential stresses on the interfaces. Packing of aggregate grains with such size distribution may also contribute to greater compressive strength.

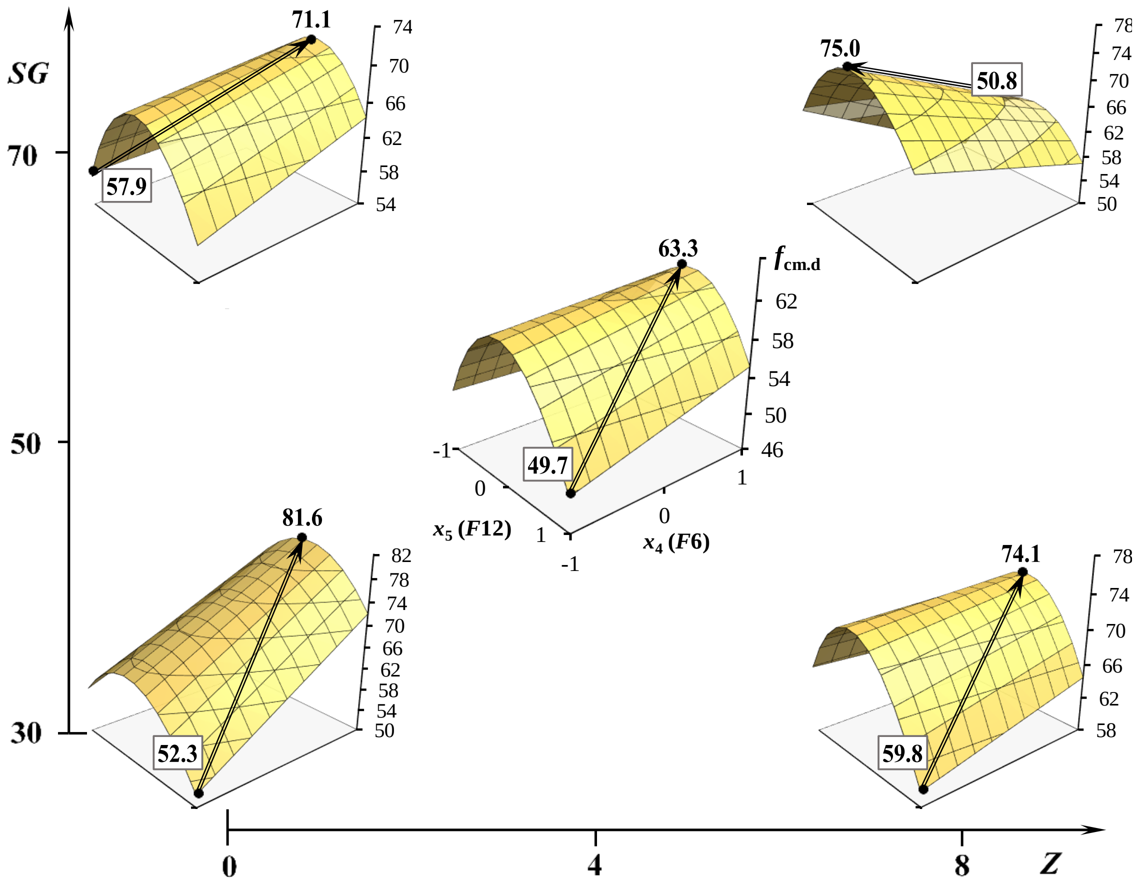

Fig. 3. Surfaces of the fields $f_{cm.d}(x_4, x_5)$, MPa, in dependence on contents of zeolite (Z, x_1) and fine sand (SG, x_2) at upper dosage of superplasticiser ($MF = 0.7$, x_3=+1)

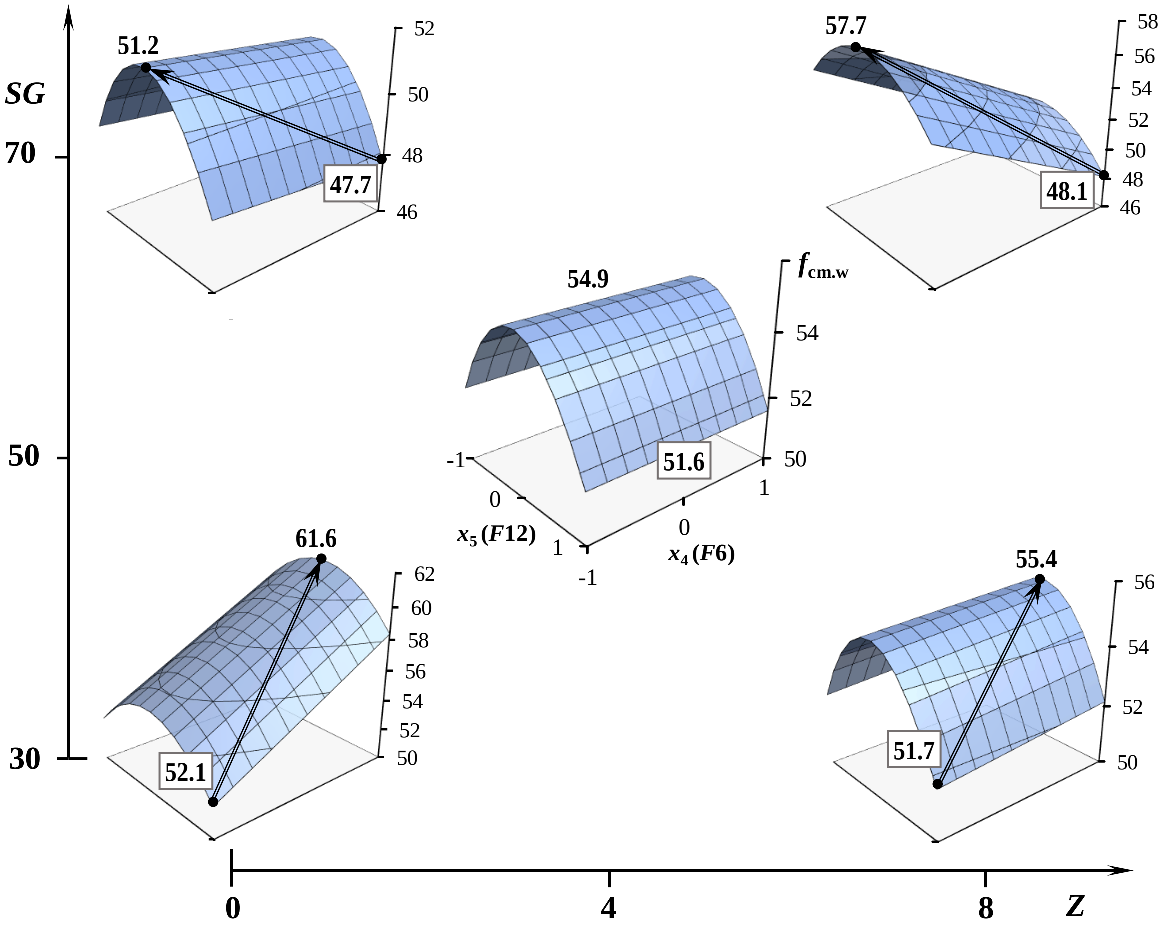

Fig. 4. Surfaces of the fields $f_{cm.w}(x_4, x_5)$, MPa, in dependence on contents of zeolite (Z, x_1) and fine sand (SG, x_2) at upper dosage of super plasticiser (MF = 0.7, x_3=+1)

In the concretes on fine-grained sand (SG = 70 %, x_2 = +1) the effectiveness of replacing the part of cement with finely dispersed zeolite is observed at median dosage of long fibre. With greater amount of zeolite the strength of the composite increases, the absolute increase being from 13.1 to 24.2 MPa for $f_{cm.d}$ (Fig. 3) and from 3.5 to 9.6 MPa for $f_{cm.w}$ (Fig. 4).

For the concretes with large amount of coarse sand the replacement of cement with 8 % of zeolite (binder mass %) allows the minimal level of $f_{cm.d}$ to be increased by 14 % (Fig. 3, SG = 30).

The interaction effect of these two components can probably be associated with an increase in the density of cement matrix due to decrease in porosity and with strengthening of the contact zone between cement stone and the aggregates, including the filaments, which prevents their pulling out.

However, the positive effect of short fibre ($F6$) on compression strength at high content of coarse sand (SG = 30) becomes negative with fine grains content at upper level (SG = 70) and high dosage of zeolite.

The influence of composition factors on **flexural strength** of the concretes in dried and water saturated states ($f_{ctfm.d}$ and $f_{ctfm.w}$, MPa) has been analysed with the help of ES-models of the same kind (2), describing the whole fields of these criteria, in 5-dimentional domain of $\mathbf{x}$. The diagrams in Fig. 5 and in Fig. 6, with isosurfaces of local fields of the strength inside the cubes of 3 normalised factors on the «carrying» square of 2 other factors, help to analyse the effects of composition.

On the section $0 \leq Z \leq 4$ the maxima of $f_{ctfm.d}$ are achieved by compositions with low quantity of superplasticiser (MF = 0.3 %), at upper and median dosages of hybrid fibre components ($F6$ = 0.03 %, $F12$ = 0.01-0.02 %). With increase of zeolite content, from 4 to 8 %, the interaction of the components of the cement-sand matrix with the fibre changes, specifically, for MF and $F6$ in the opposite direction (Fig. 5). The maximum levels of $f_{ctfm.d}$ correspond to compositions at upper MF value (0.7%) with an average content of 12 mm long fibre and without short fibre.

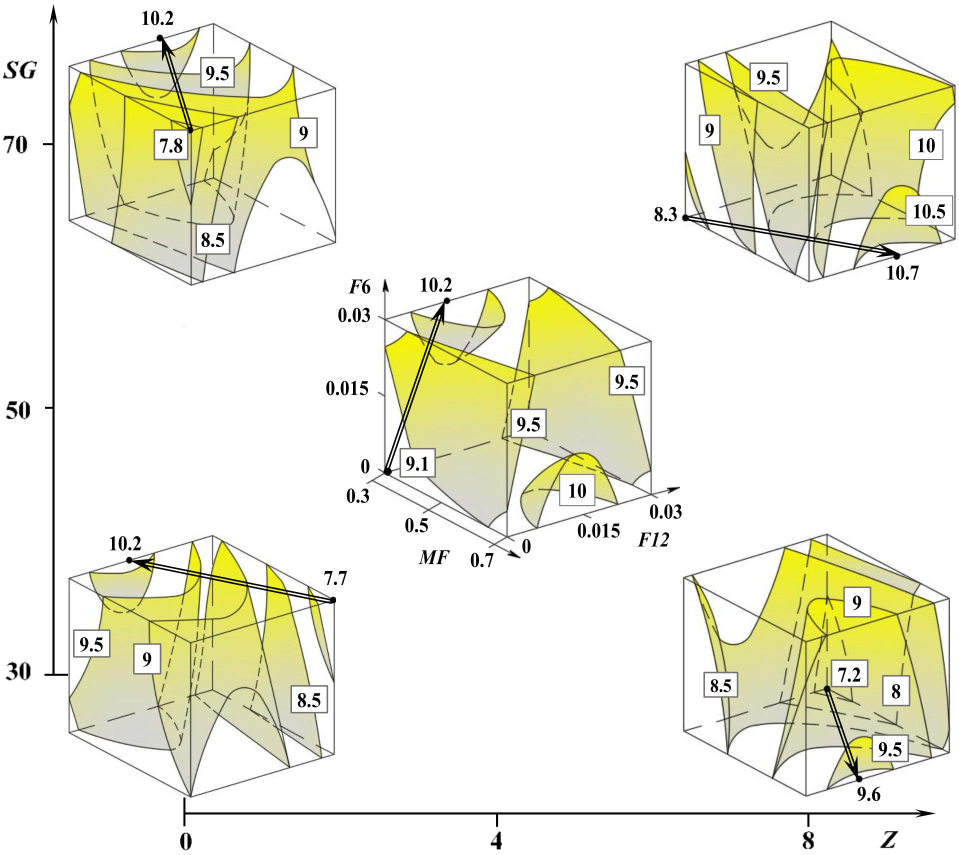

Fig. 5. The influence of composition on fractural strength of decorative concrete in dry state, $f_{\text{ctfm.d}}$ (MPa)

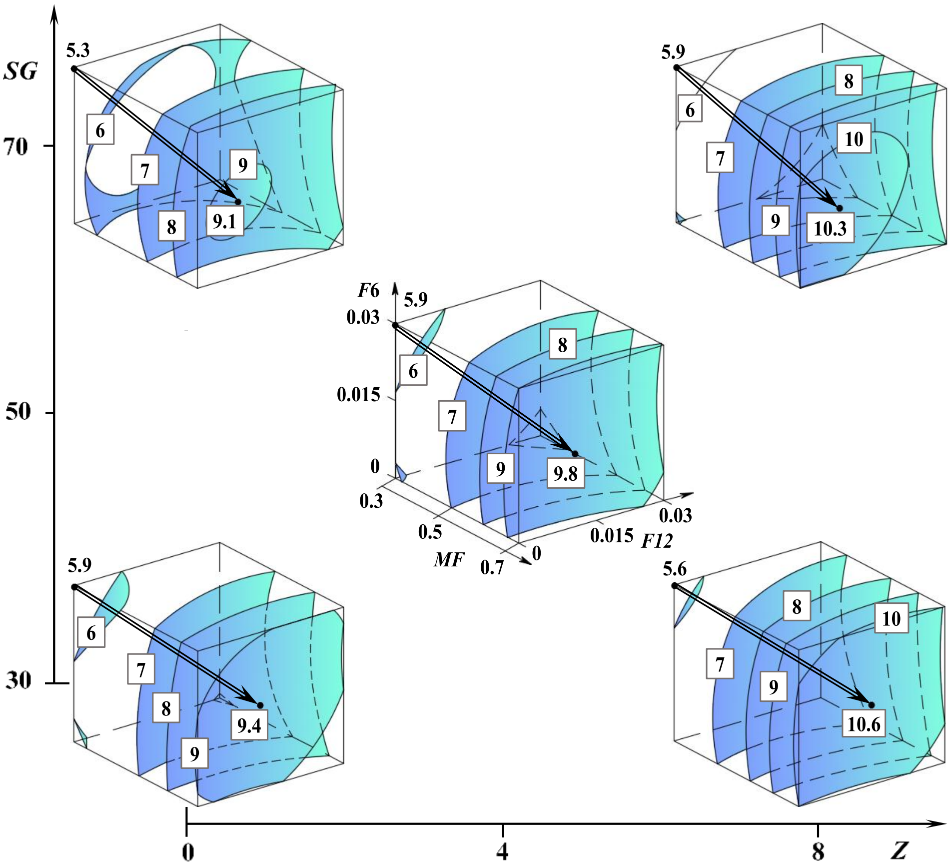

Fig. 6. The influence of composition on fractural strength of decorative concrete in water-saturated state, $f_{\text{ctfm.w}}$ (MPa)

The joint introduction of short and long fibres, the replacement of cement with zeolite (up to 8%), and increased content of coarse sand (from 50 to 70%) have positive effect on the bending strength of water-saturated material, as evidenced the maxima on the local fields of $f_{ctfm.w}$ (Fig. 6).

In particular, in water-saturated concrete on coarse sand the presence of zeolite (8 %) does not reduce the flexural strength (as in dried samples), but on the contrary increases it by about 10%. This effect confirms the fact of strengthening of the contact zone between the cement matrix and the sand aggregate at the expense of natural pozzolana and reinforcing fibers.

It could be also noted that at high content of superplasticiser the tensile strength during bending of the concrete saturated with water depends little on the presence of fibres (Fig. 6). At water saturated state $f_{ctfm.w}$ of the composites with any Z and SG (in the intervals under study) depends little or not at all on the presence of both short and long fibres.

Conclusions. The obtained data on strength characteristics of decorative concrete, on plastic strength of concrete mix and mechanical strength of hardened composites, have enabled to evaluate and analyse the effects of the components, including hybrid glass fibre and zeolite, on the process of forming the structure of the material. The effects differ for different characteristics. The compositions providing their best levels are also different. Therefore, at the next stages of the study, it is planned to analyze the correlation between different strength characteristics at different times of hardening, of strength characteristics with frost resistance and other performance properties, in different zones of the compositions region. The possibilities to predict the strength of mature concrete by the levels of strength at early age could be also considered. The search for compromise between the best levels of certain optimality criteria under conditions of specifications requirements is also planned.

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ДИСПЕРСНО-АРМОВАНИЙ ДЕКОРАТИВНИЙ КОМПОЗИТ: ВПЛИВ СКЛАДУ НА МІЦНІСТЬ

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Анотація. В статті представлені результати дослідження характеристик міцності високофункціонального декоративного бетону. До представленого раніше аналізу впливу складу на процес росту пластичної міцності бетонної суміші добавляються відомості про міцність бетону після 1, 3, 7, 14 і 28 діб твердіння в нормальних умовах, а також результати міцності при стиску і згині бетону в сухому та водонасиченому стані. Отримані дані дозволяють кількісно описати процес росту міцності (спочатку пластичної, потім механічної), від перших хвилин до 28 днів життя матеріалу. Вплив на міцність вмісту тонкодисперсного цеоліту (активної мінеральної добавки), кількості дрібного піску в суміші з більш крупним, дозування суперпластифікатору та фібри довжиною 6 і 12 мм (при постійному співвідношенні в'яжучого і заповнювача) оцінюється за допомогою експериментально-статистичних моделей другого порядку, побудованих по даним про міцність 27 композицій, у відповідності з 5-факторним планом експерименту. Візуалізація локальних полів міцності в координатах окремих факторів та їх максимальних і мінімальних рівнів, що змінюються під впливом інших факторів, допомагає проаналізувати індивідуальні та синергетичні ефекти компонентів і намітити наступні задачі дослідження. Припускається аналіз зв’язків між характеристиками міцності в різні терміни твердіння (маючи на увазі можливість прогнозу нормативних показників за міцністю в ранньому віці), міцності з іншими експлуатаційними властивостями дисперсно-армованих декоративних композитів, в різних зонах рецептурної області. Оскільки склади, що забезпечують індивідуальні оптимуми різних властивостей матеріалу, виявляються різними, планується також багатокритеріальний пошук компромісу між кращими рівнями певних критеріїв оптимальності, за умов виконання вимог до інших критеріїв.

Ключові слова: дрібнозернистий бетон, скляна фібра, цеоліт, міцність при стиску, міцність при згині, план експерименту, експериментально-статистична модель.

ДИСПЕРСНО-АРМИРОВАННЫЙ ДЕКОРАТИВНЫЙ КОМПОЗИТ: ВЛИЯНИЕ СОСТАВА НА ПРОЧНОСТЬ

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Аннотация. В статье представлены результаты исследования прочностных свойств высокофункционального декоративного бетона. К представленному ранее анализу влияния состава на процесс роста пластической прочности бетонной смеси добавляются сведения о прочности бетона после 1, 3, 7, 14 и 28 суток твердения в нормальных условиях, а также результаты рассмотрения прочности при сжатии и изгибе бетона в сухом и водонасыщенном состоянии. Полученные данные позволяют количественно описать процесс роста прочности (сначала пластической, затем механической), от первых минут до 28 дней жизни материала. Влияние на прочность содержания тонкодисперсного цеолита (активной минеральной добавки), количества мелкого песка в смеси с более крупным, дозировок суперпластификатора и фибры длинной 6 и 12 мм (при постоянном соотношении вяжущего и заполнителя) оценивается с помощью экспериментально-статистических моделей второго порядка, построенных по данным о прочности 27 композиций, в соответствии с 5-факторным планом эксперимента. Визуализация локальных полей прочности в координатах части факторов и их максимальных и минимальных уровней, изменяющихся под влиянием других факторов, помогает проанализировать индивидуальные и синергетические эффекты компонентов и наметить следующие задачи исследования. Предполагается анализ связей между характеристиками прочности в разные сроки твердения (имея в виду и возможность прогноза нормативных показателей по прочности в раннем возрасте), прочности с другими эксплуатационными свойствами дисперсно-армированных декоративных композитов, в разных зонах рецептурной области. Поскольку составы, обеспечивающие индивидуальные оптимумы разных свойств материала, оказываются разными, планируется также многокритериальный поиск компромисса между лучшими уровнями определенных критериев оптимальности, при условиях выполнения требований к другим критериям.

Ключевые слова: мелкозернистый бетон, стеклянная фибра, цеолит, прочность при сжатии, прочность при изгибе, план эксперимента, экспериментально-статистическая модель.

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