

This study investigates cement-plasticized slurry for the production of decorative concrete based on it. Given the difficult operating conditions of concrete in architectural elements, it is important to enable the preservation of its functional properties. Due to the fact that the microstructure of the material of articles is a rather disordered system, consisting of substructures and discontinuities of different composition, it is necessary to optimize the process of cluster aggregate formation and its interparticle interaction.

This paper considers issues related to the study of the influence of modifiers and fibers on the processes of structure formation of 25 pastes. Analysis of changes in rheological parameters revealed that, depending on the composition of discrete particles and their modification, it is possible to significantly improve the adhesion strength and energy of the interaction of aggregates. It was found that when replacing part of the cement with zeolite in highly plasticized unreinforced systems, the plastic strength increases by 11.5 times, and the rate of its growth at the point of 2 kPa increases by 1.7 times.

It was established that among discrete fibers, short fibers have a significant impact on the initial process of structure formation of pastes, especially in compositions with a low level of modification of binder systems. An increase in the content of short fibers while simultaneously reducing long fibers provides an increase in plastic strength and speed by 4.2 and 3.3 times, respectively.

The use of kinetic equations of structure formation processes together with experimental and statistical models for analyzing the influence of formulation factors on rheological indicators is appropriate in the design of rational compositions of binder slurry for decorative concretes. The devised compositions of cement slurry, subject to comprehensive analysis and optimization of the parameters of the structure of the binder stone, will be implemented in the practice of manufacturing concrete for architectural elements

Keywords: cement paste, fiber concrete, pozzolanic activity, experimental-statistical model, decorative concrete

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REVEALING THE INFLUENCE OF ZEOLITE AND FIBER ON THE PROCESSES OF STRUCTURE FORMATION IN PLASTICIZED CEMENT COMPOSITIONS

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1. Introduction

In recent decades, there has been a clear trend towards an increase in demand for architectural items (parts, elements) made from decorative cement composites similar to natural stone of various origins. The use of decorative elements for the exterior decoration of various infrastructure facilities makes it possible to significantly diversify the artificial environment in which people reside and create comfortable conditions for their lives.

With the progress of science and technology and the development of the cement composites industry, architectural elements are now produced in a variety of colors, textures, plastic outlines and curvilinear shapes, which most clearly reproduce the beauty of elements created by nature. Given that decorative solutions (concretes) have already gained significant technical capabilities in the industrial design of articles, they have a good future in use for the coming decades. In addition, an important aspect is that these composites are made from environmentally friendly non-combustible building materials, and the articles, at the stages of production and installation, do not require complex and lengthy technological processes. Due to the use of various raw materials, architectural elements are obtained, the material of which initially has regulatory indicators of physical and mechanical properties and an aesthetically expressive front surface.

However, during the operation of elements due to the deterioration of the environment, the synergistic effect of climatic and other factors, structural changes occur in decorative composites. The destructive effect of these factors leads to a deterioration in aesthetic properties, the appearance of cracks and other defects on the surface of the elements, and subsequently to the loss of structural connections between material components in the volume of the material. In order to enable the operational reliability of the material in articles, in addition to organo-mineral additives, discrete fibers of various nature and geometric parameters are introduced into its composition. The use of various fibers certainly strengthens the structure of composites. However, in most cases, it does not provide proper control over the preservation of the decorative surface and functional properties of articles during their service life. This is due to the fact that the stability of the bonds between the structural aggregates of the material depends on the compatibility of the fiber and the cement matrix that binds them. That is, on the ability of the fibers and particles of the dispersed phase, at the initial stage of the formation of the microstructure of the decorative composite, to form bonds without possible destruction of them under the influence of physicochemical and physical-mechanical processes of structure formation.

At the same time, the degree of mutual influence of the fibers and dispersed particles on the formation of optimal

structural bonds depends on the presence of additives, the ratio of the initial components, the dispersion, and the area of the contact surface between them in the volume of the matrix, specifically, on the interaction energy and the density of contacts of the fiber with the particles of the matrix material. Filling the cement matrix with various highly dispersed particles requires a deeper understanding of their interactions at the interface of discrete elements. To assess interparticle interactions at the initial stage of structure formation, the most appropriate are structural-rheological indicators of dispersed systems (plastic strength, water-cement ratio, etc.).

Therefore, scientific research into the processes of structure formation of cement slurry in a decorative composite is relevant.

2. Literature review and problem statement

The effect of polycarboxylate additive on the microstructure of cement pastes was studied in [1–3]; the characteristics of the distribution of hydration products and pores were analyzed; the heat and degree of hydration and the hardening time of cements were determined. The results showed that the introduction of the additive reduces the content of flocculent structures of the cement paste, contributes to better dispersion of particles within the system, moreover, with a smaller average distance between them. This leads to a decrease in porosity, a more uniform distribution of pores in the volume of the stone and can prevent the further formation of discontinuities in the form of cracks due to moisture loss. The authors share the opinion that polycarboxylate delays the process of cement hydration, reduces the growth rate of hydration products in proportion to the amount of introduction [2] but increases the maximum rate of heat flow [1] compared to the composition without the additive. However, from a practical point of view, the mechanism of the influence of polycarboxylate on the formation of initial bonds between cement particles at the early stage of structure formation of binder systems is not entirely clear. In work [1], the researchers tested 4 different pastes at the age of 9, 12, and 24 h, and in compositions with the same water-cement ratio. Similarly, in [2], when studying the effect of polycarboxylate on the growth rate of hydration products of model cement C_3S , the study was carried out on compositions with different slurry mobility, and on a simplified binder system. The test methods used by the authors do not allow a qualitative assessment of the effect of the additive on the development of the microstructure of the cement paste in the initial period of its formation. In work [3], a number of mechanisms of interaction of the additive with the surface of cement particles are highlighted. The authors note that different functional groups of polycarboxylate can have different effects on the dispersive and adsorption capacity of particles, as well as on the induction period of cement hydration. They also emphasize that the issues of the formation of bonds between particles and the development of the microstructure of the material plasticized with polycarboxylate remain open.

In turn, it was established in [4–6] that by providing the appropriate rheology parameters, it is possible to effectively influence the interaction of clinoptilolite zeolite particles and cement matter within the system. It was found that the efficiency of zeolite is related to the size of its particles and the specific surface area, the ratio of chemically active oxides SiO_2/Al_2O_3 and the content of exchangeable cations

in the volume of its elementary cells. Due to the increased pozzolanic activity of finely ground zeolite, the possibility of the formation of natural crystallization centers and a variety of hydroxyl phases of calcium silicate is created in the binder system. But at the same time, the heat of hydration and the volume of chemical shrinkage [5] of pastes increase, and the density [6] of composites decreases. On the one hand, the introduction of clinoptilolite makes it possible to increase the number and variety of new silicate phases, and on the other hand, provokes the development of larger volumetric deformations during the formation of substructures of the composite. However, there are contradictions in [4–6] regarding the influence of clinoptilolite on the structure-forming processes of hardening of binder pastes. In work [4], it is shown that although the pozzolanic activity of zeolite accelerates the early and late hydration of cement, the content of portlandite $Ca(OH)_2$ remains unchanged. Given the comprehensive studies reported in [5] on the influence of zeolite of various degrees of grinding on the rheological properties of cement systems, the cited work does not consider the optimal dispersion of pozzolana and a detailed analysis of the microstructure of the composite. At the same time, in [6], it was demonstrated that replacing cement with zeolite slows down hydration processes, but no data were provided on the influence of the water-cement ratio (W/C) on the composite performance and zeolite on the kinetics of early hydration of the binder. Also, in work [7], when studying the influence of modified Portland cement on the durability of the composite, the influence of different amounts of zeolite on the ease of workability of the mixtures was not considered. According to the data provided, the mixtures were prepared with the same content of polycarboxylate and a constant W/C ratio. And as is known, clinoptilolite zeolite is a highly porous material, which significantly increases the water consumption of compositions. All this gives grounds for conducting research to establish a rational amount of organo-mineral additives to obtain proper rheological properties of the slurry and to improve properties at the interface. At the same time, an option for solving the issue of restraining the development of deformation processes during the transition of cement slurry from a plastic state to a solid state may be the introduction of discrete reinforcement into the mixture.

That approach was used in [8] when filling cement pastes with hydrophilic fiber. The results of the studies demonstrate that the presence of fiber, although it reduces the development of the maximum temperature and the heat of hydration of the slurry, increases the water absorption and porosity of the stone, and there is a low interaction of fibers with cement particles. In turn, in a number of papers [9–11], researchers prove that the amount of hydration products and the degree of compaction of the interfacial transition phase play a key role in the strength of the fiber-matrix bond and the properties of composites. The addition of polycarboxylate and pozzolanic additives generally allows for strengthening the bond of the fiber with the cement matrix. However, the authors of the cited works pay little attention to the mechanism of the influence of fiber on the rheological behavior of the binder slurry modified by additives. The conclusions they summarize mainly focus on the results of microscopic and physical-mechanical studies of cement composites. In [9], the researchers do not indicate whether the fiber is an active element around which cement particles and mineral additives are structured, in particular, they do not provide information on the mechanism of organization of hydrated particles with

fiber. Instead, in work [10], it is noted that the fiber is interconnected with the products of cement hydration and forms a three-dimensional network in the composite, and also, with a rational amount of it, can improve the integrity of the matrix. However, experts have not identified the reason for the deterioration of the strength indicators of the material, with a greater saturation of it with dispersed fiber. It would be advisable to investigate the kinetics of the heat of hydration of cement or the growth of the structural strength of the paste over time.

Finally, it is demonstrated in [11] that the use of fiber of different composition and geometry affects not only the mechanical but also the rheological parameters of composites. However, the cited work does not analyze the mechanism of the influence of discrete fibers on the initial structure formation of pastes, although the authors emphasize that the introduction of synthetic fibers and CaCO_3 microfibers significantly reduces the fluidity of the mixture. From this point of view, it is important to evaluate the initial contact interaction of fibers with binder particles, since stresses (deformations) that arise under the influence of the structure formation processes lead to the rupture of bonds between discrete elements.

Therefore, the use of additives and fibers, diverse in nature, geometric shape and specific surface area, should contribute to obtaining substructures of the binder system with a greater strength of their contact interaction and with a smaller number of discontinuities. However, during the formation of the microstructure, it is important to control the course of the initial processes of structure formation of cement pastes. This is due to the fact that the formation of the structure of the compositions (up to 10 h) is accompanied by an increased effect of deformation processes, which lead to a decrease in the density and strength of contacts between discrete particles in the volume of the material. In this context, the issue of ensuring the appropriate rheological parameters of the binder slurry for the most favorable build-up of the physical and mechanical properties of the composite substructures on the intercluster interfaces remains open.

All this gives grounds to argue that it is advisable to conduct a study on the influence of zeolite and fiber on the initial processes of structure formation of plasticized cement pastes using structural and rheological indicators of binder compositions.

3. The aim and objectives of the study

The aim of our study is to identify the influence of discrete glass fibers and finely dispersed zeolite on the formation of structural bonds in the initial period of the process of structure formation of cement slurry, plasticized with a polycarboxylate additive. This will make it possible to establish the structure-forming role of fibers and organo-mineral additives in the organization of the microstructure of the decorative composite at the early stage of its hardening.

Achieving the specified goal necessitates the implementation of the following tasks:

- to investigate the rheological parameters of the processes of structure formation of different compositions of the binder paste with control over the hydration temperature of the hardening of the compositions;
- to determine and analyze the general indicators of plastic strength, to identify correlations between the structural parameters of the matrix;

- to build experimental-statistical models of the indicators of the initial process of coagulation structure formation of the binder slurry.

4. The study materials and methods

4.1. The object and hypothesis of the study

The object of this study is cement-plasticized slurry (matrix material) for the production of decorative concrete based on it.

The principal hypothesis assumes that the introduction of rational amounts of modifiers and fibers of a certain length into the slurry could make it possible at the initial stage of structure formation to form optimal structural connections between particles (clusters) of the material.

The assumptions adopted in the study are that the fiber, being distributed into monofibers during slurry preparation, is an active center around which various particles of the dispersed phase are grouped in a dispersion-plasticized environment. As a result, the volume of the matrix is permeated with a fine-fiber structural network with different, in terms of interaction energy, contacts between discrete particles (aggregates) of the binder system. Therefore, the nature of the interparticle interaction at the initial stage of the organization of cluster substructures should affect the kinetics of the structure formation of the binder slurry, and subsequently the mechanical strength of the bond between the contacting phases.

The study used a hydrophilic fiber that is well wetted by water and easily disintegrates into monofibers. The cross-section of the monofibers is commensurate with the average diameter of the initial cement and zeolite particles. This allows for improved distribution of discrete elements in the volume of the binder paste and contributes to a more compact packing of all the initial particles of the dispersed phase.

4.2. Description of the experimental conditions

Planning and conducting experimental studies of the properties of the dispersed system were performed using experimental statistical modeling (ESM) and the methodology of formulation-technological fields [12].

Full-scale tests of the cement matrix were carried out in two stages: in the first, the structural and rheological parameters of the slurry were determined; in the second – the physical and mechanical indicators of the stone. The experiment was carried out according to a symmetrical unsaturated plan, which included the study of the characteristics of 25 different compositions of the binder slurry. The experimental plan with the compositions is reported in [13]. The dosages of 4 formulation factors X_i were varied in the experiment. To study the influence of input factors on the initial processes of structure formation of binder minerals, the variables X_i were combined into two groups.

The first group included the factors “Modifiers of the cement system”:

- finely dispersed zeolite at levels $X_1 (Z) = 4 \pm 4\%$, was introduced to replace part of the cement. Natural zeolite is a group of framework aluminosilicates with a concentration of clinoptilolite mineral 83–96% and contains in a chemically active form silica and alumina, the ratio between which is 5.5. A feature of the zeolite from the Sokyrynsky deposit (Transcarpathian oblast, Ukraine) is a porous structure with a pore volume of 54% and a size of 2–9 Å;
- the superplasticizer *Melflux* was dosed in an amount of $X_2 (MF) = 0.3 \pm 0.15\%$ of the mass of the binder. The

additive (manufacturer – BASF Construction Polimers, Germany) is a powdered polycarboxylate ether, characterized by a comb-like spatial structure. Due to the increased steric effect, Melflux improves the initial dispersion of the binder slurry particles and can to some extent affect the hydration of cement grains.

The second group of composition factors consisted of “Discrete reinforcement parameters”:

– alkali-resistant discrete glass fibers with a length of 3 and 12 mm, the concentration of which in the mass of the binder slurry varied at the levels $X_3 (F3) = X_4 (F12) = 0.15 \pm 0.15\%$. The fiber manufacturer is Owens Corning (USA). The peculiarity of hydrophilic fibers, characterized by a density of 2680 kg/m^3 and an elastic modulus of 72 GPa, is their high degree of distribution during the preparation of cement compositions.

The formulation factors X_i according to typical formulas [12] are normalized within the limits of $-1 \leq x_i \leq 1$. The basic component for 25 different in composition plasticized dispersed systems is white Portland cement of the CEM I 52.5R brand from the Turkish manufacturer CIMSA (EN 197-1:2011). To achieve optimal distribution and a certain adhesion between the initial particles of the slurry, fiber was used to reinforce the matrix structure, which in cross section is commensurate with the average diameter of the cement and zeolite grains. The specific surface area of the cement binder is $S = 4600 \text{ cm}^2/\text{g}$ according to Blaine.

The reference for the experiment in [13] was taken a composition #16 with a low level of plasticization of the binder slurry ($x_1 = x_2 = x_3 = x_4 = -1$ or $X_1 = X_3 = X_4 = 0, X_2 = 0.15\%$). The compositions of the matrix material were made with the same flowability in terms of the diameter of the cement slurry spread ($\varnothing_p \approx 300 \text{ mm}$), at minimum and maximum water-cement ratios (W/C) of 0.20 and 0.31, respectively.

4. 3. Methods for studying the properties of the matrix material

To study the initial process of structure formation of dispersed systems, the penetration method was used. The essence of the method is to determine the depth of immersion (h , mm) of a cone-shaped indenter into the hardening binder slurry. Measurements of h , which were carried out under the action of a constant load (F , H) and after the same period of time (every 10 min), allow one to estimate the plastic strength (P_m , kgf/cm^2) of the cement system from the following formula

$$P_m = k \frac{F}{h^2}, \quad (1)$$

where k is the constant of the device, the value of which depends on the angle at the apex of the cone.

Determination of plastic strength in time (τ) was performed over a limited period of structure formation, up to $\tau \leq 2.08 \text{ h}$. Given that the time of preparation of the binder slurry affects the kinetics of growth P_m , τ was taken constant and was 5 min. The CurveExpert program (Daniel G. Hyams, USA) was used to process P_m data in time.

The process of formation of the structure of cement systems was additionally evaluated by changing the temperature of the hardening slurry at a certain point in time. In the study, it was decided to control the temperature (T , °C) of the cement slurry by direct measurement of the value in a calorimeter, which corresponds to [14] by design. The first reading of T was taken 20 min after preparation of the binder paste, and then every 30 min until $\tau \leq 6 \text{ h}$. During

the experiment, curves of temperature changes in time were obtained for different compositions of the matrix material. Comparison of kinetic curves allowed me to judge the initial formation of the structure of the compositions.

Auxiliary criteria for assessing the quality of structural bonds between discrete matrix components at their interface were the compressive strength (f_{cm} , MPa), average density (ρ , kg/m^3), and damage (K_D) of cement stone. It should be noted that the larger the K_D value, the denser and stronger the bond between discrete elements of the binder system. The study of f_{cm} is due to the fact that the matrix material at the stage of determining its plastic strength P_m perceives the same internal stresses that arise when a compressive load is applied to the stone. In particular, the bond strength at the interface of structural aggregates (particles, phases) controls the mechanical behavior of the material. The manufacture and testing of samples for f_{cm} at the age of 28 days was carried out according to [15]. The determination of the K_D value of binder stone samples was carried out according to the methodology specified in [16].

To analyze the relationships between formulation factors and structural and rheological parameters of the dispersed system, experimental statistical models (ES models) were calculated based on experimental data [13]. The construction of ES models was performed in the COMPEX program (ODA-BA, Ukraine). In this case, the relative error of the experiment $s_e \leq 10\%$ was taken into account at a two-sided risk $\alpha = 0.1$; the hypothesis of the adequacy of the model was tested using the Fisher criterion.

5. Results of experimental studies of matrix properties

5. 1. Parameters of rheological curves of the kinetics of structure formation of cement pastes

The full rheological curves (or plastograms) of the plastic strength P_m for all 25 different compositions of the binder slurry over the studied time interval τ were described by an exponential function of the following form

$$P_m = e^{p(\tau)} = \exp(a_0 + a_1\tau + a_2\tau^2 + a_3\tau^3 + a_4\tau^4 + a_5\tau^5). \quad (2)$$

In function (2), the exponent is a polynomial $p(\tau)$ of the 5th power with a high coefficient of determination ($R^2 > 0.99$) and a standard error $s\{\ln P_m\} = 0.031 \div 0.314$ (the error was calculated in the CurveExpert program). For some compositions, the corresponding reliability of the approximation was achieved with polynomials of the 3rd and 4th powers, which indicates the presence of a high functional relationship between the quantities and the course of research with a small deviation. As an example, the model with a polynomial of the 4th power (3), describing the growth of P_m in time for the binder slurry #15 (Table 1), was obtained with a coefficient of determination $R^2 = 0.999$ and an error of 0.099

$$P_m = \exp(0.344 + 2.089\tau + 7.834\tau^2 - 9.294\tau^3 + 3.586\tau^4). \quad (3)$$

To identify the individual influence of zeolite and fiber on the processes of cement slurry structure formation, it is advisable to show the rheological curves P_m of binder pastes filled only with pozzolan (#4) or fibers (#15). And, accordingly, to analyze the rheological indicators of compositions #4 and #15 in relation to reference #16. However, due to the fact that zeolite in the manufacture of uniform cement pastes significantly increases their water consumption, it is

appropriate to demonstrate the plastogram of cement-zeolite slurry (#6) with a higher level of chemical modification of its initial particles. At the same time, to analyze the rheological parameters of cement-zeolite pastes #4 and #6, plasticized with minimum and maximum levels of polycarboxylate. The compositions analyzed in this chapter are given in Table 1.

tion of the compositions (Table 1), and further when $P_m = 5$ kPa was reached with an equal interval of 10 kPa. Visualization of the kinetic curves of velocity $\nu\{P_m\}$ generally demonstrated a similar correspondence to their plastograms of cement pastes. In order to obtain more thorough information on the speed, the intensity of its change was estimated according to (4) on the studied time interval P_m

Compositions of 4 out of 25 types of matrix material and their quality indicators

Composition No.	Normalized variables				Full-scale values				*P_m , kPa	ρ , kg/m ³	K_D	f_{cm} , MPa
	x_1	x_2	x_3	x_4	X_1 (Z)	X_2 (MF)	X_3 (F3)	X_4 (F12)				
#4	+1	-1	-1	-1	8	0.15	0	0	1.36	1950	0.859	67.0
#6	+1	+1	-1	-1	8	0.45	0	0	1.36	2187	0.919	90.2
#15	-1	-1	+1	+1	0	0.15	0.03	0.03	1.68	2126	0.915	106.4
#16	-1	-1	-1	-1	0	0.15	0	0	1.36	2104	0.900	75.8

Note: * - the value of the plastic strength after the preparation of compositions

Fig. 1 shows the curves of changes in plastic strength for 4 (Table 1) out of 25 formulations of the composition, the initial mobility of which was provided by different water-cement ratios. It should be noted that when the maximum value $P_m = 1221.8$ kPa was reached, the end of the slurry hardening period came for all compositions.

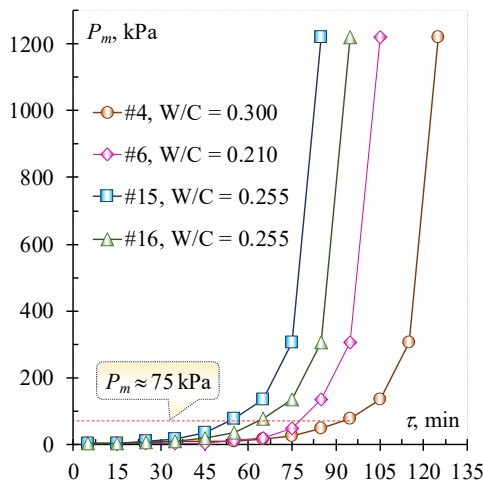


Fig. 1. Plastograms of formulations #4, #15, and #16 with a low level of plasticization of the compositions and with a high level — for slurry #6

For a visual representation of the staged processes of composition structure formation (Table 1), Fig. 2 shows changes in plastic strength over time in the logarithmic scale of the P_m data.

The plots show the stages of coagulation, induction, and crystallization periods of the structure formation of the binder slurry. The transient processes are especially pronounced during the hardening of cement paste #4, which initially has a higher W/C ratio of 0.30.

To establish the structure-forming role of the initial components of the slurry, the rate (ν , kPa/h) of increase in plastic strength P_m in time, up to $\tau \leq 2.08$ h, was calculated for 25 compositions. The determination of ν was performed at fixed points of the full rheological curve P_m (Fig. 1). The calculation of ν was started at the value *P_m , obtained immediately after the prepara-

$$\Delta \nu\{P_m\} = \frac{\nu_i\{P_m\} - \nu_{i-1}\{P_m\}}{\Delta P_m}, \tag{4}$$

where $\nu_i\{P_m\}$, $\nu_{i-1}\{P_m\}$ is the rate of increase in plastic strength at the end of “ i ” and previous “ $i - 1$ ” intervals, kPa/h; ΔP_m is the interval of plastic strength, kPa.

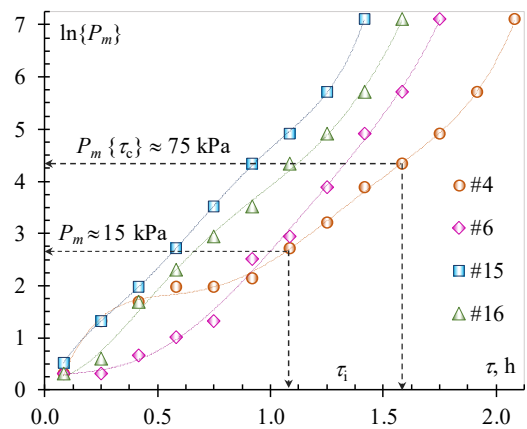


Fig. 2. Rheological curves of plastic strength of different slurry compositions

According to the obtained data (4), as an example, Fig. 3 shows curves for 4 (Table 1) different types of binder pastes, characterizing the kinetics of change in $\Delta \nu\{P_m\}$ depending on the qualitative and quantitative content of the composition factors and W/C of the slurry.

The diagram shows that the rate of change in plastic strength in the induction and crystallization periods depends on the initial conditions of the organization of cluster structures at the stage of coagulation structure formation of compositions. At the same time, the strength of coagulation structures is determined by the adhesion force of particles, the concentration of cluster aggregates (particles), the degree of uniform distribution of active particles in the dispersion medium of the binder slurry and the level of chemical modification of the particle surface by the polycarboxylate additive.

When studying the rheological parameters of dispersed systems, it is important to have a complete understanding of the processes of their structure formation. Indirectly, the initial processes of structure formation can be judged by the kinetics of temperature changes (T , °C) of hardening binder pastes. In Fig. 4, for compositions, graphical dependences of change in T of cement slurry for 6 hours are demonstrated.

As can be seen from the comparison of the curves in Fig. 4, the kinetics of the temperature change of the pastes are significantly influenced by the presence of highly dispersed fillers in the plasticized compositions of the binder composition. Moreover, the nature of the influence of finely dispersed zeolite and discrete fibers on the increase in temperature during the hydration of clinker minerals on the surface of cement grains is fundamentally different.

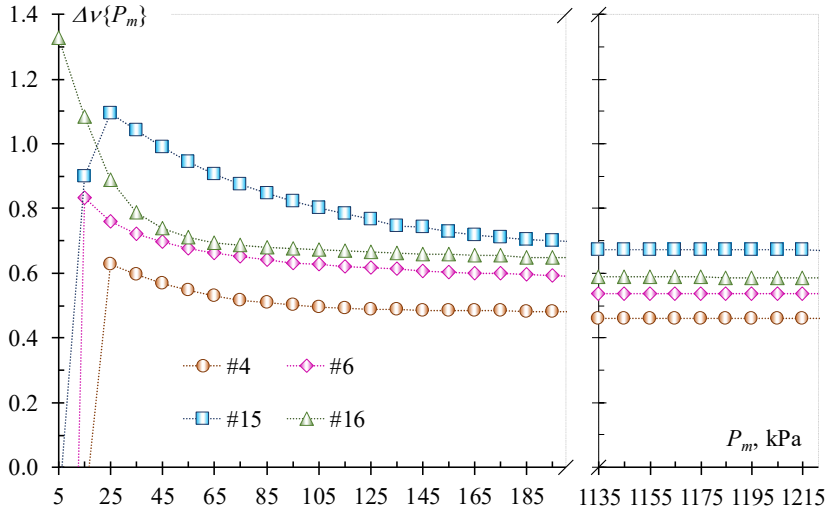


Fig. 3. Intensity of change in the rate of growth of plastic strength of hardening compositions for 4 formulations

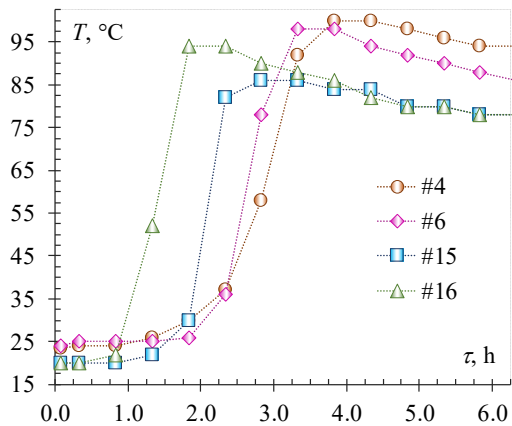


Fig. 4. Kinetic temperature curves of binder slurry of different compositions

The data obtained on the kinetic curves of the structure formation of binder pastes are characterized by a wide

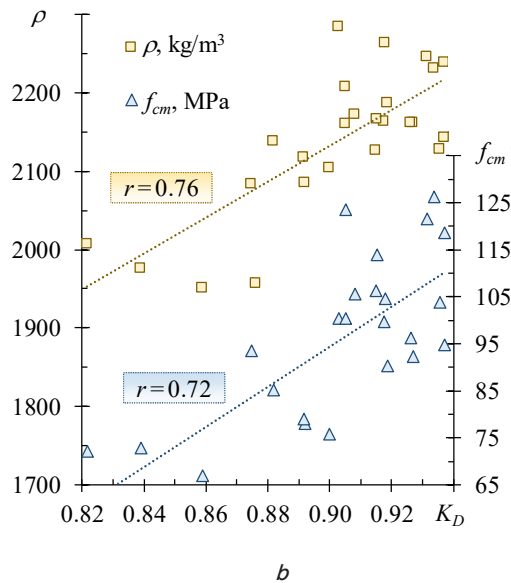
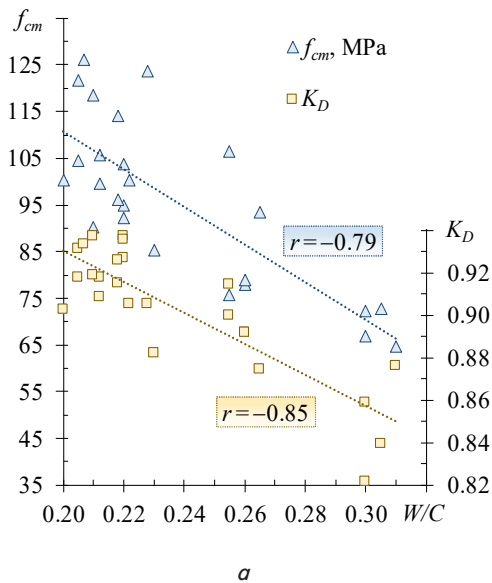


Fig. 5. Scatter diagrams of 25 pairs of values of material characteristics: a – W/C and f_{cm} , W/C and K_D ; b – K_D and ρ , K_D and f_{cm}

distribution of the values of indicators, which requires the further application of the experimental-statistical method [12] to analyze the results of the study on 25 compositions of the cement system.

5. 2. Generalizing indicators of slurry structure formation, correlation dependences between structural parameters of experimental data

For a deeper understanding of the processes of structure formation (during the formation of transitional structures of cement slurry), it is useful to obtain some numerical measures, generalizing indicators (G) according to the function $P_m(2)$. Some of these indicators were used in the study of decorative fine-grained mixtures [17].

It is known that for obtaining optimal structures of the binder stone, coagulation structures of dispersed systems are of great importance, especially at the initial stage of organization of cluster aggregates. Therefore, for 25 compositions, two generalizing indicators G of the rheological curve P_m , belonging to the initial period of coagulation structure formation of cement slurry, were determined:

- the value of plastic strength after 15 min (or 0.25 h) after mixing the dispersed starting materials with water, $P_m\{\tau = 0.25\}$;
- the rate of growth of the plastic strength $v\{P_m = 2\}$ at point 2 kPa of the P_m curve.

This work analyzed the correlation between the rheological indicators of plastograms P_m . Namely, the indicators of the primary stage with the parameters of the structures related to the subsequent stage periods of the formation of the structure of the binder paste (Table 2). The evaluation of the rheology criteria also allowed me to study the relationships with the physical and mechanical properties of the compositions. The dependences between the characteristics of cement stone were separately considered (Fig. 5).

Correlation ratios r of generalizing indicators in the P_m curve

r	Growth rate of plastic strength, $\nu\{P_m\}$ kPa/h				
	$\nu\{P_m = 2\}$	$\nu\{P_m = 5\}$	$\nu\{P_m = 15\}$	$\nu\{P_m = 75\}$	$\nu\{P_m = 1221.8\}$
$P_m\{\tau = 0.25\}$	0.894	0.988	0.955	0.776	0.610

Additionally, the correlation between the values of structural and mechanical parameters and the average density of cement stone (ρ , kg/m³) was considered.

5.3. Experimental-statistical models of indicators in the initial process of coagulation structure formation of binder slurry

When analyzing the influence of input factors X_i on the indicators of P_m curve, it is irrational to consider the coefficients a_i of exponential function (2) because it is difficult to assess their physical content. It is advisable to use the coefficients of experimental and static models (Table 3) as they directly link the properties of compositions with the formulation factors of the compositions.

According to the numerical data on P_m plastograms, non-linear quadratic models were constructed that describe the “full” fields of indicators in the coordinates of the 4 normalized factors x_i . In Table 3, for two criteria G , the coefficients of ES models, their maximum G_{max} and minimum G_{min} levels. The plastic strength models $\ln P_m\{\tau = 0.25\}$ and velocity models $\ln \nu\{P_m = 2\}$, obtained with 11 and 10 statistically significant effects, respectively, are adequate to the experimental data with root mean square errors $s_{\ln P_m} = 0.299$ and $s_{\ln \nu} = 0.695$.

The ES models are structured by the factor groups “Cement system modifiers” and “Discrete reinforcement parameters” (Table 3). The coefficient b_0 is equal to the value of the G indicators in the center of the factor space, with $x_i = 0$. Three blocks are distinguished in the models, which are separated by a double line. The first block contains the effects of x_1 and x_2 modifiers at average dosages of discrete fibers $x_{3,4} = 0$. The second block describes the effect of discrete reinforcement of different x_3 and x_4 lengths at basic levels of modification factors $x_{1,2} = 0$. Accordingly, the third block evaluates the synergistic effect of composition factors from the 1st and 2nd blocks on the binder system.

Table 3 demonstrates that the extreme levels (G_{max} and G_{min}) of the models demonstrate significant differences in rheological parameters within the full field. Therefore, it is advisable when interpreting the coefficients of the models to graphically represent the results of G modeling also on a logarithmic scale. In general, according to the ES models (Table 3), local fields can be constructed for various combinations of formulation factors x_i . Thus, according to the coefficients of the models, two-factor fields of the G criteria ($\ln P_m$ and $\ln \nu$) are constructed in the coordinates of two groups of gradient

Table 2 factors $x_{1,2}$ (Fig. 6, a, b) and $x_{3,4}$ (Fig. 6, c, d). At the same time, the fields of the $\ln P_m$ and $\ln \nu$ indicators are transformed under the influence of changing factors: discrete fibers $x_{3,4}$ (Fig. 6, a, b) and matrix modifiers $x_{1,2}$ (Fig. 6, c, d).

Table 3

ES model coefficients for generalizing P_m rheological curve indicators

G	$\ln P_m\{\tau = 0.25\}$	$\ln \nu\{P_m = 2\}$
b_0	0.268	1.386
b_1	-0.223	-0.514
b_2	-0.383	-0.682
b_{11}	0	0
b_{22}	+0.679	+0.783
b_{12}	+0.145	0.379
b_3	+0.146	+0.328
b_4	-0.156	-0.385
b_{33}	-0.276	0
b_{44}	0	0
b_{34}	0	0
b_{13}	-0.294	-0.522
b_{14}	0	0
b_{23}	-0.117	-0.393
b_{24}	+0.158	+0.385
G_{min}	-0.548	0.262
G_{max}	2.294	5.759

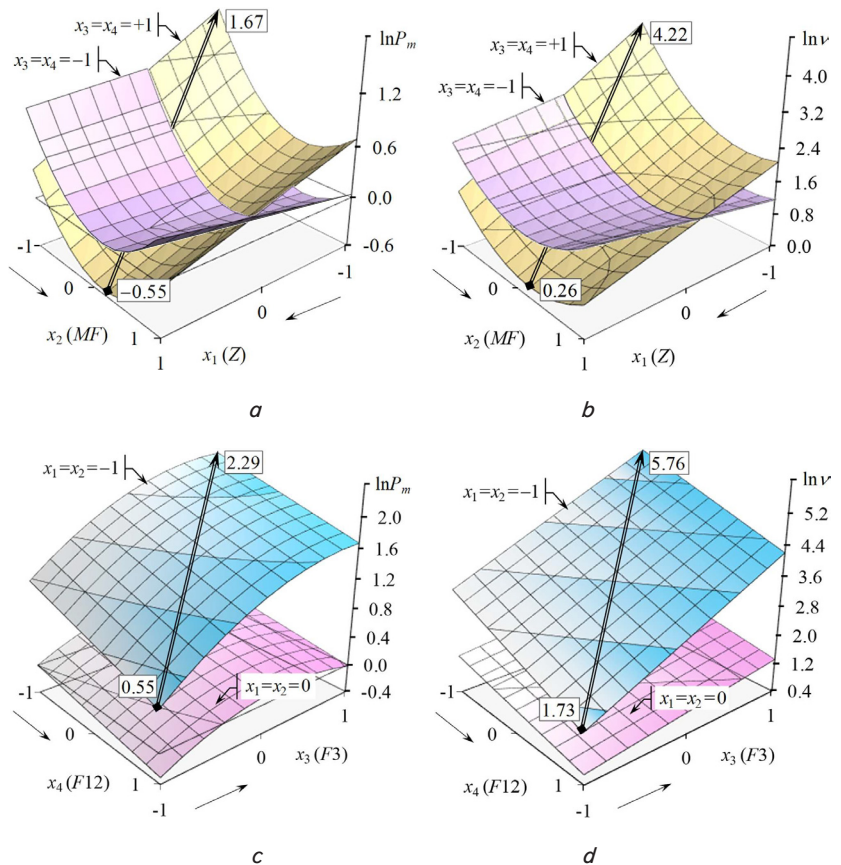


Fig. 6. Local fields of two rheological indicators in the coordinates of factors: a – “Modifiers of the cement system” at $x_{3,4} = -1$ and $+1$ for $\ln P_m$; b – “Modifiers of the cement system” at $x_{3,4} = -1$ and $+1$ for $\ln \nu$; c – “Parameters of discrete reinforcement” at $x_{1,2} = -1$ and 0 for $\ln P_m$; d – “Parameters of discrete reinforcement” at $x_{1,2} = -1$ and 0 for $\ln \nu$

For comparison and analysis of the modeling results, each diagram (Fig. 6) shows two surfaces that reflect the largest difference in G values at the specified levels of changing factors. In particular, on one of the two surfaces of the local field, the points of the maximum and minimum values of the indicator and the vector connecting them are plotted. These data allow me to estimate the change in the criterion within the factor space by the relative increase (δ_G).

6. Discussion of results based on investigating the processes of structure formation in binder compositions

As a result of studies on the structural and rheological parameters of 25 compositions, it was found that the formulation factors are active participants in the initial processes of structure formation of the binder slurry. Comparative analysis of rheological curves, which take into account different water-cement ratios of the compositions (Fig. 1), makes it possible to note the different nature of the influence of composition factors on the course of the structure-forming processes of the cement slurry. When studying logarithmic plastograms (Fig. 2), it was established that the “main” formation of the primary structures of different compositions ends in the period when the binder slurry reaches a plastic strength P_m of about 15 kPa (≤ 1.09 h). A characteristic feature of all compositions is a different time period of the induction period ($\tau_i \leq 0.5$ h). Along with this, the beginning of the rapid formation of the crystallization structure for 25 pastes occurs approximately at the same point of the curves $P_m \approx 75$ kPa. At the same time, an important factor affecting the rheological behavior of cement slurry from a technological point of view is the water-cement ratio (W/C). From the data on W/C compositions shown in Fig. 1, it follows that when preparing uniform compositions filled with zeolite, a larger amount of mixing water or an increase in polycarboxylate is required for chemical modification of the surface of dispersed particles. This is due to the fact that pozzolan grains have a highly developed specific surface area, unlike particles of cement matter. Naturally, a decrease in W/C , due to the increased content of polycarboxylate in the dispersion medium, has a positive effect on the process of forming interparticle contacts in composition #6 and has a favorable effect on the mechanical strength f_{cm} (Table 1). With a reduced water content of 30% in cement paste #6 compared to #4, the damage to the stone decreases by 7%, the density and strength increase by 12.1 and 34.6%, respectively. Thus, due to the increased chemical modification of the surface of the binder particles, it is possible to significantly improve the adhesion strength and interaction energy between the structural aggregates of the system. Despite the fact that the concentration of dispersed phase particles in the volume of system #6 is higher, the process of forming cluster aggregates in a highly plasticized dispersion medium is slower compared to the reference composition #16 (Fig. 1). The reason for this, as noted by the authors of work [3], is a peculiar interaction of polycarboxylate with the aqueous medium of the cement system. As a result, a water film forms on the surface of the dispersed phase particles, the thickness of the hydration layer increases and to a certain extent the hydration process of cement grains is delayed. The clarity of the influence of zeolite on the increase in plastic strength in the initial period ($\tau \approx 1$ h) of hardening of pastes #4 and #6 is clearly visible on

the logarithmic P_m curves in Fig. 2. At the same time, it is observed that the formation of the primary structure in composition #4 within 0.33 h proceeds faster than in the reference composition #16. This is undoubtedly due to the highly porous structure of zeolite, which is permeated with a system of free cavities (channels), and the ability of clinoptilolite grains to easily adsorb free water from the binding slurry. The openness of the aluminosilicate framework of the filler with a minimal level of chemical modification encourages finely dispersed zeolite grains to both dissolve and directly interact with cement particles through thicker water films. And the presence in the zeolite channels of sufficiently mobile cations (sodium, calcium, magnesium, etc.), capable of relatively easy exchange with other cations, also affects the formation of the spatial network of the cement paste. Therefore, zeolite grains can have a direct effect on the organization of hydration products of cement clinker minerals. As can be seen from plastogram #4 in Fig. 2, the process of increasing plastic strength, in the time interval from 0.33 to 1.09 h, is slowed down. According to the review of literature sources, experts [4] explain this by the fact that the surface of zeolite grains is a crystallization center for the precipitation of the newly formed C-S-H gel, which slows down the pozzolanic reaction of active oxides. The conclusion of experts in this work is confirmed by the data on the intensive change in the rate of increase of plastic strength over time $\Delta v\{P_m\}$ (4) for binder pastes #4 and #6 (Fig. 3).

In general, the comparison of the full kinetic curves $\Delta v\{P_m\}$ (Fig. 3), which take into account the end of the hardening period of the compositions at the point of 1221.8 kPa, is accompanied by a gradual decrease in the angle of their inclination above the P_m axis. At the same time, the $\Delta v\{P_m\}$ curves do not intersect on the segment of the points of P_m plastograms from 15 to 1215 kPa. The location of the curves demonstrates that the most intensive change in the rate of growth of plastic strength is characterized by composition #16. Thus, an interim conclusion can be made that the increase in the structural strength of the unreinforced composition is strongly accompanied by a change in the bulk density and the development of chemical shrinkage. At the same time, the visualization of the quantitative kinetic curves in Fig. 2, 3 shows that the presence of hybrid fibers in cement slurry #15 clearly leads to changes in the initial conditions for the formation of the composition structures. The increase in the plastic strength of paste #15 over the entire study area P_m (Fig. 2) is ahead of the curve, unlike the reference and cement-zeolite compositions. However, the results obtained for $\Delta v\{P_m\}$ (Fig. 3) somewhat contradict the data of the rheological P_m curve. The kinetics of the formation of coagulation contacts show that the highest rate of initial structure formation is possessed by cement paste #16 without fiber and zeolite. Apparently, the disorder of the dispersed particles of the unreinforced system leads to the manifestation of high hydraulic activity of cement grains, as a result of which the rate of growth of the plastic strength of the paste during this period sharply increases. However, subsequently, the intensity of the change in $\Delta v\{P_m\}$ speed rapidly decreases, compared to the dispersion-reinforced paste #15. Given the lack of time for the formation of stable interparticle connections, coagulation contacts in the structural aggregates of the reference slurry #16 are distinguished by a lower adhesion force of dispersed particles. When forming coagulation structures in the hybrid-reinforced composition #15, more stable bonds are initially created between cement particles and discrete

fiber ($P_m = 1.68$ kPa, Table 1). This is undoubtedly due to the increased number of interparticle contacts in the volume of the system. The presence of fiber in the slurry significantly enhances the manifestation of the binding properties of cement grains, which subsequently affects the physicochemical processes of structure formation. Both during the short induction period ($\tau_i = 0.34$ h) and during the crystallization formation of the structures of composition #15 ($P_m > 75$ kPa). This is confirmed by the slowed-down decline in the rate of growth of plastic strength by the end of the hardening period (Fig. 3). In the reinforced system, due to the initially “better” ordering of cement grains, the growth of the crystallization structure occurs with a smaller decline during this period. Therefore, it can be argued that the introduction of discrete fibers into the binder system makes it possible to reduce the level of volumetric changes (stresses, deformations) during the set of structural strength, thus preventing the formation of an increased number of discontinuities. Practical evidence of this conclusion is the results obtained on the magnitude of damage and compressive strength of samples of dispersion-reinforced cement stone (Table 1). Therefore, this emphasizes that the interaction energy and density of contacting particles of the binder with discrete fibers are higher.

In turn, additional evidence of the previously drawn conclusions is the kinetics of changes in the hydration temperature of binder systems. According to Fig. 4, the results of the study of the thermokinetics of slurry structure formation indicate that the greatest influence from the action of temperature and shrinkage stresses (deformations) is experienced by unreinforced structures of compositions. The hydration process of cement-zeolite pastes, slowed down at the initial stages, significantly increases during the period of accelerated reaction of the silicate phase, approximately 2.33 h after the preparation of slurry #4 and #6. Apparently, at this stage, the main zeolite oxides begin to perform their main structure-forming function. Namely, SiO_2 and Al_2O_3 actively interact with the products of cement hydration. At the same time, the kinetic data of the reference slurry demonstrate both a sudden increase and an accelerated drop in temperature, compared to other compositions. Therefore, it can be assumed that the hydration processes during this period lead to the formation and development of various kinds of defects in the hardening compositions, at the same time disrupting the contact interactions of discrete elements of the paste. An example of this is the somewhat weak structural bonds of the intercluster interface surfaces in the cement stone of compositions #4 and #16 (Table 1). It is likely that when forming the structures of these systems, destructive processes prevail over structure-forming ones, which determines the lower f_{cm} strength. Due to the higher concentration of the initial particles of the dispersed phase in the volume of system #6 and due to the pozzolanic reaction of zeolite particles, the interaction energy of the contacting aggregates is higher, which is confirmed by the structural and mechanical parameters of the stone. At the same time, the regulation of intercluster (interparticle) contacts in the spatial structure of the binder systems can be carried out by reinforcing them with discrete fibers. The course of the kinetic temperature curve in Fig. 4 shows that the hybrid fiber slows down the development of both hydration and destructive processes. Although at a certain time interval there is a rapid increase in the hydration temperature of composition #15. However, due to the fact that the fiber is able to perceive and evenly distribute the internal stresses of the system during the gain

of strength, volumetric changes in the structure are less negatively reflected in the interparticle contact interactions (Table 1). This conclusion was drawn by the data from previous experiments [13, 18–20], which were carried out on different models of different disperse systems. Thus, the results of experimental studies of the processes of structure formation of binder pastes indicate that the adhesion force between the initial particles of the material is important at the initial stage of the organization of cluster structures in the volume of disperse systems.

On the other hand, the truthfulness of the above-mentioned intermediate conclusions is also expressed by the correlations between the structural parameters of different compositions of the binder system. Linear relationships have been established between the plastic strength after 0.25 h, $P_m\{\tau = 0.25\}$, after mixing the dispersed starting materials with water, and the rate of strength growth at specific points of $\nu\{P_m\}$ plastograms, Table 2. At the same time, it was found that with an increase in the value of $\nu\{P_m\}$, such a relationship is gradually lost. A similar subordination is observed between $P_m\{\tau = 0.25\}$ and the time τ , which is necessary for the hardening compositions to achieve a certain level of plastic strength P_m . When studying the dependence of rheology indicators G on the initial water-cement ratio of the slurry, a low correlation is observed, $r \leq 0.28$. Despite the fact that the correlation with the W/C of P_m curve indicators is insignificant, there is a significant functional relationship between the average density of the binder stone ρ and W/C , $r = -0.942$. In particular, close correlations with the W/C of the compressive strength f_{cm} and damage K_D of the material have been determined, Fig. 5, *a*. Given that ρ , f_{cm} and K_D are directly dependent on W/C , the quality of the formed contacts between discrete elements in the matrix volume can be analyzed through the properties of the stone. Since the density of the interface surfaces of the composite structures is affected by W/C , the dependence of ρ and f_{cm} on K_D value is additionally considered in the work. Analysis of the scatter diagram of the parameter values (Fig. 5, *b*) reveals that the reduction of discontinuities in the volume of the material clearly improves the mechanical connection between structural units. This is also evidenced by the correlation between the average density and strength of the binder stone, $r\{\rho : f_{cm}\} = 0.823$.

Analysis of the generalizing indicators (Table 3, Fig. 6), carried out using ES models and the methodology of formulation-technological fields, generally confirmed their compliance with the main aspects described above. A characteristic feature of the formation of structural strength is the need for compact packing of the initial particles of the dispersed phase when organizing cluster aggregates. Modeling the rheological parameters $\ln P_m\{\tau = 0.25\}$ and $\ln \nu\{P_m = 2\}$ of 25 different compositions of cement slurry demonstrates the following.

Unreinforced compositions ($x_3 = x_4 = -1$) with a minimum level of chemical modification ($x_2 = -1$) are characterized by high hydration activity of binder particles (Fig. 6, *a, b*). At the same time, the maximum values of the generalizing indicators G_{\max} are achieved in the composition without zeolite ($\ln P_{m,\max} = 1.18$ and $\ln \nu_{\max} = 3.27$). The increase in the polycarboxylate content within $-1 < x_2 \leq +0.6$ under the condition $x_1 = -1$ is accompanied by the greatest decrease in the value of $\ln P_m$ (Fig. 6, *a*) and, accordingly, a drop in $\ln \nu$ (Fig. 6, *b*) by 3 times. It was found that in highly plasticized ($x_2 = +1$) unreinforced systems, with a gradually increased replacement of part of the cement with zeolite ($x_1 \Rightarrow$ from -1 to $+1$), polycarboxylate ceases to exert an influence on the hydration

process of the binder. This is certainly due, as already noted, to the larger specific surface area of the zeolite particles, as well as to the surface area of the particles of the new phase, which also adsorbate the additive x_2 . Because the polycarboxylate is not sufficient to modify the particles of unreinforced systems, the plastic strength increases by a factor of 11.5, and the growth rate of P_m at the 2 kPa point increases by a factor of 1.7.

The maximum plastic strength $\ln P_m = 1.67$, as well as the speed $\ln \nu = 4.22$, has a hybrid-reinforced composition ($x_{3,4} = +1$) with a minimum content of organo-mineral additives ($x_{1,2} = -1$), Fig. 6, *a, b*. The obtained data fit well with the results of the analysis of Fig. 1-4 and prove that linear particles act as an active center for binder particles, which, in particular, confirms their compatibility. Due to the large surface area of the particles of the dispersed phase (fiber, cement), the areas of which are not fully modified by the additive x_2 , clustering of the system substructures occurs relatively quickly. Comparative analysis of G_{\max} of local fields, the surfaces of which are transformed under the influence of changing factors $x_{3,4}$ indicates that the fiber increases the increase in $\ln P_m$ and $\ln \nu$ compared to the unreinforced composition (Fig. 6, *a, b*). At the same time, it was found that filling the hybrid-reinforced system with zeolite grains, regardless of the level of plasticization of the compositions, undoubtedly leads to a decrease in the adhesion forces of the particles at the first stage of structure formation of the binder pastes.

Analysis of the change in the generalizing indicators in the coordinates of discrete fibers (Fig. 6, *c, d*) once again emphasized that the growth of the synergistic effect of organo-mineral additives ($x_1 + x_2$) largely depends on the level of modification of the compositions. From the obtained data in Fig. 6, *c, d*, it follows that the simultaneous increase in the content of polycarboxylate and zeolite to average levels ($x_{1,2} = 0$) causes a rapid decrease in the initial plastic strength and growth rate P_m of the compositions. Moreover, the minimum values of the indicators at different levels of modifying factors ($x_{1,2} = -1$ or 0) are achieved in a composition reinforced with a fiber 12 mm long. In addition, it was established that of the discrete fibers, the short fiber x_3 has the most significant impact on the initial process of structure formation of the compositions. This is especially noticeable in compositions with a low level of modification of the binder systems ($x_{1,2} = -1$). An increase in the content of short fibers (x_3 from -1 to $+1$) with a simultaneous decrease in long fibers (x_4 from $+1$ to -1) provides an increase in $\ln P_m$ and $\ln \nu$, respectively, by 4.2 and 3.3 times. A similar effect of discrete fibers on the change in G indices within local fields (Fig. 6, *c, d*) is observed when the modification factors are stabilized at average levels $x_{1,2} = 0$. The increase in plastic strength in the initial period is interpreted as an increase in the number of coagulation contacts between discrete particles in the paste volume, a more compact arrangement of particles and a greater force of their contact interaction. Due to the "better" packing of binder particles with short fiber x_3 , cluster substructures with stronger structural bonds between aggregates are formed, in contrast to the reference composition #16. It was also found that in compositions reinforced only with long fibers, due to the probable formation of fibrillar substructures, the number of direct contacts of the x_4 fiber with the binder particles in the composition volume decreases. This is evidenced by the decrease in the plastic strength and the rate of its growth. Therefore, the presence of discrete reinforcement of a certain geometry in the binder systems

leads to a noticeable change in the hydration processes of the initial structure formation, which is ultimately reflected in the structural and mechanical indicators of the compositions.

A feature of my research results is the establishment of regularities in the influence of two groups of formulation factors on the rheological parameters of the plasticized binder slurry. The introduction of clinoptilolite zeolite and fibers of a certain length into the plasticized cement slurry enables the formation of stable structural bonds between the material components in the volume of the binder matrix. The use of kinetic equations of the structure formation processes together with experimental-statistical models for the quantitative analysis of the influence of formulation factors on the general indicators of plastic strength is advisable when developing rational compositions of the binder slurry. This makes it possible to significantly increase the informativeness and reliability of the results of experimental research. The devised compositions of the cement slurry, subject to comprehensive analysis and optimization of the parameters of the structure of the binder stone, will be introduced into the practice of manufacturing decorative concrete for architectural elements. Potentially expected results are the following – the use of rational amounts of modifiers and fibers contributes to obtaining substructures of the binder system with greater strength of their contact interaction and with fewer discontinuities. As a result, this will improve the operational reliability of decorative concrete and enable the preservation of the decorative surface and functional properties of architectural elements throughout their service life.

Limitations in the technology of decorative concrete include the requirements for the manufacture of cement mixtures with the same mobility and with a certain set of structural strength over time. Such mixtures are obtained in compositions with a fixed content of cement binder system modifiers and a combined dosage of discrete fibers of different lengths.

The disadvantage of this study is that it would be appropriate to report the results from determining the shrinkage deformations of hardening pastes and capillary suction of cement stone together with the rheological properties of decorative compositions. Therefore, this does not allow me at this stage to determine the rational compositions of cement pastes for decorative concrete. The area of further research is to identify the influence of two groups of composition factors on the magnitude of plastic shrinkage deformations during the hardening of binder pastes.

7. Conclusions

1. The influence of formulation factors of cement compositions on the processes of structure formation in 25 compositions of binder slurry has been studied. It was found that modifiers of the cement system and discrete fibers of different geometry have a significant effect on the structural and rheological properties of the paste. Analysis of changes in rheological parameters revealed that, depending on the qualitative and quantitative composition of particles in the dispersed phase, it is possible to significantly improve the adhesion force and interaction energy between cluster aggregates in the volume of compositions. At the same time, the intensity of the rate of increase in the plastic strength of the slurry depends on the initial organization and interparticle interaction of discrete elements. The rate of increase in the

strength of cement pastes must be controlled in order to prevent the early formation and development of discontinuities during the formation of the structure of the compositions. It was found that highly dispersed zeolite and discrete fibers have a significant effect on the hydration temperature of cement slurry hardening. Analysis of kinetic temperature curves demonstrated that hybrid fiber slows down the development of hydration and destructive processes in a composition with a low level of chemical modification of dispersed particles. Binder systems should be filled with active cells – discrete fibers capable of organizing dispersed particles of cement matter in such a way as to achieve the formation of optimal bonds between structural aggregates.

2. For a deeper understanding of the processes of structure formation of dispersed systems, it is proposed to use two generalizing indices of the rheological curve, which relate to the primary stage of structure formation of the binder slurry. The correlation of rheological indices of the initial stage with the parameters of the structures of the subsequent stage periods of the cement composition has been assessed. Linear relationships were established between the plastic strength after 0.25 h and the rate of its growth at specific points of the full rheological curve. A low correlation of plastogram indicators with the water-cement ratio of the compositions was found ($r \leq 0.28$). Despite the fact that the correlation of rheological indicators with W/C is insignificant, there is a significant functional relationship between the average density, compressive strength, and damage of the binder stone with the water-cement ratio. Close correlations between the structural and mechanical properties of the stone were revealed ($r \geq 0.72$). This makes it possible to analyze the quality of the formed contacts between the structural aggregates through the characteristics of the cement stone.

3. Studies have confirmed that unreinforced slurry with a minimum level of chemical modification is characterized by high hydration activity of cement particles. When replacing part of the cement with zeolite in highly plasticized unreinforced systems, it was found that polycarboxylate ceases to influence the hydration process of the binder. The plastic strength increases by 11.5 times, and the rate of its growth at the point of 2 kPa increases by 1.7 times. Filling the hybrid-reinforced slurry with zeolite grains, regardless of the level of plasticization of the compositions, undoubtedly leads to a decrease in the adhesion forces of the particles at the first stage of the structure formation of the binder pastes. At the same time, it was found that of the discrete fibers, the short fiber has the most significant effect on the initial process of the structure formation of the compositions, especially in compositions with a low level of modifi-

cation of the binder systems. Increasing the content of short fibers while simultaneously reducing long ones provides an increase in plastic strength and speed, respectively, by 4.2 and 3.3 times. The use of kinetic equations of structure formation processes together with experimental-statistical models to analyze the influence of formulation factors on the general indicators of plastic strength is appropriate in the development of rational compositions of binder slurry for decorative concretes.

Conflicts of interest

The author declares that she has no conflicts of interest in relation to this research, whether financial, personal, authorship, or otherwise, that could affect the research and its results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The author confirms that she did not use artificial intelligence technologies when creating the current work.

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Author's contribution

Alexandra Dovgan: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration.

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