Optimization of the composition and technological processes of dispersed cement systems with high performance properties

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Abstract. The technological parameters of obtaining cement disperse systems are considered. It is shown that the optimization of technological processes allows the development of dispersed cement systems with high protective resistance during the operation of buildings and structures. It was determined that optimization of the parameters makes it possible to select the most effective ratio of cement and finely ground filler from concrete scrap, the optimal amount of modifier additives, and then the ratio of colloidal cement glue and sand (aggregate) in order to obtain mortar compositions for decorative coatings with high strength properties. It was found that grinding sand or crushed concrete scrap allows not only to increase their specific surface and obtain the required particle size distribution, but also to improve the surface quality of particles by removing and destroying surface inactive films, which increases the reactivity of the filler in various processes. Mechanical activation in combination with modifying additives allows to give the necessary properties to colloidal cement composites using optimal technological parameters of processing. The influence of the particle size distribution of sand on the strength characteristics of decorative coatings based on colloidal cement glue is determined depends on the ratio of colloidal cement binder to sand. Studies have shown that the fractional characteristics of sand are optimal, in which dense packing of grains and approximately equal fractions of fractions are ensured. It has been established that dispersed cement systems with an optimal fractional composition of the filler have a water-holding capacity that significantly exceeds the standard values.

1. Introduction
Optimization of technological processes allows to obtain the maximum surface of a solid substance with minimal energy costs [1-6]. Mechanical activation, which allows you to fully reveal the hidden properties of some substances and use the potential of others (binders) [2-5]. Among the methods of mechanical activation of concrete mixtures, activation is distinguished by pressing, grinding, mixing, etc. The first attempts to apply mechanical activation in the production technology of building materials are related to the preparation of binders when, when the cement is re-ground, its reactivity and specific surface area increase, which intensifies the process of hardening products on such a binder and reduces its consumption in them. Mechanoactivation fully gains applied value, improving existing technological schemes and revealing fundamentally new production methods, based entirely on technological processes with the advent of highly efficient grinding equipment.

According to the authors of [7–9], the fine grinding process and activation depend on the initial characteristics of bulk raw materials. Grinding and mechanochemical activation of materials can be carried out in grinding units with various types of impact on the crushed particles: slow blow and
abrasion (ball mill), intense blow with abrasion (planetary mill), abrasion with crushing (roller mill), rapid impact of particles (jet mill), pressure, abrasion and shearing force in disintegrators, large abrasive and tearing forces in a liquid medium with a combination of high cavitation effect (rotor-pulsation apparatus).

Impact and impact-abrasive grinding of cement powder can significantly increase its physicochemical activity in the most rational way, to a greater extent by adjusting the particle size distribution, changing the shape of the grain [10-12]. From the point of view of achieving a high intensity of machining and productivity, the most promising are electromagnetic mills, in which the energy of the electromagnetic field is directly converted into the kinetic energy of the motion of the grinding elements [13-14]. To obtain the fragmentation shape of the particles, cylindrical grinding elements with sharp edges are used.

Mechanical activation of functional additives for various purposes [15-19] allows to increase their working surface several times, increase their chemical activity so that the quality indicators of dry building mixtures are improved by 15%.

The mechanism of action of vibration activation of cement-sand mixtures is aimed at increasing the specific surface of the binder, changing the surface structure of solid particles and accelerating the interaction of the components of the cement-water-sand system.

Vibroactivation causes a change in the system of active components of cement clinker, and primarily an increased yield of tricalcium aluminate (C₃A), which is responsible for the set of strength in the initial period of hydration [3, 20-21]. The technology of grinding binders to increase the viscous and rheological characteristics of finely ground cement systems is implemented in high-speed vibrating devices, which ensures an increase in the dispersion of binders at lower energy costs. The criteria for the effectiveness of controlling the processes of formation of structures in the technology of obtaining solutions based on colloidal cement systems are: achieving the ultimate uniformity of the distribution of dispersed phases in the entire volume of the dispersed system [22].

The formulation of colloidal-cement mortar mixtures provides for the presence of both distribution and dispersion transport processes inside the mixer [22]. Studies [23] showed that the mixing efficiency depends on the particle size.

In this regard, when developing methods for their preparation, it is important to correctly determine the compositions of the mixtures and to select the conditions for their mixing to obtain a uniform distribution of dispersed particles throughout the dispersed medium [23].

The application of vibrational mixing to materials is devoted to the work of scientists [6–8, 22]. Effective use of vibration equipment will solve the most important technological processes and improve many indicators of the final product [6, 2]. The effect of vibrational mixing of the mixture [6] is most noticeable on the first day of hardening, when the strength of the samples can increase to 60-70%. Vibration exposure in combination with modifying additives during the mixing of mortar mixtures ensures uniform distribution and good interaction of water with mineral components and modifying additives.

Therefore, the optimization of the technology for producing coatings based on colloidal cement binder should be carried out according to the parameters of mechanical activation, modification, effective mixing and adjustment of dry mixes.

2. Methods

For the development of decorative coatings based on colloidal cement materials, we selected methods for processing the feedstock of mechanochemical activation, vibration mixing and modification of dispersed surfactant systems and other additives, allowing to obtain highly concentrated dispersed colloidal cement materials with low effective viscosity and high performance properties.

For the production of decorative coatings based on colloidal cement mixtures, Portland cement LLP company Bukhtarminskaya Cement Company LLP, natural sands, various fillers (crushed concrete scrap, metakaolin, etc.), additives and pigments were used. Instead of natural sand, crushed concrete scrap was also used. Heavy concrete waste obtained from Portland cement PC400-D0 according
to GOST 10178 was crushed and sieved to isolate fractions with grain sizes less than 5 mm. According to chemical and mineralogical analysis, the crushing screenings meet the requirements for the aggregate, in terms of grain composition the modulus of sand size (Mk = 2.8), and for the total residue on the sieve, 0.63 and 0.16 are coarse. To obtain stable research results for mixtures for decorative coatings, sand from crushed concrete scrap was fractionated.

The true density of sand from the screening of concrete scrap fractions 2.5-0.16 was 2.64 g/cm³, fractions 1.25-0.16 - 2.56 g/cm³. The bulk density of the sand fraction 2.5-0.16 was 1586 kg/m³, the fraction 1.25-0.16 - 1594 kg/m³. Sand has a voidness of 39.6% for a fraction of 2.5-0.16 and 38.5% for a fraction of 1.25-0.16.

For the modification of cement colloidal materials, various additives were used. To study the basic properties of finely ground cement systems with fillers of various genesis, the additive dispersed polymer powder (RPP) was studied. To improve the hydrophobic properties of colloidal cement systems, powder hydrophobizing agents of various chemical bases were used. The technology of colloidal cement materials used active mineral additives (metakaolin)

The characteristics and material composition of raw materials, additives according to the results of studies and tests show the possibility of their use for decorative coatings based on colloidal cement mixtures.

3. Results

Studies have been carried out to optimize the main technological parameters of the production of colloidal cement systems for the decoration of exterior panels. Previous studies have shown that sands and crushed concrete scrap have good grinding properties. It was experimentally determined that the optimal dispersion of cement and filler is 550-560 m²/kg.

Grinding sand or crushed concrete scrap allows not only to increase their specific surface and obtain the required particle size distribution, but also to improve the surface quality of particles by removing and destroying surface inactive films. The creation of a newly formed improved (without pollution) surface of the filler grains increases its reactivity in various processes. [22-23].

Therefore, studies were performed to optimize the parameters of fine grinding of cement and fillers (natural sand and crushed concrete scrap). It was previously found that the joint activation of the components of a colloidal cement binder (glue) with a modifying additive leads to an increase in the strength of samples during all hardening periods, especially almost 1.5 times on the first day. At the same time, the introduction of modifying additives provides an increase in the amount of low-basic calcium hydrosilicates in cement stone, which have adhesive ability and contribute to an increase in the adhesive strength of the solution for decorative coatings.

In the process of hydration and hardening of a colloidal cement composite, a change in the structure of cement stone occurs, which is accompanied by self-organization of the structure throughout the entire period of the interaction of Portland cement with a finely ground filler and modifying additives [20-23].

The main task of optimizing the composition of colloidal cement binder was the selection of the most effective ratio of cement and finely ground filler from concrete scrap, the optimal amount of modifier additives, and then the ratio of colloidal cement glue and sand (aggregate) in order to obtain mortar compositions for decorative coatings with high strength properties. Studies have shown that with an increase in the filler content, the setting time of the cement paste is slowed down due to the fact that under the conditions of a varying amount of cement, the relative content of minerals in it that enter the hydration reaction with water decreases. It has been revealed that the metakaolin filler and the introduced polymer additive from the moment of mixing with water have a peptizing and structure-forming effect on the cement paste, thereby accelerating the process of hydration and hardening of cement stone.

To assess the properties of a colloidal cement binder, the optimal composition was chosen: cement consumption in the binder composition was adopted 70%, the consumption of finely ground concrete scrap or natural sand - 30%. High dispersion of the powder (550 m²/kg) is able to provide the neces-
sary kinetics of the formation of the properties of colloidal cement glue for decorative coatings under the conditions of thin-layer technology, with a minimum consumption of modifying additives and provides increased plasticity and water-holding ability of the mixture, and also allows to reduce consumption per unit surface due to thin layer application, as the mineral composition is selected so that the consumption of modifying additives is minimal.

The formation of the structure of filled cement composites is the result of the joint occurrence of structure formation and the formation of a spatial crystalline framework [14]. Previous studies have shown that finely ground filler takes an active part in shaping the strength of a filled cement system, and this requires an optimal concentration of the dispersed component.

Structuring in colloidal-cement systems is the result of the synthesis of chemical, physico-chemical and physico-mechanical processes, as a result of which the strength of the stone is formed, in which sand (aggregate) takes an active part [23]. Sand is an integral component of colloidal cement adhesives. For different jobs and mortar layers, sand with different grain sizes is used, which can reduce the consumption of CCB (binder) without a noticeable drop in the strength characteristics of cement stone, as well as reduce shrinkage deformation.

To create effective compositions, it is necessary to use a combination of several fractions of sand, which will complement the characteristics of another. In formulations intended for application in a thin layer, sands shall not contain more than 1.25 mm. Compositions intended for applying textured, decorative plasters and for applying a thick layer are based on sand with the largest size 2.5-1.255 mm.

The best option is if the sand contains at least three different fractions by size, since it is in this case that the highest mechanical properties are achieved [15-16]. Optimization of dry colloidal cement mixtures consists in the fact that the components that make up the mixture provide the main molecular bonds between the particles and ensure adhesion of the particles to each other and to the base surface [5, 19].

To select the optimal mixture composition for decorative coatings based on a colloidal cement binder, natural sand with a grain size of 0.16-2.5 mm was used. The sand was used dry, clean with optimal particle size distribution (grain composition) in accordance with the purpose of the mixture to be prepared for decorative coatings. For different layers of the solution used sand grains of various sizes. 1.25-0.63 mm was used for the upper layer, sand with a grain size of 2.5-1.25 mm was used for the first layers. The sand used for the experiments had a sharply ribbed and rough surface, which ensured good adhesion to the colloidal cement binder.

The most effective from the point of view of technology and screening costs is the separation of sand into fractions with particle sizes of 2.5-1.25, 1.25-0.63, 0.63-0.315, 0.315-0.16.

The effect of the particle size distribution of sand on the strength characteristics of decorative coatings based on colloidal cement glue depends on the ratio of colloidal cement binder to sand. It has been established that the samples obtained using fine sand with a fineness modulus of 1.0-1.5 have the least strength with a binder: sand ratio (1:3). The samples are most durable when using medium sands with a particle size modulus of 2.0-2.5. Studies have shown that it is very important to maintain optimal sieve characteristics of sand, in which dense packing of grains and approximately equal fractions of fractions are ensured.

The optimal granulometry of sand was determined by the ratio of aggregate fractions providing the densest particle packing. The maximum value of bulk density served as a criterion for the dense packing of sand grains. The density of natural sand was measured according to ST RK 1217. The true density of the sand of the 2.5-0.16 mm fraction was 2.64 g / cm³, the 1.25-0.16 mm fraction was 2.56 g / cm³. The bulk density of the sand fraction of 2.5-0.16 mm was 1586 kg / m³, the fraction of 1.25-0.16 mm - 1594 kg / m³. The voidness of coarse and fine fractions of sand was determined. Experimental studies have shown that the sand of the 1.25-0.16 mm fraction - 20.35%, has the lowest intergranular voidness. The sand fraction 2.5-0.16 mm has a voidness of 21.8%.

The granulometric composition of sand, providing the maximum packing of grains, is also presented in table 1. Based on the results of the studies, a number of compositions were selected (table 1), which have the most improved technological and physical-mechanical characteristics. Studies have
shown that colloidal cement mixtures, which include large fractions of sand, have higher strength indices (1, 3, 4, 5, 8, 9, and 11). The sand fraction of 2.5-1.25 mm creates a framework and affects the strength characteristics. Smaller fractions of sand 1.25-0.63 mm, being medium, fill the intergranular space of larger fractions. Of single-fraction compositions, compositions 14 and 15 have the highest strength characteristics. With an increase in the content of a finer fraction of 0.63-0.315 mm and 0.315-0.16 mm, the bulk density of the mixture increases due to the receipt of a denser packing of grains in them. An increase in the composition of the mixture of the fraction 1.25-0.63 mm and 2.5-1.25 mm leads to a decrease in the packing density of grains with a maximum content of the fraction 0.315-0.16 mm.

### Table 1. Granulometric composition of sand, providing maximum packing of grains.

| Composition number | Astringent | Sand fractions, mm | Bulk density, kg / m³ | Bulk density in the compacted state, kg / m³ |
|--------------------|------------|--------------------|-----------------------|--------------------------------------------|
|                    | 2.5-1.25   | 1.25-0.63          | 0.63-0.315            | 0.315-0.16                                |
| 1                  | 100        | 100                | 100                   | 100                                       |
| 2                  | 100        | 100                | -                     | 100                                       |
| 3                  | 100        | 100                | 200                   | -                                          |
| 4                  | 100        | 100                | -                     | 200                                       |
| 5                  | 100        | 200                | 100                   | -                                          |
| 6                  | 100        | 200                | -                     | 100                                       |
| 7                  | 100        | 200                | -                     | 100                                       |
|                    |            |                    |                       |                                            |
| 8                  | 100        | -                  | 100                   | 100                                       |
| 9                  | 100        | -                  | 100                   | 200                                       |
| 10                 | 100        | -                  | 100                   | -                                          |
| 11                 | 100        | -                  | 200                   | 100                                       |
| 12                 | 100        | -                  | 200                   | -                                          |
| 13                 | 100        | 300                | -                     | -                                          |
| 14                 | 100        | -                  | 300                   | -                                          |
| 15                 | 100        | -                  | -                     | 300                                       |
| 16                 | 100        | -                  | -                     | 300                                       |

Studies have shown that colloidal cement mixtures, which include large fractions of sand, have higher strength indices (1, 3, 4, 5, 8, 9, and 11). A sand fraction of 2.5-1.25 mm creates a framework and affects the strength characteristics. Smaller fractions of sand 1.25-0.63 mm, being medium, fill the intergranular space of larger fractions. With an increase in the content of the finer fraction of 0.63-0.315 mm and 0.315-0.16 mm, the bulk density of the mixture increases due to the receipt of a denser packing of grains in them. With an increase in the composition of the mixture of the fraction 1.25-0.63 mm and 2.5-1.25 mm, on the contrary, it leads to a decrease in the packing density of grains, with a maximum content of the fraction 0.315-0.16 mm.

As the results of experimental studies showed, it was found that compositions 1, 3, 4, 5, 8, 9, and 11 have the highest rate of curing in the early and subsequent periods.

The next important technological indicator of colloidal-cement mortar mixtures is water-holding ability, ensuring high rates of which helps to prevent stratification of the mixture and apply them to porous substrates. According to GOST 31357, the water holding capacity should be at least 95%. It was experimentally established that all formulations have a water holding capacity of 98.99%, which is significantly higher than the required values.

Studies of the properties of colloidal cement-sand mortars were carried out in accordance with GOST 5802 and GOST 31356 on cubic samples measuring 70 × 70 × 70 mm. Determination of capil-
lary water absorption was carried out on samples-beams of 40 × 40 × 16 mm. In the manufacture of the samples, the dry components were first mixed, after which the mixture was shut with water. The mobility of the mixtures was the same and amounted to 8–9 cm. Studies of hardened solutions were carried out after 28 days of storage of samples in normal humidity conditions. For testing, cement-sand mortars were prepared with a binder: sand ratio of 1:3. A mixture of sand fractions 2.5-1.25, 1.25-0.63 and 0.63-0.315 in a ratio of 40:30:30 was used as a filler. For solutions for applying thin plaster coatings, sand fractions of 0.63-0.315 and 0.315-0.16 were used. The results of water absorption studies are shown in table 2.

The study of colloidal cement mortars based on the developed formulations showed that the water resistance of the obtained solutions is from 1.2 to 1.6 MPa, which corresponds to the waterproof grade B10-B16.

The frost resistance of a cement stone based on colloidal cement glue (KCC) is at least 300 cycles of alternate freezing and thawing in water. Studies of the cold resistance of the CCC showed that the main factor that determines the magnitude of the stresses in the walls of the capillaries of cement stone when water freezes, determines not only the degree of filling of the existing capillaries with water, but also the internal dimensions of the capillaries and the wall thickness.

| Name of mortar mixture                        | Water absorption, % by weight | Water absorption during capillary suction, kg / m²·h⁰·⁵ |
|-----------------------------------------------|------------------------------|-------------------------------------------------------|
| Colloidal cement mortar for plaster coatings   | 5,5                          | 0,35                                                  |
| Colloidal cement mortar for thin coatings      | 5,3                          | 0,32                                                  |

The main properties of colloidal cement mortar mixtures and hardened mortar are presented in table 3 (composition numbers are given in table 2).

From the results of the studies it follows (table 3) that the developed colloidal cement mortars for decorative coatings possess not only the necessary mobility, but also high strength indices: ultimate compressive strength at 28 days of age - 59.0-59.9 MPa; adhesion strength to the base - 2.0-2.52 MPa. The use of finely ground concrete scrap, used as a filler additive in Portland cement, allows to produce effective high-strength decorative coatings with a specific consumption of colloidal cement powder from 8.7 to 11.7 kg per 1 MPa of strength. The obtained colloidal cement material is characterized by low shrinkage deformation (0.313-0.694 mm / m).

| Parameter                            | Mixture number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|--------------------------------------|---------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Water-holding capacity of the mixture, % |               | 99.87 | 98.1 | 99.84 | 99.85 | 98.65 | 98.4 | 98.25 | 98.75 |
| Mixture storage, min                    |               | 55   | 50   | 50   | 50   | 45   | 50   | 50   | 45   |
| Mobility grade                         |               | PK3             |       |      |      |      |      |      |      |
| Density of the mixture, kg / m³               |               | 3139 | 2140 | 2136 | 2125 | 2121 | 2140 | 2152 | 2145 |
| Water absorption by weight, %                        |               | 3.2  | 3.9  | 3.3  | 3.5  | 3.4  | 4.5  | 4.7  | 4.0  |
| Water absorption during capillary suction, kg / m²·h⁰·⁵    |               | 0.17 | 0.19 | 0.18 | 0.19 | 0.18 | 0.29 | 0.32 | 0.27 |
| Compressive                                  |               | 1 day | 19.5 | 18.8 | 19.2 | 19.5 | 19.3 | 18.9 | 18.7 | 18.0 |
|                                              |               | 3 day | 27.1 | 26.4 | 27.5 | 27.0 | 26.5 | 26.5 | 26.2 | 25.2 |
4. Discussion
Optimization of the main technological parameters made it possible to obtain dry building mixtures for decorative concrete coatings with high performance properties.

The main task of optimizing the compositions of the colloidal cement binder was to select the most effective ratio of cement and finely ground filler from concrete scrap, the optimal amount of modifying additives, and then the ratio of colloidal cement glue and sand (filler) in order to obtain mortar compositions for decorative coatings with high strength characteristics. Studies have shown that with an increase in the filler content, a slowdown in the setting time of the cement paste is noted, due to the fact that, under conditions of a changing amount of cement, the relative content of minerals in it that react with hydration with water decreases.

An increase in the sand content in the mortar mixture helps to reduce the development of shrinkage deformation, reduce the risk of shrinkage cracks propagation and destruction of the coating, as well as reduce the proportion of binder, and therefore cement, which is a priority area for increasing economic efficiency.

In terms of their construction and technical characteristics, the developed dry building mixtures meet the requirements for these types of building materials, and in some indicators they significantly exceed them and can be recommended as basic compositions for manufacturers of dry building mixtures. The results obtained confirm the prospects of using finely ground concrete scrap, which is an environmentally friendly material used as fillers in colloidal cement binder to reduce cement consumption, as well as to stabilize the mixture and prevent water separation.

5. Conclusion
Thus, the studies carried out have shown that the optimization of the technological parameters for the production of decorative coatings based on dispersed cement systems leads to an improvement in the
technological properties of the mixtures, the strength and performance characteristics of the final product.

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