Assessment of the impact of modifier and filler on the physical and mechanical and operational properties of plastering mortars

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Abstract. To assessment of the impact of the addition of microsilica on the mechanical properties of the plaster mortar, experimental-statistical modeling was used. A complex of engineering problems based on models describing the change in the technological and physical and mechanical properties of the plaster mortar during the control of the dosages of microsilica and superplasticizing admix was solved. The problem of choosing the optimal dosage of the filler was solved under the condition of the equality of the water-cement ratio and the mobility of the compositions without and with microsilica additive, which was achieved by appropriate adjusting the dosage of the superplasticizing admix on the consumption of microsilica, i.e. the concentration of the superplasticizing admix was dependent on the consumption of microsilica. Analysis of the effectiveness of the addition of microsilica in the entire factor space using the model of relative efficiency was carried out. The areas of optimal compositions of plaster mortars, in which the increased technological and mechanical parameters are performed, have been determined. An assessment of the effect of ultrafine filler on the operating ability of plaster mortars has been carried out. The main indicators were: the value of adhesion of the plaster layer to the concrete base; the strength of the concrete base ("old" concrete); strength of the plaster layer; indicator of water absorption of the plaster layer.

1. Introduction
In the modern construction industry, ready-made dry plaster mixes are the main material for external and internal finishing works. For building facades, cement-based dry plaster mixes are optimal. In respect that the aggressiveness of the environment, the variability of weather conditions, special requirements are imposed on the plaster mixture.

The most important properties of plaster mortars are: the uniformity of the composition achieved due to well mixing of the initial materials, which excludes the tendency of the mixture to segregation; the ability to actively adhere to the base under the coating; provided by the composition of the water-retaining ability; the course of the hardening process, using a hardening process in accordance with construction technology, taking into account weather conditions. The above-mentioned properties are ensured through the use of optimal formulations of plaster compositions, which include chemical additives and fillers that increase adhesion, strength, and water resistance. Facade mixtures can be used not only as the final stage of finishing, but also as a basis for subsequent decorative cladding.

The system becomes more complex if polyfunctional modifiers are used, which can especially strongly affect the structure and properties of composites. These modifiers include superplasticizing admix (SP) and ultrafine fillers such as technogenic microsilica (MS). Microsilica – a waste of
ferroalloy production is distinguished by a uncharacteristic specific surface area for most used fillers (ash, slags, organic mineral additives) and an increased content of a silica component.

2. **Analysis of recent research and publications**

Analysis of literature data [1-3] showed that using microsilica in combination with a superplasticizing admix can increase the strength of cement stone by 1.5-2 times with ordinary materials. Plasters can be prepared with high physical-mechanical and operational characteristics if select optimal recipe-technological conditions. The complex use of MS and SP also saves resources by reducing the consumption of the binder.

The improvement of the structure of the cement stone occurs due to the fact that microsilica, interacting with the products of cement hydration, forms an additional amount of hydrated neoplasms, thus contributing to an increase in the strength and density of the solution [4-6]. At the same time, microsilica contributes to the acceleration of carbonization, which significantly reduces destructive processes, increases the chloride and sulfate resistance of cement systems [7].

The introduction of MS promotes an increase in pore volume from 37 to 0.175 μm and, while maintaining the integral porosity, a decrease in the average diameter of air pores and the formation of a microporous structure of a cement stone with a reduced capillary porosity and which causes an increased impermeability of the cement slurry.

Other factors that have a significant effect on the durability of plaster mortars are the composition of the mortar in the pores. During the introduction of microsilica, the pH value of the solution in the pores decreases.

3. **Purpose of the study**

The purpose of this study is to determine the optimal concentrations of microsilica and superplasticizer to improve the physical, mechanical and operational properties of plaster mortar.

4. **Objects and research methods**

To find optimal solutions, mathematical models were used, i.e. mathematical description of specific recipe-technological situations [8-11]. A complex of engineering tasks was solved using models describing the change in the technological and mechanical properties of the plaster mortar during controlling the dosage of microsilica $X_1 = 10\pm10\%$ (from the mass of the binder), the ratio between sand and cement $S:C = X_2 = 2.5\pm0.5$ with this normalization: $x_1 = -1$ corresponds to no additive composition, $x_2 = -1$ – high cement consumption. The mobility (M) of the mortar mixtures corresponded to $M = X_3 = 5\pm2$ cm by the immersion of the cone.

The basis for taking these factors into account in the model is the following prerequisites. The addition of the MS – the main regulating factor. An increase in the MS dosage over 20% can cause increased plastic shrinkage of the layer and lead to unreasonable consumption of the superplasticizing admix.

A standard C-3 plasticizer with a density of 1.17 g/cm³ at a concentration of 38.4% was used as a superplasticizing admix. In the experiments, no additives Portland cement with an activity of 375 kg/cm² of the Olshansk plant was used as a binder. River sand with $M_{cr} = 2.1$ was used as a fine aggregate, which meets the requirements for plaster mortar. To determine the mechanical properties, samples - beams with size $4\times4\times16$ cm were tested.

Taking into account the possible operating conditions of the plaster mortar, its properties were studied (Figure 1, c) after 20, 40 and 60 cycles of freezing (at $T = -20\degree C$) and thawing under capillary suction conditions with a plaster mortar of salt solution (at $T = +20\degree C$).

The method of manufacturing and testing samples consisted of the following operations:

1. Samples of "old" concrete (beams with a section of 40×40 mm and a length of 120-140 mm – depending on the expected thickness of the plaster mortar) on the ends of which a plaster mortar was applied (Figure 1, b) and placed in special special form (Figure 1, a). Thus, filling completely one cell, depending on the length of the "old" concrete beam, a layer of plaster mortar of a given thickness was
formed (2, 3 and 4 cm).

2. Preparation of samples of "old" concrete before applying the plastering solution included treatment with an abrasive material and wetting the surface of the application of the plastering solution. After application, the mortar sags were carefully cut away without damaging the freshly formed layer.

Figure 1. Method of manufacturing and testing samples of the plaster layer:
a) special form for applying a layer of plaster on samples; b) sample with a layer of solution; c) holding samples during alternate freezing and thawing; d) the scheme of testing the plaster layer for spalling and compression; 1 − special form; 2 − "old" concrete; 3 − a layer of plaster mortar; 4 − a collecting gutter for thawing; 5 − salt solution; 6 − refrigerator.

3. After a 14-day exposure in normal humidity conditions, the samples were sent for freezing for 12 hours and thawing in a salt solution also for 12 hours (Figure 1, c). The salt solution level was 1 cm and monitored every cycle. The temperature of the salt solution was automatically maintained at +20°C. Freezing was carried out in refrigerator with an accuracy of maintaining the temperature of ±2°C. Thus, without taking into account the 1 cm layer, which was constantly in a liquid medium during thawing, the working layer thickness varied from 2 to 4 cm.

4. After 60 cycles of freezing and thawing, the plaster mortar layer was tested for spall relative to the "old" concrete and the strength of the plaster mortar layer (Figure 1, d).

5. The results of research
The selection of the optimal dosage of the filler was performed under the condition of the equality of the water-cement ratio and the mobility of non-additive compositions and with microsilica, which was achieved by adjustment of the dosage of the superplasticizing admix as the MS consumption increased, i.e. the concentration of the superplasticizing admix was dependent on the consumption of microsilica.

The experiment was carried out according to the B3 plan [8] with one central point. The dosages of the superplasticizing admix required to obtain a predetermined mobility of the mixture with an increase in the amount of filler from 0 to 20% (the water content of the mixture was constant) were preliminarily determined.

The dependence between the concentration of the superplasticizing admix and the factors under study had a nonlinear character (Figure 2, a):

$$D_{sp} = 0.77 + 0.62x_1 - 0.09x_1^2 - 0.15x_1x_2 - 0.14x_2 - 0.08x_2^2 + 0.18x_1x_3 + 0.17x_3 + 0.15x_2x_3$$

from which it follows that to maintain the specified mobility (5 cm) and water content, it is necessary to introduce 0.3-0.4% of the superplasticizing admix for every 5% of the filler. The use of SP in concentrations above 1.0%, although it allows the use of increased (more than 15-20%) dosages of MS, isn’t economically justified, since it increases the cost of the material. Isoline $D_{sp} = 1.0$ % on the diagram $D_{sp} = \varphi (x_1, x_2, x_3)$ limits the area of economically justified SP dosages with a mixture mobility of 5 cm (dashed line in Figure 2, a).
Figure 2. Influence of microsilica on the main physical and mechanical properties of the plaster mortar: a) change in the concentration of SP; b) flexural strength (R_b, MPa).

The nomogram of the strength R_b of the plaster solution depending on the concentration of MS and the S:C ratio is shown in Figure 2, b. The coefficients of the models used to plot the strength nomograms are given in Table 1.

Table 1. Coefficients of the strength models of solutions on the 28th day after the normal hardening regime.

| Strength, MPa | Model coefficients |
|--------------|---------------------|
|               | b_0     | b_1   | b_2   | b_3   | b_11  | b_22  | b_12  | b_13  | b_23 |
| R_b          | 7.3     | 1.1   | -1.1  | -0.3  | -0.5  | 0.6   | -0.7  | 0.2   | –    |
| R_c          | 26.4    | 5.0   | -4.5  | -2.4  | –     | 1.5   | 2.9   | 1.3   | –    |

The positive effect of the ultrafine filler on the hardening of the solution is due to the increase in the number of contacts in the cement system and the intensive accumulation of an additional amount of hydrated neoplasms as a result of the interaction of MS with the products of cement hydration. Due to the introduction of microsilica fractions, a well compaction of the cement system is achieved and about a third of the space between the cement grains is filled with filler fractions. This explains the fact that the compressive strength R_c of plaster compositions with the addition of microsilica (curve 2 in Figure 3, a) is 40-50% higher than the strength of the non-additive composition (\(\varepsilon[R_c] = 100\%\)). However, these data refer to one of the S:C = 2.5:1 ratios. If we consider the change in strength R_c with varying two factors – MS concentration and S:C ratio, it can be seen that the strength for mixtures with low S:C increases significantly more than for mixtures with high S:C (Figure 3, b) which requires careful selection of the composition of the plaster solution.

The analysis shows that by increasing the D_MS from 0 to 18%, the consumption of the binder can be reduced to 1.5 times (for example, when obtaining the grade strength R_c^{28} = 30 MPa mixtures with S:C = 3:1 can be used instead of S:C = 2:1). In this case, the effective concentration of the superplasticizer can be reduced (D_SP<1.0 %).
Figure 3. Influence of microsilica addition on the compressive strength of the plaster mortar:
a) increase in strength (1 - initial mortar S:C = 2.5:1, S = 5; 2 - modified; b) nomogram of compressive
strength; c) the relative efficiency of MS in the entire recipe-technological space.

This conclusion is confirmed by the analysis of the effectiveness of the addition of
microsilica
in the entire factor space, carried out using the relative efficiency model:
\[
\varphi \{ R \} = R\{ D_{MS} \} : R\{ D_{MS} = 0 \} , \%
\] (2)

The main advantage of a model of type (2) is that it can be used to compare the results of testing
qualitatively different additives and various factors, since on the base side of the square (in particular,
shown in Figure 3, c) there is always \( \varphi \{ x_i \} = 1 \).

A function of type (2) was built for a 3-dimensional space, and the two-factor model of no additive
plaster mortar \( R = \varphi (X_1, X_2) \), was taken as the base one, which was provided for organizing this
experiment. The analysis of the \( \varphi \{ R_c \} \) model indicated the peculiarities of the effect of microsilica on
the strength of the plaster solution under compression. In the recipe space, there is a large area, within
which the strength of plaster mortars with filler is practically equal to the strength of concrete at
\( D_{MS} = 0\% \). It was noted that the loss of strength of mortars with a decrease in the binder content
becomes less noticeable in the presence of microsilica.

With an increase in the water content of the mixtures, the increase in the strength of the solutions
on the filled binder increases, but the zone of the most effective effect of microsilica, in contrast to
\( \varphi \{ R_b \} \), moves towards compositions with a low binder content. The combined positive effect of the
plasticity index of mixtures and the amount of ultrafine filler can be explained by an increase in the
cohesion of solutions, while for a non-additive mortar, prevails the negative effect of an increase in the
W/C on strength.

For solutions from plastic mixtures (7 cm) with S:C = 3:1, containing 20% microsilica additive, the
compressive strength is 2.3 times higher than the strength of no additives composition. At the next
stage, the task of obtaining a composition of a plaster mortar with improved technological and
mechanical parameters was set. For this purpose, the models describing the influence of the
investigated technology parameters on the quality indicators of the plaster mortar were analyzed in one
factor space:
- concentration of SP;
- the relative increase in tensile strength in bending;
- the relative increase in compressive strength.

The need for a compromise solution is due to the fact that microsilica acts ambiguously on these
indicators and its effectiveness depends on the levels of other factors, in particular, S:C ratio and the
mobility of the mixture. Thus, the increment in strength \( R_b \) increases for a mixture with a high S:C, but
under the same conditions the effect of MS on the increment in the brand strength in compression may be
insignificant. The compromise task was solved under the following restrictions: a) concentration of SP not
more than 1.0% (economy of superplasticizing admix); b) an increment in tensile strength in bending of at
least 20%; c) increment in compressive strength \( \alpha \{ R_c \} \) not less than 25%. For this purpose, the diagram combined the corresponding isolines of models of quality and efficiency indicators. The graphical-analytical analysis of the task posed is presented in the form of a field bounded by isolines \( D_{SP} = 1.0\% \), \( \alpha \{ R_b \} = 120\% \) and \( \alpha \{ R_c \} = 125\% \) (Figure 4, a).

In the field of effective solutions, the requirements for the plaster mortar are fulfilled (unshaded area). It is characteristic that they cannot be performed for additive-free compositions, but only for modified compositions containing 8-16% microsilica additives and 0.7-1.0% superplasticizing admix. In this case, the rational ratio of sand and cement is 2.3-2.8:1, i.e. the mixtures should contain the average values of the binder consumption for the given experiment. Thus, microsilica can be used both as a quality regulator and as a factor contributing to the reduction of the clinker component of cement.

Further, the properties of the modified compositions were analyzed in comparison with those without additives. In particular, in Figure 4, b shows the change in the kinetics of the strength gain of the modified composition at point "M", selected from the field of effective formulating solutions \( D_{MS} = 13\% \), \( D_{SP} = 1.0\% \) and no additive at point "B" at the same S:C = 2.5:1. The analysis of changes in the strength of plaster solutions showed that at all control periods the strength of the modified plaster of the optimal composition "M" is higher than the strength of the non-additive composition "B" and at the brand age the increment in strength is at least 40%.

Among the main factors affecting the frost resistance of the mortar, the following are highlighted: the mineralogical composition of cement, the water content and structure of the cement stone, as well as the effect of additives. The structure of the cement stone and its pore space depends on the mineralogical composition of the clinker, the content of alkalis, the type and amount of additives [12-14]. Consequently, these factors will also effect on frost resistance. Researches by various authors, including [13, 15, 16] have shown that the properties of the main minerals – hydrosilicates and hydroaluminates are very different and determine the difference in strength and rate of its formation. At the same time, calcium hydroaluminate, which is the main mineral of the aluminate phases \( (3CaO\cdot Al_2O_3 \cdot 6H_2O) \), has low water resistance and can lose strength in water [15]. This gives reason to assert that the reduction of tricalcium aluminate in the clinker will contribute to increase the hardness experimentally confirmed that during using the active mineral additives capable of binding C₃A, the greatest effect is achieved when the complex used in conjunction with an air-entraining and plasticizing additives.

The high activity of microsilica, the ability to absorb calcium hydroxide, the compacting effect on the structure of the cement stone and the increase in strength will probably determine the increased frost resistance of the mortar.
In order to assess the frost resistance (F) of the modified plaster, special researches were carried out, reflecting the working conditions of the surface. The hardened plaster was evaluated for various quality parameters, which works in conjunction with a base: compressive and flexural tensile strength, adhesion strength to strip-off, shear and spall from the surface of the base, water permeability. In any case, those indicators that will be decisive for plaster solutions in real-life conditions are used as an assessment criterion. Taking into account the peculiarities of plastering work and possible difficult working conditions of the plaster layer (up and down temperature changes, especially in winter, saline waters, etc.), a method was developed for assessing the plaster layer after testing for frost resistance. The layer of plaster mortar is exposed to the one-sided effect of the external environment, therefore, moistening was carried out with capillary suction (Figure 1, c) in a salt solution (freezing at T=-20°C).

Since the most important indicator that determines the intensity of the destructive effect of freezing is the degree of water saturation of the mortar, freezing with capillary suction of water and with full immersion in a liquid medium turns out to be more destructive than freezing in air.

Determination of the properties of the plaster layer was carried out after 20, 40 and 60 cycles of freezing and thawing. The main indicators were considered:

- the amount of adhesion of the plaster layer \( R_{ad} \) to the concrete base;
- strength of the concrete base ("old" concrete);
- the strength of the plaster layer;
- indicator of water absorption of the plaster layer.

In Figure 5, a shows the curves of the adhesion strength to the cleavage of the non-additive plaster layer "B" and the modified "M". The modification allows to increase the adhesion strength of the plaster layer to the base ("old" concrete) by 10-15%, depending on the number of freezing and thawing cycles. This fact can, in particular, be explained by an increase in the adhesion forces of the modified composition.

It is known [17] that the seam (contact zone) is the boundary of the change in the directed shrinkage deformations, so the contact zone becomes "prestressed" tensile force. As shown by the results of experiments for various S:C, with an increase in the amount of cement, the adhesion strength increases by 5-7%. With an increase in the amount of microsilica up to 10%, the adhesion value increases by 10-15%, however, a further increase in the concentration of the ultrafine filler is ineffective, especially for compositions with a reduced binder consumption. This confirms the conclusions about the need to use low dosages of microsilica in plaster mortars. Limitations on the dosage of MS are also caused by a certain tendency of such mortars to plastic shrinkage, which requires the use of special measures to protect against moisture loss.

To assessment the possibility of reducing material consumption, a plaster layer was obtained not only with a thickness of \( h = 4 \) cm, but also \( h = 2 \) cm. The results of the experiments are presented in the form of a graph in Figure 5, b. The strength of the plaster layer with ultrafine filler and SP ("M") is higher than the strength of the no-additive plaster mortar "B" at all times of frost resistance tests.

Comparison of curves "M2" and "B1" shows that the strength of the concrete base ("old" concrete) on which no additive plaster mortar with a thickness of \( h = 4 \) cm and a layer of modified plaster mortar with a thickness of \( h = 2 \) cm were applied are close in their values. Thus, due to the use of a modified plaster mortar, not only the operational characteristics of the structure can be improved, but also the thickness of the plaster layer itself can be reduced without changing the quality of the base.

The strength of the modified plaster mortar in all test periods is higher than the strength of the unadded one by 20-30% (Figure 5, c), which is explained by an increase in its density and an improvement in the pore structure of the cement stone.

Changes in density can be characterized by water absorption curves for compositions "M" and "B", which show that the density of the modified composition changes insignificantly with an increase in the effect of the destructive medium and, in general, becomes smaller with the introduction of modifiers by 1.3-1.5 times.
Figure 5. Assessment of the properties of the plaster layer after frost resistance tests (F):

a) the strength of adhesion of the plaster layer to the base ("B" − no additives composite, "M" − modified, S:C = 2.5:1); b) the strength of the base − "old" concrete with different thickness of the plaster layer ("B₁", "M₁" − 4 cm, "B₂", "M₂" − 2 cm); c) the strength of the plaster layer; d) the density of the structure, assessment by water absorption (W).

According to [14, 18, 19], the micro-filler additives are characterized by a densifying effect. These additives contribute to the creation of a fine-grained structure characterized by evenly distributed and difficult-to-pass pores for the filtering liquid. At the same time, "microskeletons" are created in the intergranular cavities, which impede the flow of contraction and sedimentation processes, as well as the development of a system of filter pores and capillaries.

6. Conclusions

The use of a modified plaster solution improves its technological and mechanical characteristics. At the same time, in order to maintain a predefined mobility of plaster mortars (without changing their water content), it is necessary to introduce, as a rule, 0.3-0.4% of a superplasticizing admix for every 5% filler. The use of micro-filler makes it possible to increase the tensile strength in bending in 15-20%, and the compressive strength by more than 1.5 times, and the efficiency of microsilica increases with a decrease in the cement-sand ratio and an increase in the mobility of the mixture. With optimal ratios of all the factors under investigation, the economy of the superplasticizing admix can be ensured, as well as a noticeable increase in the tensile strength in bending and compression.

The modification made it possible to increase the adhesion strength of the plaster layer to the base by 10-15%, retain the characteristics of the base concrete after impact of an aggressive environment, increase the strength of the plaster layer itself by 20-30% and make it less permeable due to the
compaction of the structure, and also reduce the thickness of the plaster layer almost 2 times while maintaining its protective properties.

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