УДК 691:519.24

DECORATIVE CONCRETE WITH HYBRID GLASS FIBRE: DESIGN AND FIRST RESULTS OF THE EXPERIMENT

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Abstract. The first results of experiment in the study aimed at getting high performance decorative concrete are presented. Varied in the experiment were the content of zeolite as active mineral additive, ratio of fine to coarse sand, dosage of superplasticizer, quantities of short and relatively long alkali resistant glass fibres, at constant content of the binder (white cement + zeolite) and the aggregate. Plastic strength of concrete mix (at 10 minutes intervals), water-cement ratio at equal workability, early linear shrinkage and early compression and bending strength, other mechanical and performance properties were determined for 27 compositions according to design of the experiment, enabling to describe the dependencies of material characteristics on composition factors with 2nd order experimental-statistical models. The curves of plastic strength are shown and numerical characteristics generalising them are proposed and estimated. The later allow the processes of initial structure formation for various mix proportions to be compared and analysed.

Keywords: fine-grained concrete, zeolite, glass fibre, plastic strength, shrinkage, design of experiment, experimental-statistical model, generalising index.

ДЕКОРАТИВНІ БЕТОНИ З ГІБРИДНОЮ СКЛЯНОЮ ФІБРОЮ: ПЛАНУВАННЯ І ПЕРШІ РЕЗУЛЬТАТИ ЕКСПЕРИМЕНТУ

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Анотація. Представлено перші результати дослідження з метою отримання високофункціонального декоративного бетону. У спланованому експерименті варіювалися вміст цеоліту, співвідношення двох фракцій піску, дозування суперпластифікатору, кількість короткого і відносно довгого скловолокна, при постійному вмісті в’яжучого та заповнювача. Пластична міцність суміші, лінійна усадка і міцність в різні терміни, інші властивості визначені для 27 композицій відповідно до плану експерименту. Це дозволяє описати залежності характеристик матеріалу від складу експериментально-статистичними моделями другого порядку. Показані криві пластичної міцності та їх узагальнюючі показники, що дозволяють порівнювати і аналізувати процеси початкового структуроутворення.

Ключові слова: дрібнозернистий бетон, цеоліт, скляне волокно, пластична міцність, усадка, план експерименту, експериментально-статистична модель, узагальнюючий показник.

ДЕКОРАТИВНЫЙ БЕТОН С ГИБРИДНОЙ СТЕКЛЯННОЙ ФИБРОЙ: ПЛАНИРОВАНИЕ И ПЕРВЫЕ РЕЗУЛЬТАТЫ ЭКСПЕРИМЕНТА

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Аннотация. Представлены первые результаты исследования с целью получения высокофункционального декоративного бетона. В спланированном эксперименте варьировались содержание цеолита, соотношение двух фракций песка, дозировка суперпластификатора, количество короткого и относительно длинного стекловолокна, при постоянном содержании вяжущего и заполнителя. Пластическая прочность смеси, линейная усадка и прочности в разные сроки, другие свойства определены для 27 композиций в соответствии с планом эксперимента. Это позволяет описать зависимости характеристик материала от состава экспериментально-статистическими моделями второго порядка. Показаны кривые пластической прочности и их обобщающие показатели, позволяющие сравнивать и анализировать процессы начального структурообразования.

Ключевые слова: мелкозернистый бетон, цеолит, стеклянное волокно, пластическая прочность, усадка, план эксперимента, экспериментально-статистическая модель, обобщающий показатель.

Introduction. Decorative fine-grained concrete could be good material for decorative elements when creating beautiful and comfortable environment, in which people would live and work [1]. To serve this purpose the material should have high manufacturability (possibility of molding products of various curved shapes with a smooth interface of surfaces, by different methods). It must be high performance material (weather and frost resistant, i.e., durable, with sufficient strength and crack resistance, with high-quality texture of the front surface).

To create high performance concrete (HPC) various kinds of fibre, reinforcing cement matrices, are widely used [2]. 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 [3, 4].

As I. Markovič reminds [4], «the application of different types of fibres together in a concrete mixture was proposed for the first time in 1987 by Rossi et al. [5], as the so-called multi-modal fibre reinforced concrete (MMFRC)». In more recent works the possibilities to combine individual merits of various fibre and to use hybrid fibres (poly-reinforcement) are investigated [6-9] when developing specific HPC.

The analysis of the influence of hybrid reinforcing system consisting of the glass and polypropylene fibres on strength, crack resistance, and other properties when developing fine-grained concrete (Ukrainian patent № 45587, V. Voznesensky, P. Dovgan, A. Dovgan) has shown not only substantial positive individual effect of the first (significantly greater than that of the second), but the negative synergism (antagonism) of two fibrous components as well [10].

These results prompted the direction of the new experimental study purposed to get high performance decorative compositions. Presented below is what was taken into account when designing the experiment and then some generalisation of data obtained at the first stage of the study.

Conditions of the experiment. In order to obtain workable HPC mixes, the composition of concrete matrix must correspond to applied types and quantities of fibres so that they can be

Table 1 – Values of varied dosages of the components

i	Factor X_i	Values		
		$x_i = -1$	$x_i = 0$	$x_i = +1$
1	Content of zeolite introduced instead of a part of cement, *Z* (% of binder mass)	0	4	8
2	Mass part of fine sand (average diameter *d* = 0.22 mm) in mixture with coarse sand (*d* = 0.37 mm), *SG – Sand Granulometry*, %	30	50	70
3	Dosage of polycarboxylate based superplasticiser «*Melfux*», *MF* (% of binder mass)	0.3	0.5	0.7
4	Amount of alkali-resistant glass fiber, 6 mm long (*Owens Corninng*, 14 μ in diameter), *F*6 (% of concrete mix mass)	0	0.015	0.03
5	Quantity of alkali-resistant glass fibre,12 mm long (the same manufacturer and diameter), *F*12 (% of concrete mix mass)	0	0.015	0.03

«accommodated in a proper way in the matrix». This means that an appropriate quantity and type of cement, quantity and fractions of aggregate should be determined. As it was formulated in [4], the matrix around each fibre must be dense enough «to ensure efficient utilisation of fibres in their pullout during opening and bridging of crack». To provide this when glass fibre is used some active mineral additive (metakaolin, microsilica…) should be introduced (as it was shown, specifically, in [3, 11], and was confirmed in [10]).

These considerations and some previously obtained experimental data have been taken into account when defining the factors to be varied in the experiment and their intervals of varying.

The content of the binder, «white cement (produced by CIMSA) + zeolite (fine clinoptilolite)», and of the aggregate (2 fractions of sand, 3.4 of cement mass) remained constant.

Presented in Table 1 are varied composition factors and their values in the experiment.

Characteristics of technological mix and properties of hardened material have been determined for 27 compositions, according to 5-factor 3-level design of the experiment (with Rechtschaffner structure [12, 13] and added central point, Table 2).

Plastic strength of concrete mix (P_m, kPa, at 10 minutes intervals, by the Vicat apparatus), water-cement ratio (*W/C*) at about equal workability (slump class S4), early and late linear shrinkage and strength, other mechanical and performance properties were determined for each of 27 compositions, enabling to describe the dependencies of material characteristics on composition factors (normalised to $|x_i| \le 1$) with 2nd order experimental-statistical (ES) models (as one shown below).

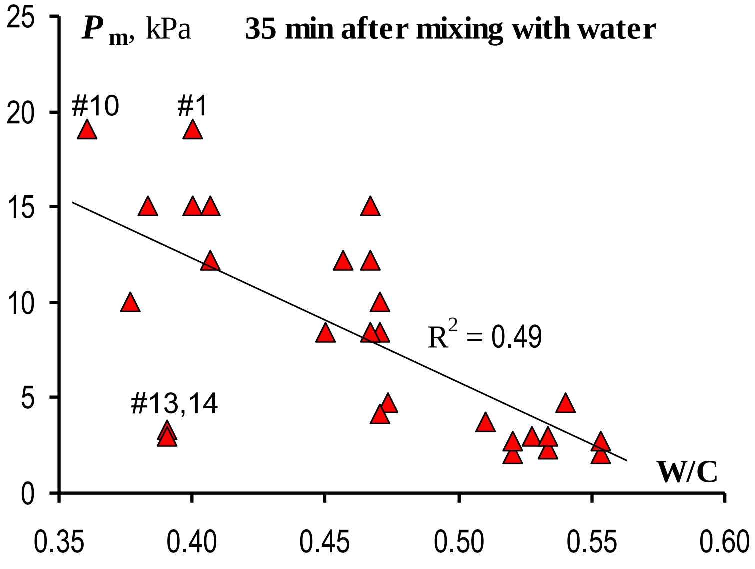

Fig. 1. Scatter diagram of experimental values of *W/C* and P_m for 27 compositions:
#1 – *Z* and *MF* at upper level, no long fibre,
#10, #13, #14 – *Z* at lower level, *MF* at upper level

Table 2 – Design of experiment

#	Normalised values of factors					Natural values of the factors				
	x_1	x_2	x_3	x_4	x_5	*Z*	*SG*	*MF*	*F*6	*F*12
1	1	1	1	1	–1	8	70	0.7	0.03	0
2	1	1	1	–1	1	8	70	0.7	0	0.03
3	1	1	–1	1	1	8	70	0.3	0.03	0.03
4	1	1	–1	–1	–1	8	70	0.3	0	0
5	1	–1	1	1	1	8	30	0.7	0.03	0.03
6	1	–1	1	–1	–1	8	30	0.7	0	0
7	1	–1	–1	1	–1	8	30	0.3	0.03	0
8	1	–1	–1	–1	1	8	30	0.3	0	0.03
9	–1	1	1	1	1	0	70	0.7	0.03	0.03
10	–1	1	1	–1	–1	0	70	0.7	0	0
11	–1	1	–1	1	–1	0	70	0.3	0.03	0
12	–1	1	–1	–1	1	0	70	0.3	0	0.03
13	–1	–1	1	1	–1	0	30	0.7	0.03	0
14	–1	–1	1	–1	1	0	30	0.7	0	0.03
15	–1	–1	–1	1	1	0	30	0.3	0.03	0.03
16	–1	–1	–1	–1	–1	0	30	0.3	0	0
17	1	0	0	0	0	8	50	0.5	0.015	0.015
18	–1	0	0	0	0	0	50	0.5	0.015	0.015
19	0	1	0	0	0	4	70	0.5	0.015	0.015
20	0	–1	0	0	0	4	30	0.5	0.015	0.015
21	0	0	1	0	0	4	50	0.7	0.015	0.015
22	0	0	–1	0	0	4	50	0.3	0.015	0.015
23	0	0	0	1	0	4	50	0.5	0.03	0.015
24	0	0	0	–1	0	4	50	0.5	0	0.015
25	0	0	0	0	1	4	50	0.5	0.015	0.03
26	0	0	0	0	–1	4	50	0.5	0.015	0
27	0	0	0	0	0	4	50	0.5	0.015	0.015

Plastic strength: the data, descriptions of curves, generalising indices. The values of P_m at fixed moments of time have been viewed in relation with *W*/*C*. Correlation of P_m with *W*/*C* is detected starting from 25 minutes after mixing with water (correlation coefficient r = –0.60 significant at risk less than 0.1 %, with a sample size of 27), is closest at τ = 65 min (r = –0.74).

Spread diagram of W/C and P_m in Fig. 1 shows the data for 27 mixes at τ = 35 min (the time when the mix begins to correspond to the consistency of the class S4, r = –0.70).

The process of initial structure formation for each of 27 compositions is described with exponential function (1), with exponent being polynomial of 5th degree (for some compositions adequate at 3rd or 4th degree).

$$P_m = \exp(a_0+a_1\tau+a_2\tau^2+a_3\tau^3+a_4\tau^4+a_5\tau^5) \quad (1)$$

Function (2) describe the growth of plastic strength for composition # 3 (Fig. 2; got with *CurveExpert*, standard error 0.103, coefficient of determination 0.997).

$$P_m = \exp(1.011 + 0.355\tau + 2.688\tau^2 - 2.794\tau^3 + 1.012\tau^4) \qquad (2)$$

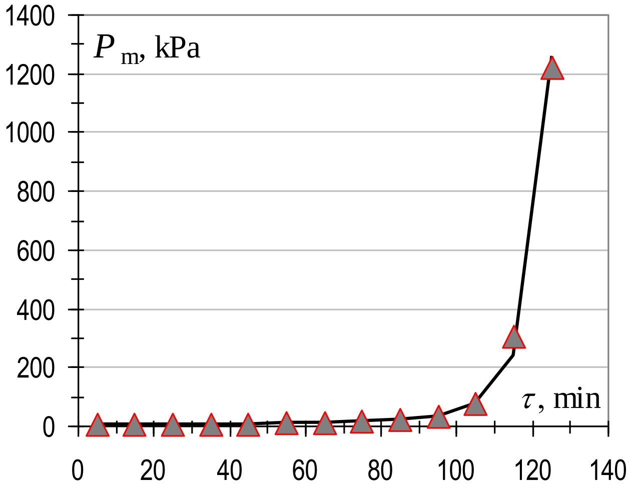

Fig. 2. Values and curve of plastic strength of composition # 3 (lower content of superplasticiser, other factors at upper levels)

Shown in Fig. 3 are the examples of plastic strength curves on logarithmic scale.

Three first stages of initial structure formation can be seen on such graphs, in particular, for composition # 13: forming of coagulation structure, induction period and then crystallisation stage.

Generalising indices of plastic strength growth. To compare, analyse, and control the processes of structure formation some numerical measures, generalising criteria (*G*) could be used. In case of consistancy growth process, those could be values of P_m at some specific points on the curve, the time corresponding to certain P_m-value, or characteristics of structure formation rate. Some of the later were put forward in [14, 15].

The following criteria *G*, in particular, have been estimated for 27 mixes on the data obtained:

- the value of P_m in half an hour after mixing with water, $P_m\{\tau=0.5\}$;
- the time of achieving P_m equal 35 kPa, the real root of equation (1) for this condition, $\tau\{P_m=35\}$;
- «instantaneous» rate of plastic strength growth (3) at some time, in particular, τ_c relating to the crystallisation stage, $v\{P_m(\tau_c)\}$.

$$v(\tau) = dP_m/d\tau = (a_1+2a_2\tau+3a_3\tau^2+4a_4\tau^3+5a_5\tau^4)\cdot\exp(a_0+a_1\tau+a_2\tau^2+a_3\tau^3+a_4\tau^4+a_5\tau^5) \qquad (3)$$

The instantaneous rate has been calculated for the time τ_c when P_m = 135 kPa is reached (shown in Fig. 3).

The estimates of generalising indices of the initial structure formation processes in 27 compositions (at 27 points of experiment design) have allowed ES-models to be built, such as one (4) for $P_m\{\tau=0.5\}$.

Such models for numerical characteristics of time processes in concrete mixes make it possible to describe the specific features of these processes in dependence on composition. The model (4) and analogous ones for $\tau\{P_m=35\}$, $v\{P_m(\tau_c)\}$, and other characteristics of plastic strength kinetics describe the «whole» fields of these criteria, in the coordinates of all composition factors under study [16, 17].

The field of $P_m\{\tau=0.5\}$, in particular, has maximal level around 35 kPa, with contents of zeolite, fine sand and admixture at upper levels and median dosages of fibres.

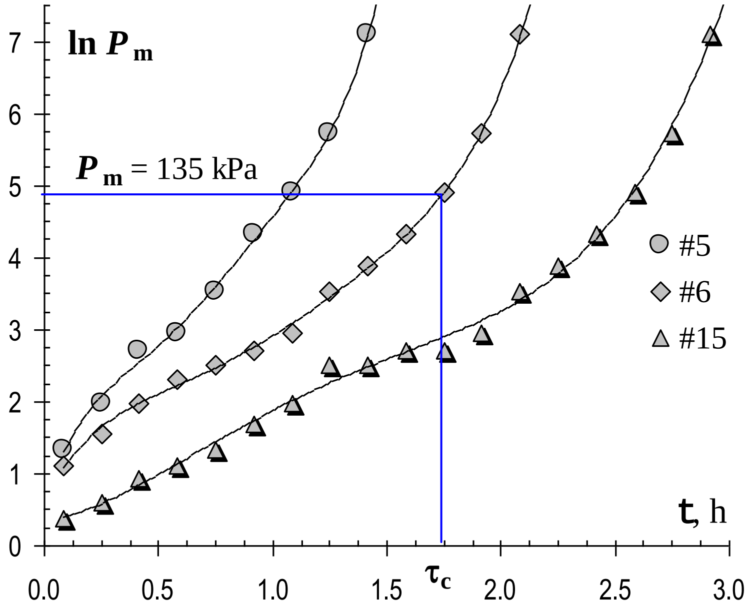

Fig. 3. Growth of plastic strength of 3 compositions: # 5, 6 – *Z* and *MF* at upper level, # 15 – at lower level

$$\begin{array}{llllll}
\ln P_m\{\tau=0.5\} = 2.08 & +\,0.22x_1 \; +\,0.20x_1^2 & \pm\,0x_1x_2 & +\,0.20x_1x_3 & +\,0.11x_1x_4 & +\,0.09x_1x_5 \\
 & +\,0.18x_2 \; +\,0.32x_2^2 & & +\,0.16x_2x_3 & \pm\;0\;\;x_2x_4 & \pm\;0\;\;x_2x_5 \\
 & +\,0.56x_3 \; -\,0.36x_3^2 & & & \pm\;0\;\;x_3x_4 & -\,0.18x_3x_5 \\
 & -\,0.07x_4 \; -\,0.34x_4^2 & & & & +\,0.20x_4x_5 \\
 & \pm\;0\;\;x_5 \; -\,0.41x_5^2 & & & &
\end{array} \qquad (4)$$

Shown in Fig. 4 are the «local» one-factor fields [17] of the indices presented above, when other four factors correspond to minimal or maximal level of the whole field.

In addition to the obvious substantial influence of superplasticiser, mentioned should be the significant effect of short fibre on the instantaneous rate at started stage of crystallisation. These and other individual and combined effects of the components could be further analysed.

The values of characteristics of plastic strength and the data on early shrinkage and strength of too different concretes, from the whole region of compositions under study, did not show any correlation. The correlation between the properties at various stages of the life of concrete could be revealed in local regions of the formulations with the help of computational experiments [17, 18], using ES-models built on the data obtained in the real experiment. It is planed to fulfill such virtual experiments in order to analyse the relations between the properties of decorative concrete.

Conclusions. The data on technological stage of the live of the decorative concrete have been obtained in the designed experiment. Numerical characteristics generalising the process of the earliest structure formation have been proposed, estimated for great number of the compositions.

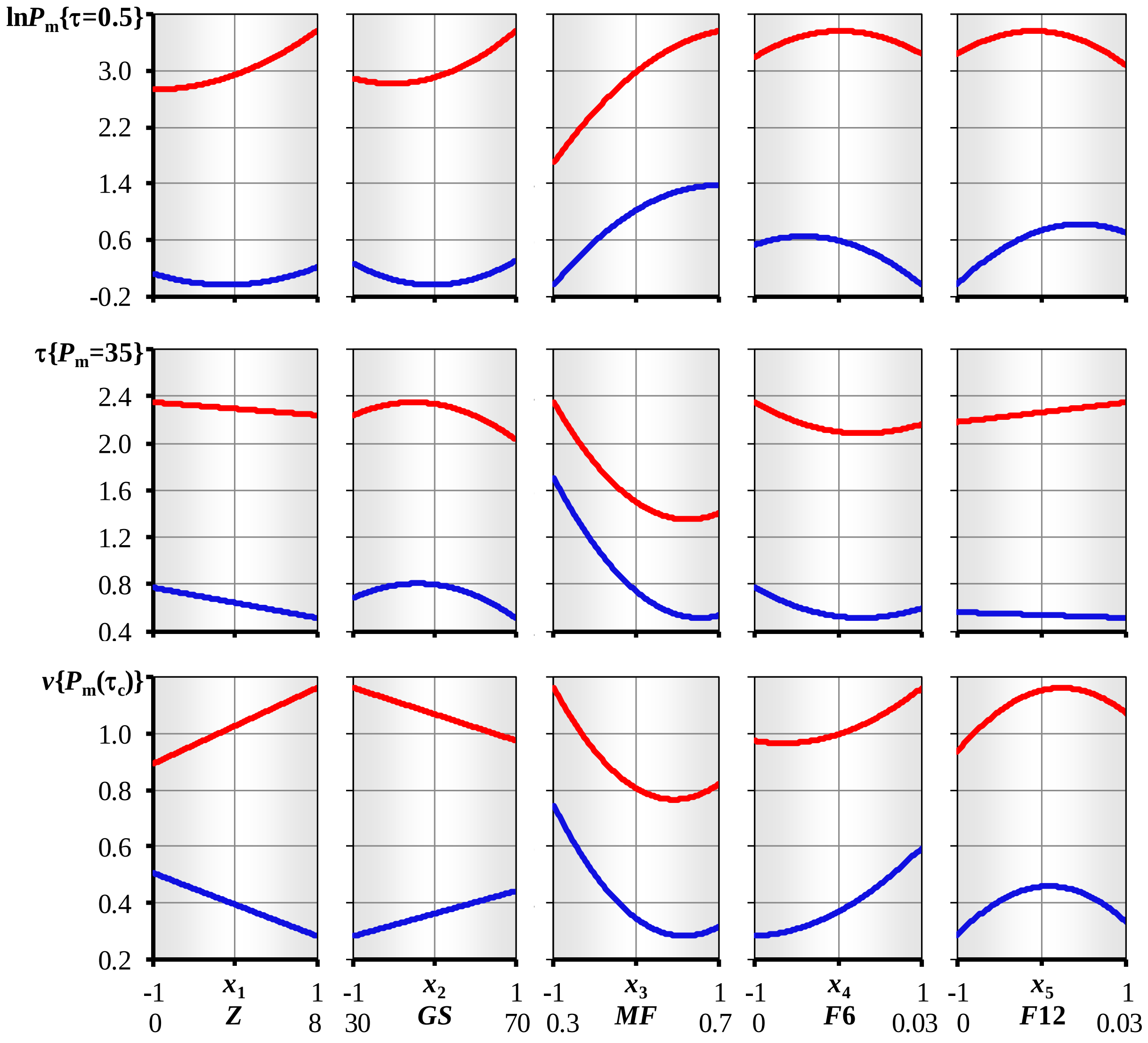

Fig. 4. One-factor dependences of numerical characteristics of the kinetics of initial structure formation in zones of their extrema

The combined use of the equations of the processes of structure formation and ES-models for their numerical characteristics, describing the fields of these criteria in coordinates of multicomponent composition, would be helpful when developing fine-grained concrete of decorative purpose.

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Стаття надійшла 18.03.2018