UDC 691:591.24 DOI: 10.31650/2786-6696-2022-2-52-59

ANALYSIS OF PROPERTIES OF DECORATIVE CONCRETE IN ISOPARAMETRIC CONDITIONS OF OPTIMALITY CRITERIA

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Abstract. The article presents two computer materials science methods for analyzing the functional properties of decorative concrete. *The method of experimental-statistical modeling* is used to build nonlinear structured models that describe the material's physical, mechanical, and technological properties in the coordinates of five factors of concrete composition. The study of the influence of recipe factors on the characteristics of the composite was carried out according to a symmetrical three-level 27-point plan. Depending on the nature of the effect on the decorative composite, varied raw materials are combined into two groups of factors – modifications of the cement-sand system and parameters of dispersed reinforcement. A comparative analysis of the local properties fields of reinforced and non-reinforced material compositions showed the feasibility of reinforcing the cement-sand matrix with hybrid glass fibers. However, based on the purpose of the work – to control the characteristics of a decorative non-reinforced composite, subject to a constant level of one of its criteria, *the method of isoparametric analysis* was used. The change in the quality criteria of composite compositions was analyzed in two versions of isoparameters. In the first one, all mortar mixes were characterized by the same viability within time $\tau = 1.0 \pm \Delta\tau$, in the second one, all concrete compositions were isosthenic within the limits of compressive strength $f_{cm} = 56 \pm \Delta f_{cm}$. For statistical testing of the characteristics of the material, together with experimental statistical models, the Monte Carlo method was used. According to the results of the isoparametric analysis of the functional properties of the decorative composite, it was fairly reliably determined by the area of compromise relationships between the zeolite and the fine-grained filler, however, the coordinates of their optimal amount don't match according to all criteria. An analysis of the results obtained by this method demonstrates that an engineering compromise between these factors should be sought in the area of their main levels of variation. Introducing finely dispersed zeolite instead of a part of cement is a technologically useful technique for improving the quality and durability of unreinforced decorative concrete.

Keywords: decorative concrete, zeolite, fibre, experimental-statistical model, strength, computational experiment, constant level of property, isoparametric analysis.

Introduction. The use of decorative concrete with a complex of given characteristics is growing in many countries. The widespread use of these concretes due to their improved quality and reliability in architectural products (structures). The priority is the invariance of artistic and aesthetic expressiveness for the entire period of operation. In the context of their functionality, decorative composites should be characterized by high rates of ease of installation, early strength, crack resistance, discoloration, etc. [1]. Therefore, during the study of the characteristics of concrete, there is an urgent need to analyze its quality indicators in combination with one or more properties that are strictly regulated by the manufacturing technology of products, especially products of complex shape (for example, architectural elements, etc.).

To solve this type of technological problems, professor V.A. Voznesensky [2] proposed the principle and methodology for isoparametric analysis (IP-analysis) to control the characteristics of building composites. IP-analysis, according to [3], is carried out based on the results of a computational experiment, for the implementation of which mathematical models are used, obtained from the data of experimental-statistical modeling of material quality criteria.

Analysis of literature data and problem statement. The analysis of domestic and foreign literary sources showed a relatively wide range of technical and economic problems. It is necessary to compare the quality indicators of building composites with the given values of their technological, physical, and mechanical properties [4-12]. At the same time, positive experience in the implementation of research tasks according to the method of V.A. Voznesensky and T.V. Lyashenko [2, 3] accumulated in the field of such composite materials: during the optimization of the structural parameters of cellular concrete according to the criteria for minimizing thermal conductivity and average density, which made it possible to identify gas silicate compositions that have a lower density at a given compressive strength [8]; during the optimization of particle size distribution and mineralogical composition of fillers for polyester resins. The resulting polymer composition is characterized by a low resin content and specified indicators of rheological and mechanical properties [3, 9]; to assess the influence of operational factors on the probable physical and mechanical parameters of fine-grained concrete. The analysis of the constructed distribution curves according to probable criteria confirmed that such characteristics as tensile strength during bending and water absorption are more sensitive to destructive processes that occur in the structure of the composite under the cyclic influence of environmental factors [10]; in the study of changes in the functional properties of modified epoxy composites. The obtained results of IP-analysis contributed to the identification of compositions that simultaneously have minimum absorption and maximum resistance to the influence of water and oil following the regulatory requirements for the criteria set for the composite [11]; while determining the rational compositions of fiber concrete used for the manufacture of architectural elements. The application of the method made it possible to determine the area of compromise ratios between glass and polypropylene fibers [12], etc., under isosthenic conditions of the properties of the composite.

The presented results in scientific papers [8-12] demonstrate – that the IP-analysis method allows to obtain several meaningful solutions that are useful for the production and use of construction materials made on various binders. In this case, IP-analysis can be used to solve the problem of obtaining decorative concrete with certain characteristics but with a slightly smaller margin of the compressive strength coefficient [1]. This is due to the fact that the architectural elements of the facades of buildings and structures during operation do not carry power loads. Therefore, taking into account the practical orientation of the use of the composite, in particular the requirements for its characteristics, it is of interest to analyse the quality criteria of the material compositions without fibrous filler. At the same time, it is important that the stage of obtaining a composition is combined with the shaping of an architectural product. Along with the requirements for the mechanical properties of concrete, requirements are put forward for the properties of the mortar mix. In this regard, the optimization of technological and mechanical quality criteria of decorative composites is an urgent problem, the solution of which requires the use of isoparametric analysis.

The purpose and objectives of the research. The purpose of the work is to determine the area of compromise ratios between the zeolite filler and the fine-grained aggregate while providing the specified levels to the characteristics of the viability of the mixture and the strength of decorative concrete.

The main task of the research is the analysis of the features of the effect of zeolite and sand granulometry on the functional properties of decorative non-reinforced composites in isorheological and isosthenic conditions.

Field experiment and modiling. The experiment to determine the properties of decorative concrete was conducted according to the 27-point, 5-factor plan [1, 13]. Two groups of composition factors were varied: "*Modifiers of the cement-sand matrix*" and "*Parameters of dispersed reinforcement*".

The first group included dosages of finely dispersed zeolite at levels of X_1 (Z) = 4±4 parts by mass or p.m. (introduced instead of a part of cement), fractions of fine-grained sand mixed with coarse-grained sand X_2 (SG) = 50±20 p.m. and superplasticizing additive based on polycarboxylate X_3 (MF) = 0.5±0.2 p.m. from the mass of the binder. In the second – highly dispersed glass fibers with a length of 6 and 12 mm, which were introduced in the amount of X_4 ($F6$)= X_5($F12$) =

0.015±0.015 p.m. from the mass of the soluble mixture. The compositions were made with different water-cement ratio, which ensured the fulfillment of the requirement for the same mobility of the mixture – grade *S*4. Production and testing of samples were carried out following DSTU B V.2.7-239:2009. The composite has requirements for the shelf life of the mixtures $\tau \geq 0.95$ hours and beyond the limit of compressive strength $f_{cm} \geq 50$MPa.

According to the experimental data [1, 13], a complex of nonlinear structured experimental-statistical models (ES-models) was built, which describe the fields of physical, mechanical, and technological properties in the coordinates of five composition factors. Thus, model (1) with 13 non-zero coefficients describes the complete field of time τ attainment of the plastic strength P_m of 35 kPa (corresponds to the initial consistency of the *S*4 mixture) in case of an experimental error $s_e(\tau\{P_m{=}35\}) = 0.127$ hour.

$$\tau\{P_m{=}35\} = 1.136 \; \boxed{\begin{array}{l} -0.141x_1 \pm 0\;x_1^2 + 0.069x_1x_2 \\ -0.102x_2 - 0.198x_2^2 - 0.053x_1x_3 \\ -0.480x_3 + 0.382x_3^2 - 0.068x_2x_3 \end{array}} \; \boxed{\begin{array}{l} -0.052x_1x_4 \pm 0\;x_1x_5 \\ \pm\;0\;x_2x_4 \pm 0\;x_2x_5 \\ +0.061x_3x_4 \pm 0\;x_3x_5 \end{array}}$$
$$\boxed{\begin{array}{l} \pm\;0\;x_4 + 0.157x_4^2 - 0.084x_4x_5 \\ \pm\;0\;x_5 \pm\;0\;x_5^2 \end{array}} \qquad (1)$$

The basic generalizing indicators [2] of this field are: $\tau\{P_m{=}35\}_{max} = 2.35$ (at $x_1 = x_3 = x_4 = -1$, $x_2 = -0.26$, $x_5 = +1$), $\tau\{P_m{=}35\}_{min} = 0.515$ hours (at $x_1 = x_2 = +1$, $x_3 = +0.77$, $x_4 = +0.29$, $x_5 = +0.99$) and relative growth δ ($\tau\{P_m{=}35\}$) – in 4.6 times. In Fig. 1 shows the local field $\tau\{P_m{=}35\}$ in coordinates of zeolite (*Z*) and fine sand (*SG*) factors at maximum plasticization of composite compositions ($MF = 0.7$ p.m.) and the content of hybrid fibers at low and medium levels ($F6 + F12 \to 0$ and 0.03 p.m.). So the diagram $\tau\{P_m{=}35\}$ shows two surfaces formed by reinforced and non-reinforced composite compositions (upper and lower planes). Suitable local fields for compressive strength f_{cm} (MPa) and flexural tension f_{ctfm} (MPa), water absorption W_m (% by weight after 24 hours of exposure), medium density $\rho_{c.d}$ (kg/m^3), and the coefficient of technological influence K_T (was determined by crack resistance [14]) are also presented in Fig. 1. The expediency of introducing hybrid fibers into the composition of composites, the presence of which makes it possible to significantly strengthen the cement-sand matrix under such conditions, is confirmed. ($f_{cm.max}$ = 72 MPa). However, as noted in the review of this work, local fields of unreinforced concrete compositions are useful for the analysis of quality criteria.

The results of the research. *Methodological bases of IP-analysis.* For a computer study of the *Y* characteristics of decorative concrete, together with the ES models, the Monte Carlo method was used, which makes it possible to evenly distribute the levels of prescription factors within the given limits. The change in the properties of the composite was analyzed in two versions of isoparametric conditions (IP conditions). In the first version, all soluble compositions were characterized by the same viability within $\tau\{P_m{=}35\} = 1.0 \pm \Delta\tau$, in the second, all concrete compositions were isosthenic within $f_{cm} = 56 \pm \Delta f_{cm}$. It should be noted that for the IP analysis on two factorial fields of these criteria (Fig. 1 – lower surface), the isolines corresponding to their median values were selected.

The width of the corridor for the isoparameters was given by the mean square error of the field-in experiment $s_e\{Y\}$, the average value of the prediction variance function *d* in the local field, and the t_α-distribution quantile for the tolerable risk α. However, the calculation of the value of the *d*-function is somewhat simplified compared to that recommended in [2] and is performed in two stages. In the 1st stage, the dispersion for the average value at each point of the experiment plan is determined; in the 2nd stage, the primary quadratic model of the dispersion of the isoparameter $d\{Y\}$ is built in the COMPEX program, which is used to calculate the model for the local field in the x_1 and x_2 coordinates while stabilizing the other factors at levels $x_3 = +1$, $x_4 = x_5 = -1$. Thus, half the width of the corridor $\Delta Y = t_\alpha \cdot s_e \cdot d^{0.5}$ amounts to $\Delta\tau = 0.05$ hour, and for $\Delta f_{cm} = 3.15$ MPa. After that, in two factorial areas,

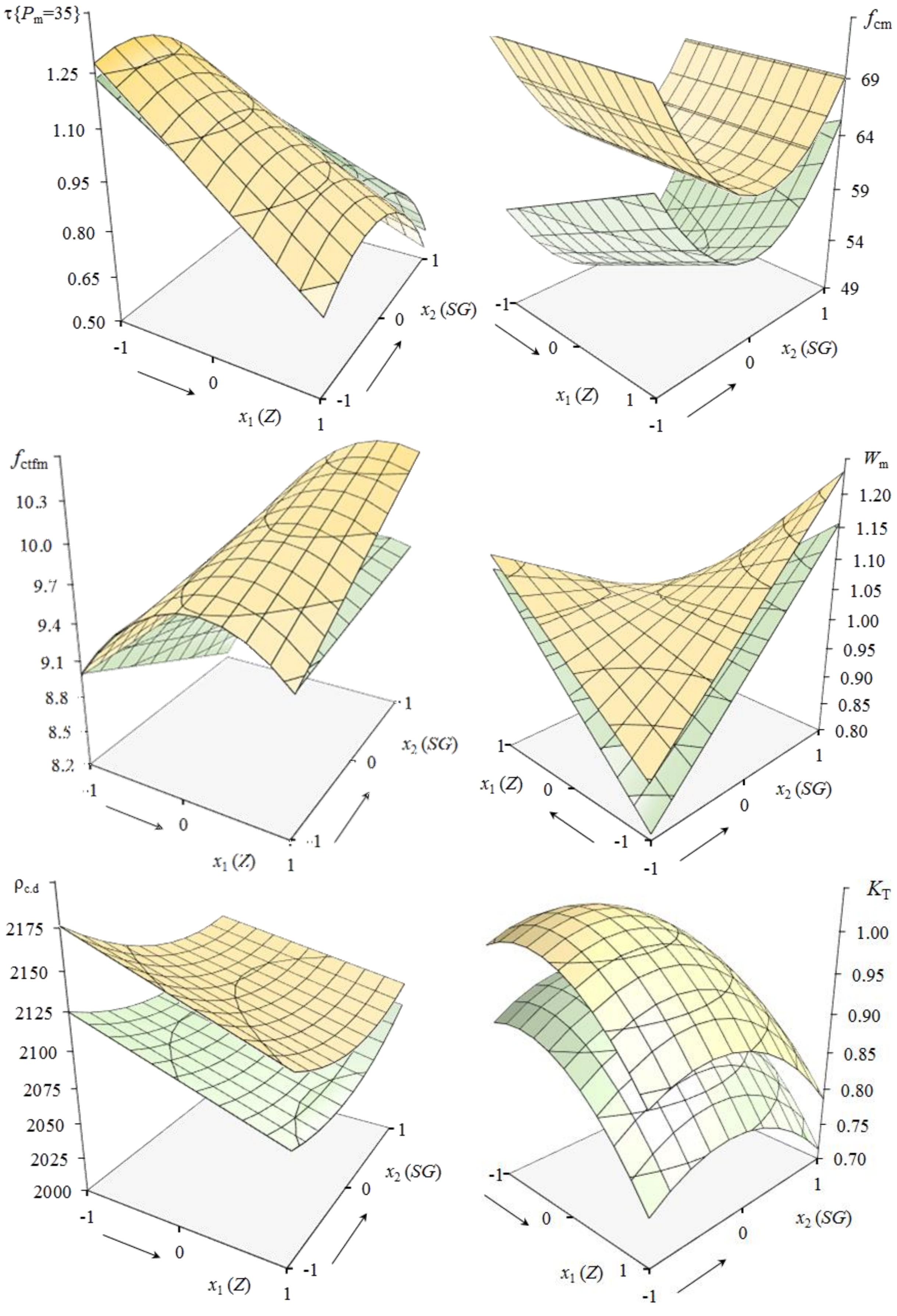

Fig. 1. Local authorities of hybrid-reinforced and non-reinforced warehouses (upper and lower upper) decorative composites with a high level of plasticization

the Monte Carlo method generates 1000 evenly distributed compositions (points) in the coordinates of the x_1 and x_2 factors, to which four mandatory ones are added at the square's vertices. Further, for each field composition, according to the EU models, the values are quantified $\tau\{P_m=35\}$ and f_{cm}. Out of 1004 generated points, only compositions of composites are selected for participation in the analysis, the isoparameter values of which fall within the confidence corridor for $0.95 \le \tau\{P_m=35\} \le 1.05$ hour, $52.85 \le f_{cm} \le 59.15$ MPa (Fig. 2a and b). It is important that the lower boundaries of the isoparametric corridor of properties correspond to the normalized levels regulated by the technology when

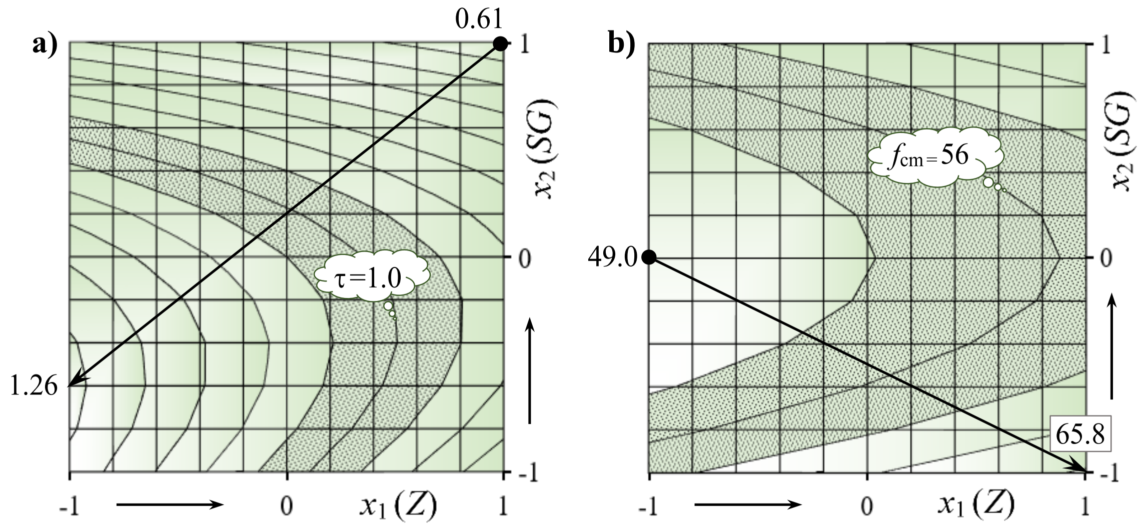

Fig. 2. The impact of zeolite x_1 and fine sand x_2 on pot life is high plasticized mixtures (a) and compressive strength of non-reinforced composite (b)

developing a decorative material. Such composites in IP-corridor for $\tau\{P_m=35\}$ and f_{cm} left 273 and 583, respectively, which covers about 27 % and 58 % of their local fields. At the same time, the continued viability of mixtures in the corridor is ensured by changing the levels of factors within limits for zeolite x_1 from -0.95 to +0.83 and fine sand x_2 from -0.99 to +0.60 and a compromise solution for concrete under isosthenic conditions is only achieved within the initially specified limits x_1 and x_2. For the resulting compositions of the composite, we estimate the levels of local fields of other properties and build corridor graphs.

Discussion of the results of the research. For the IP analysis of the quality criteria of the decorative composite, the second method of visualization of the statistical testing of material compositions was used [2, 11]. With this method, the property values were scanned along the axis of one of the x_1 and x_2 factors.

Fig. 3 shows "corridor" graphs for physical and mechanical properties, the values of which are determined under isorheological conditions $\tau\{P_m=35\}$ of the mixture. The change in the characteristics of concrete is associated with an increase in zeolite from 0.2 to 7.3 p.m. At the same time, to maintain ongoing viability, the content of fine sand in a mixture with coarse sand should decrease from 62 to 30.3 p.m. With such dosages of zeolite and fine sand, the compressive strength f_{cm} and flexural tensile strength f_{ctfm} of concrete increase by 22.8 % and 14.3 %, respectively. Here it is worth noting that all isorheological compositions of the compositions are characterized by the regulatory requirement for $f_{cm} \ge 50$ MPa. However, under such conditions of factors x_1 and x_2, the situation with regard to the coefficient of technological damage of concrete changes in the opposite way. With an increase in the content of small grains of sand x_2 in a mixture with large (to ≈ 55 p.m.), with small dosages of zeolite ($x_1 < 0$), K_T grows at 12.3 %. Some interest is observed in the water absorption of the composite. As the replacement of cement with pozzolana increases (up to 4 p.m.), the average density decreases $\rho_{c.d}$, however, the ability of concrete to saturate with water also decreases $W_m \approx 11.6$ %.

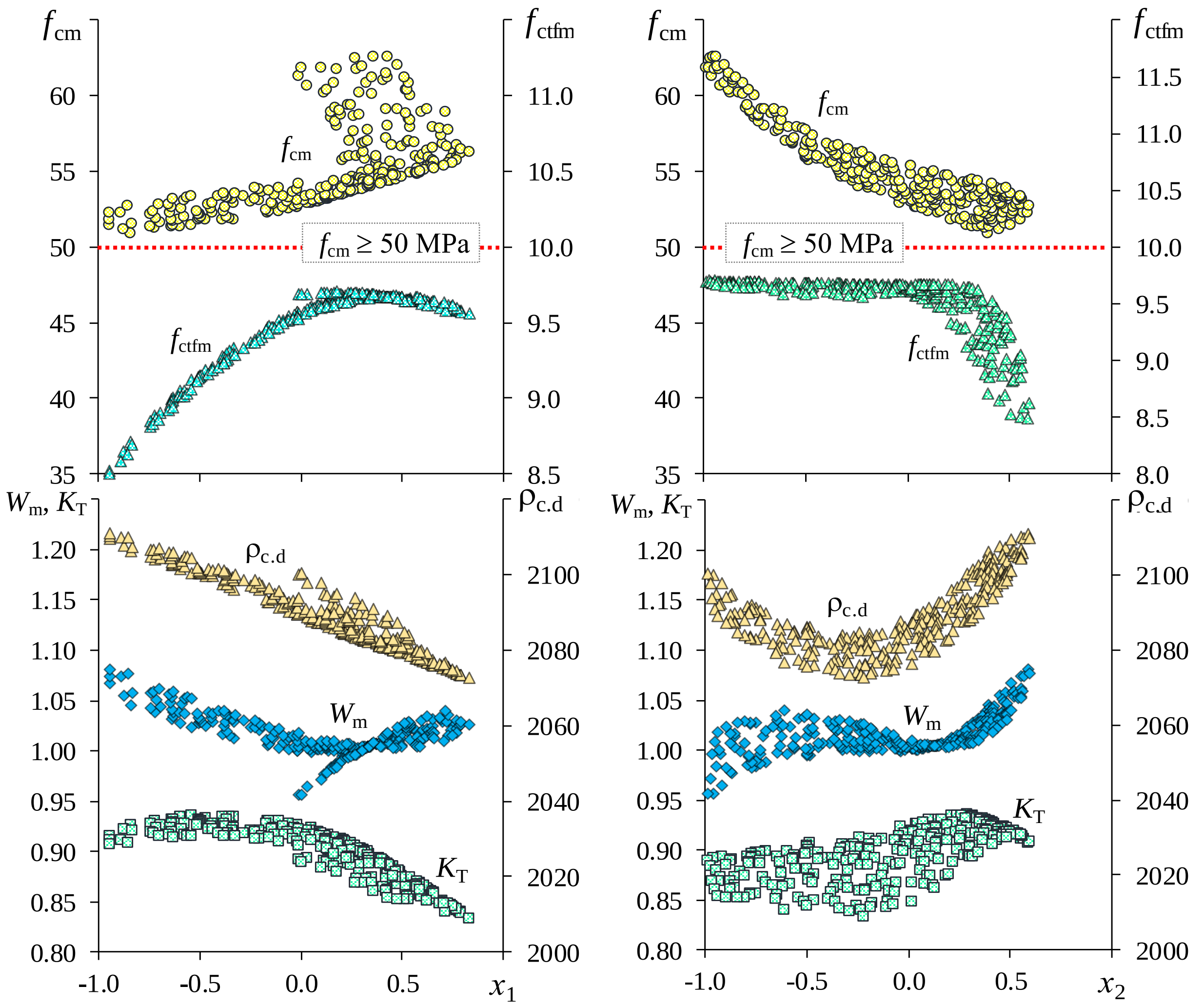

Fig. 3. Results of IP analysis of quality criteria for compositions with viability $\tau = 1.0 \pm 0.05$ hour with independent control of zeolite x_1 or sand granulometry x_2 in the range $-1 \leq x_i \leq +1$

The results of statistical testing of composite compositions in isosthenic conditions are presented in Fig. 4. The analysis of property estimates on these charts allows us to draw a number of conclusions. An increase in the content of zeolite grains, as well as the fraction of fine sand in the aggregate mixture, leads to the reduced shelf life of compositions by approximately 58 %. In addition, 245 of 583 compositions do not meet the requirement for $\{\tau\{P_m=35\} \geq 0.95$ hour. However, in such conditions, the flexural strength of concrete f_{ctfm} increases by about 17 %. At the same time, with a further increase in the grains of the fine fraction of sand from 57 p.m. (or x_2 = +0.39) in the aggregate mixture, f_{ctfm} decreases by ≈ 12 %. It is also worth recognizing that the average density decreases and the damage of the material increase K_T. At the same time, the minimum values of water absorption W_m are possessed by concrete compositions made on coarse-grained sand, the content of fine grains x_2 in the sand mixture should be ≈ 33 p.m. per 100 p.m. placeholder. A comparative analysis of the results obtained by the IP-analysis method on the influence of zeolite and sand aggregate granulometry on the characteristics of the decorative composite (Fig. 3 and 4) demonstrates that an engineering compromise between x_1 and x_2 should be sought in the area of their main levels of variation, i.e. $X_1(Z) \approx 4$ p.m. and $X_2(SG) = 50$ p.m.

Conclusions. Computer experiments on isoparametric analysis on local fields of characteristics of building materials are an effective tool for obtaining new materials science information. According to the results of the IP-analysis of the functional properties of the decorative composite, the area of compromise ratios between zeolite and fine-grained aggregate is fairly reliably determined. However, the coordinates of their optimal amount do not match according to all criteria. Introducing finely dispersed zeolite instead of a part of cement is a technologically valuable technique for improving the quality and durability of non-reinforced decorative concrete.

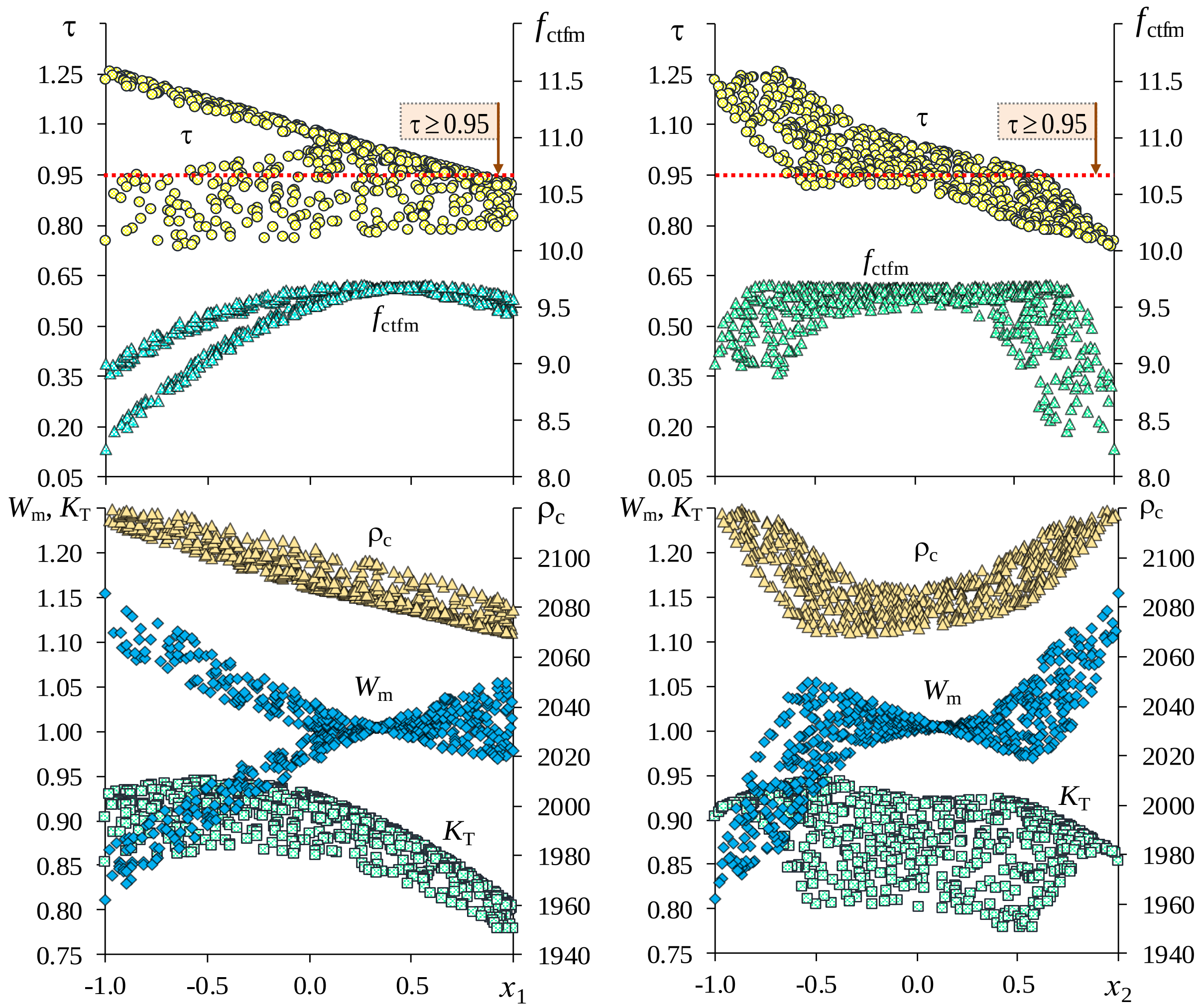

Fig. 4. Changing the quality criteria of composite compositions at different levels of factors x_1 and x_2 of the matrix, which ensure constant strength f_{cm} = 56 ± 3.15 MPa

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АНАЛІЗ ВЛАСТИВОСТЕЙ ДЕКОРАТИВНОГО БЕТОНУ В ІЗОПАРАМЕТРИЧНИХ УМОВАХ КРИТЕРІЇВ ОПТИМАЛЬНОСТІ

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Анотація. У статті представлено два методи комп'ютерного матеріалознавства для аналізу функціональних властивостей декоративного бетону. *Метод експериментально-статистичного моделювання* застосовано для побудови нелінійних структурованих моделей, які описують поля фізико-механічних і технологічних властивостей матеріалу в координатах п'яти факторів складу. Дослідження впливу рецептурних факторів на характеристики композиту виконано по симетричному трьохрівневому 27-ми точковому плану. Залежно від характеру дії на декоративний композит варійовані сировинні матеріали об'єднані в дві групи факторів – модифікації цементно-піщаної системи, параметри дисперсного армування. Порівняльний аналіз локальних полів властивостей армованих і неармованих складів матеріалу показав доцільність армування цементно-піщаної матриці гібридними скловолокнами. Однак виходячи із мети роботи – для управління характеристиками декоративного неармованого композиту, при умові постійного рівня одного із його критеріїв, застосовано *метод ізопараметричного аналізу*. Зміну критеріїв якості складів композиту проаналізовано в двох версіях ізопараметрії. В першій всі розчинні суміші характеризувалися однаковою життєздатністю в межах часу $\tau = 1.0 \pm \Delta\tau$, в другій – всі склади бетону були ізостенічними в межах міцності на стиск $f_{cm} = 56 \pm \Delta f_{cm}$. Для статистичного випробування характеристик матеріалу спільно з експериментально-статистичними моделями використано метод Монте-Карло. За результатами ізопараметричного аналізу функціональних властивостей декоративного композиту достатньо достовірно визначається область компромісних співвідношень між цеолітом і дрібнозернистим заповнювачем, проте координати їх оптимальної кількості по всіх критеріях не співпадають. Аналіз отриманих результатів цим методом демонструє, що інженерний компроміс між вказаними факторами варто шукати в області їх основних рівнів варіювання. Введення тонкодисперсного цеоліту взамін частини цементу є технологічно корисним прийомом для підвищення якості та довговічності неармованого декоративного бетону.

Ключові слова: декоративний бетон, цеоліт, фібра, міцність, ізопараметричний аналіз, експериментально-статистична модель, комп'ютерний експеримент, постійний рівень властивості.

Стаття надійшла до редакції 6.12.2022