Modified mortars for elements of multilayered constructions and repair works and developing data storage system for research results

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Abstract. Based on the research performed, a comparative analysis of the changes in the properties of activated and non-activated fine-grained mixtures and mortars depending on the different specific surface: fine fillers: finely ground tripoli or sand, as well as on the content of inorganic PFM: highly active metakaolin, wollastonite and super-plasticizing additive superplasticizer S-3 or Melflux. The carried out researches show wide possibilities of modification of compositions by organomineral ecologically harmless additives and testify to rationality of development of complex additives separately for the activated and not activated fine-grained mortars. It is shown that when switching to another type of filler, even the same chemical composition, the dosages of all components and their ratio should be adjusted optimally. When switching to another type of mixture preparation, the ratio of components. Practical results obtained by the author provide the required and additional quality indicators, increase the physical and mechanical properties of fine-grained mortars, increase productivity. Theoretically substantiated and experimentally confirmed the effectiveness of the joint use of fine fillers, superplasticizer S-3 or Melflux, the high activity of metakaolin and wollastonite as a part of the binder in the fine-grained mixture and concrete. The architectural pattern of the decision support system for analyzing the properties of fine-grained multifunctional concrete has been developed.

1. Introduction
Modern construction requires the use of new effective materials, among which an important place is occupied by high-quality fine-grained mortars and high workability mixtures. Obtaining fine-grained mixtures of high uniformity, vitality and strength is impossible without the use of multifunctional modifier additives, the most effective of which are complexes based on superplasticizers and highly dispersed mineral additives based on silica fume [1-8]. However, their high cost is an obstacle to the widespread use of such complexes in Ukraine. A competitive mineral additive, as shown in the works [9, 10] is a highly active metakaolin, presented in the form of a dispersed powder as a result of roasting enriched metakaolin clay. Different silica-containing active microfillers and macrofillers with different specific surface area, structure and polyminal composition can have different effects on the rheology of mixtures, structure formation and hardening processes [3, 7, 11, 12].

An important innovation in the technology of high workability mixtures is the use of high-speed mixers. Activation contributes to a decrease of viscosity without changing the W/C ratio, or a decrease
the W/C ratio with a constant viscosity. The use of activated mixtures with reduced W/C values provides high crack resistance and high adhesion to various bases, and also high heat-protective and acoustic properties on porous fillers. At the same time, the issues of the joint action of different additives and the priority of their influence on the properties of mixtures and concrete has not been studied enough [2, 6, 8, 10].

The use of information technologies, in particular decision support systems (DSS), is one of the factors that make it possible to intensify research in this area and to implement the results of analysis. Systematization of investigated parameters and experimental results allows to quickly answer questions raised by producers in the decision-making process, as well as to increase the volume of analytic information, reduce the probability of erroneous decisions [13]. However, the design issues of computer systems for building materials science have not received coverage in the literature.

1.1. Objective and tasks.
Objective: to develop compositions of high workability mixtures modified by silica additives of different origin and structure micro fillers and macro fillers, to obtain based on them concrete of multifunctional assignment with high physical and mechanical properties, as well as ensuring storage of development results in a form accessible for DSS systems for building materials science.

To achieve this goal it is necessary to solve such problems:
- to analyze, according to experimental and statistical (ES) models, the patterns of influence of silica-containing additives of macro- and micro-fillers of various nature with different specific surface areas, and superplasticizers on the rheological, physical and mechanical, construction and operational properties of mixtures and concrete prepared in two different ways;
- to develop optimal compositions for plastering, erection, masonry and installation of floor elements with improved properties, taking into account the technologies for their preparation;
- to determine possible DSS design patterns as the result of monitoring the synthesis process of fine-grained concrete compositions based on high workability mixtures modified with multifunctional modifiers (MFM).

1.2. Materials applied in the research.
The following materials were used to make fine-grained concrete: mark PC 1-500 portland cement («HeidelbergCement Group»); pit sand from the Voznesenskoye (Nikitinskoye) field with Mₙ=1.25. Additives - superplasticizer S-3 or polycarboxylate hyperplasticizer Mellflux; mineral macro-filler - finely ground tripoli from the Kirovograd Mechanical Plant, ground to specific surface area Sₛ₆₆=300, 450 и 600 m²/kg; for comparison - ground quartz sand, also crushed to S₠₀₀=300, 450 и 600 m²/kg; wollastonite (WL, CaSiO₃, Impexinvest LLC, Kharkov) was used as an additive reducing shrinkage processes, increasing crack resistance; highly active metakaolin (HAMK) was used to seal the concrete structure.

2. Experimental research
Comprehensive studies included full-scale experiments using the planned multivariate experiments to obtain ES models. The construction and analysis of ES models was carried out using the statistical data processing system and standard Microsoft Office programs. The method of selecting the composition of the fine-grained mixture using ES modelling was used to determine the optimal composition. As a result of full-scale experiments, ES models of changes in seven rheological properties for 24 different compositions of mixtures and fourteen physical and mechanical properties of concrete were calculated.

Not only the choice, but also the rational combination of materials, additives and fillers is important. The analysis of the mutual influence of filler additives and plasticizer additives and the assessment of synergistic effects between them were carried out according to the same six-factor MTQ plans. Ground tripoli was used in two experiments, ground sand - in the other two. As independent
compositional factors, the following varied: the content of micro-fillers HAMK = (6 ± 4) %; WL = (5 ± 5) %; and superplasticizer S-3 = (1 ± 0.5) %.

In the first and second experiments, mixtures were prepared in the traditional way: workable not activated mixtures with a finely ground dense filler in the form of quartz sand (NAM-S) and light in the form of tripoli (NAM-T) with Water/Cement (W/C = 0.5). In the third and fourth experiments, high workability activated mixtures of similar compositions with quartz sand (AM-S) and tripoli (AM-T) were prepared in a high-speed mixer with W/C = 0.7.

3. Analysis of experimental results

ES models, that describe the effect of selected and reasonable composition factors on properties, are calculated and analyzed.

As a result of the experiments, four groups of ES models, which describe the change of the same group of properties in each experiment, were calculated. The rheological properties were evaluated and analyzed at the first stage of research. The technological conditions for the preparation of mixtures were taken into account during analysis. Technological efficiency of mortar mixtures is determined substantially by its workability.

The workability of mixtures depends on the technological conditions of their preparation and varies in the range of Dp = (6 ÷ 16) cm for workable mixtures and Dp = (20 ÷ 30) cm for high workability mixtures. This indicates a high sensitivity of the mixtures to external effects.

The density of mixtures varies on average by 40 %: \( \rho_{\text{NAM-S}} = 2080 \div 2360 \text{ kg/m}^3 \), \( \rho_{\text{NAM-T}} = 1760 \div 2020 \text{ kg/m}^3 \), \( \rho_{\text{AM-S}} = 1840 \div 1980 \text{ kg/m}^3 \), \( \rho_{\text{AM-T}} = 1650 \div 2040 \text{ kg/m}^3 \).

Segregation index according to standard norms should not exceed 5 %. Non-activated mixtures (NAM) are not delaminated. For activated mixtures with a S-3 content < 1 % and in the absence or minimum VL content, the delamination index exceeds the norm. This may indirectly indicate insufficient, in this case, plasticization of the mixture. The increased content of S-3 to 1.0 ÷ 1.5 % contributes to the normalization of delamination regardless of the content of WL and HMK and may be associated with a highly developed pore space structure of the used fillers. In this case, WL and HMK in the optimal amount serve as stabilizers and homogenizers of mixtures.

Therefore, for AM and NAM it is important to define such indicators as segregation and mortar separation, which are not provided in standard norms. The activation of mixtures generally reduces segregation and mortar separation.

Solidification time is adjusted by composition and preparation conditions. The increased content of S-3 superplasticizer delays the moment of solidification start. However, the addition of the WL (CaSiO3) additive in conjunction with the HMK results in an acceleration of cement minerals hydration period. The beginning of solidification terms is within 50 ÷ 180 min, and the time interval between the beginning and the end of solidification (the availability period or the pot life) is 120-270 min depending on the type of finely ground fillers, workability and preparation conditions of the mixtures. Inactive mixtures with tripoli solidify a little slower than with quartz sand. This may be due to an increase in silicic acid content and a decrease in pH, especially at the initial point in time.

Computational experiments on ES models allow us to make an important conclusion that even with equal workability \( P = \text{const} \) of mixtures, the rheological indicators that characterize the effectiveness of mixtures in the process of technological processing can differ significantly.

Different trends in the behavior of mixtures on silica-containing fillers of different types, structures, structures, and dispersions may indirectly indicate that the mechanisms of structure formation in such mixtures will take place differently, which affects the levels of changes in physical and mechanical properties. Therefore, it is necessary to simultaneously take into account the rheological effectiveness of fillers of different nature and granulometry, superplasticizer and conditions for the preparation of mixtures: slow or high-speed mixers.

At the next stage of the research, a comparative analysis of the change in physical and mechanical and operational properties was carried out.
Compressive strength analysis shows that combined use of WL and HMK has a positive effect on $R_{\text{comp}}$, increasing $\delta R_{\text{comp}}$ to 25% (for NAM-S). Due to the synergistic interaction of all the selected factors, taking into account the conditions for the preparation of the mixtures, the range of changes in $\delta R_{\text{comp}}$ varies: with fine-ground tripoli - by 1.54 times, with fine-ground sand - by 2.1 times. When choosing the optimal compositions, one should take into account the important conclusion that the influence of S of macro-fillers (tripoli/sand) is up to 35% higher than the combined effect of micro-fillers of WL, HAMK, and S-3, and that the maximum values of $R_{\text{comp}}^\max$ of the four different mixtures are achieved at different specific surface $S_{\text{ss}}$ of sand or tripoli. $R_{\text{comp}}^\max = 37; 40; 38; 25$ mPa for the four test mixtures, respectively.

Bending strength analysis shows that WL, which performs the function of micro reinforcement similar to HAMK, synergistically interact with each other, as a result, the variation range of $R_{\text{bend}}$ increases to 2 times.

Maximum and minimum strength values $R_{\text{comp}}$ and $R_{\text{bend}}$ significantly exceed the values rated by standard norms for different types of mortars, including floor elements: tie bars TB1, TB2, TB3 = 3.5; 4.5; 6 mPa, floor coverings FC1, FC2 = 5 mPa, repair compounds RC3 $\geq$5 mPa, for seams embedment $\geq$7 mPa, for masonry of all types of blocks MS2, MS3$\geq$7 mPa. On average, the values of $R_{\text{comp}}$ and $R_{\text{bend}}$ differ by more than 2.5 times. General trends for the four types of mixtures are different. It should be noted the positive synergistic effect from the influence of both micro-fillers (WL, HAMK, S-3) and macro-fillers dispersion.

Crack resistance varies by 2 times: from 0.5 to 1 mPa·m$^{0.5}$. General trends in crack resistance of activated and non-activated mixtures are different. Areas of maximum values of crack resistance on non-activated mixtures are achieved at maximum content of HAMK, S-3 and WL.

Micro wollastonite CaSiO$_3$ (pH=9.5−10.5) increases the deformation and abrasion resistance. There is a neutralization of the significant presence of WL by modifications of quartz to pH=7.5−8.5.

The water resistance of compounds on tripoli is higher than compounds on thin sand. Softening factor in the first case $k_{\text{sf}}=0.82\pm1$, which is associated with the formation of secondary water-resistant calcium hydroxilicates as a result of the interaction of amorphous silica with Portland cement. The greatest influence on $k_{\text{sf}}$ is exerted by $S_{\text{ss}}$.

The water absorption of modified concrete, which characterizes the porosity and penetration of liquids and gases, does not exceed 3-6%, primarily due to the replacement of quartz ground sand with tripoli with $S_{\text{ss}}=300$ and 600 m$^2$/kg.

Frost resistance is included in the set of standardized properties of mortars and should be at least F50 cycles. The frost resistance of the FR was determined on samples with finely ground tripoli and samples of optimal composition and reaches 50-75 cycles. The best frost resistance F75 obtained when the content of HAMK = 10%, WL = 5-10% and S-3 = 1-15%. It should be noted that the Tripoli fraction $S_{\text{tr}}=600$ m$^2$/kg has a significant effect on the frost resistance of the mortar.

At the final stage of the research, multicriteria optimization of the compositions of FR concrete was carried out. Formulated conditions for optimisation tasks of obtaining mortars for arrangement of floor elements, in particular tie bars of three different types TB1, TB2 and TB3, for arrangement coating FC1 and FC2, for masonry MS2 and MS3, surface repair RC3 and for surface plastering MS1 (Tables 1-3).

Results of monitoring compositions synthesis process allowed to determine standard tasks for data processing which take place at the initial stage of analytical researches automation. These include the accumulation of experimental data, the use of standard analysis algorithms, tabular and graphical visualization of research results.

Electronic forms of reference tables (materials, masses and specific surfaces of additives); input data form (list of additives); experimental results form (composite properties) can be used for data storage.
Table 1 Properties of tie bars based on activated and non-activated mortar mixtures.

| Name                                | Standard norms requirements | Properties of tie bars |
|-------------------------------------|----------------------------|------------------------|
|                                     |                            | NAM-S | AM-S | AM-T | NAM-T |
| Tie bar brand                       | TB1 TB2 TB3                | TB3   | TB2  | TB1  | TB2   |
| Workability not less than cm        |                            | <15 cm | ≥8 cm | >17  | >17   |
| Pot life no less than, min          |                            | 80÷260^a | 80÷260^a | 90÷300^a | 360^a  |
|                                    |                            | 30÷45^b | 35÷50^b | 40÷85^b | 40÷85^b |
| Filler fineness                     |                            | 1.25  | 1.25 | 1.25 | 1.25  |
| Compressive strength, mPa           |                            | 15    | 36   | 19÷25 | 27÷28  |
| after 3 days                        |                            | 10    | 3     | 3     | 9     |
| after 28 days                       |                            | 5     | 36    | 19÷25 | 27÷28  |
| Bending strength, mPa               |                            | 7÷12  | 7.5÷10 | 4.5÷7 | 8÷9.5  |
| after 28 days                       |                            | 6     | 3     | 3     | 9     |
| Strength of adhesion with concrete base after keeping in air under dry conditions mPa. Not less than | | >0.5 | >0.5 | >0.2 | >0.5 |
| Shrinkage, no more mm/m             |                            | <2.0  | <2.0  | <2.0  | <2.0  |
| Frost resistance cycles             |                            | 50    | –     | –     | –     |
| Additional requirements             |                            | –     | –     | 50    | –     |
| Mortar separation, no more          | tga≥0.25 (4 %)             | tga≥0.25 | tga≥0.25 | tga≥0.25 | tga≥0.3 | tga>0.3 |
| Segregation, %, no more             |                            | <5    | <5    | <5    | <5    |
| Mixture density, kg/m³              | –                            | 1780÷1760^a | 1850÷1760^a | 1650÷1650^a | 1760÷1760^a |
|                                    | –                            | 2110  | 2240  | 2040  | 2040  |
| Mortar density, kg/m³               | –                            | 2040÷2030÷ | 2040÷2030÷ | 1930÷1930÷ | 2030÷2030÷ |
| Crack resistance mPa*m^-0.5         | –                            | 0.95/1 | 0.65  | 0.95  | 0.65/1 |
| Heat conductivity W/m²              | –                            | λ<0.95 | λ<0.85 | λ<0.85 | λ<0.95 |

^a Compounds with S-3.

^b Values based on Melflux.
### Table 2 Properties of coatings based on activated and non-activated mortar mixtures.

| Name                          | Standard norms requirements | Properties of coatings |
|-------------------------------|-----------------------------|------------------------|
|                               | AM-T | NAM-T | AM-S | NAM-S |
| Coating brand                | FC1  | FC2   | FC1  | FC2   | FC2   |
| Workability not less than, cm| 17   | 17    | >17  | >17   | >17   |
| Pot life no less than, min    | 20   | 20    | 90÷300<sup>a</sup> | 90÷360<sup>a</sup> | 80÷260<sup>a</sup> | 80÷260<sup>a</sup> |
| Filler fineness               | 1.25 | 1.25  | 1.25 | 1.25  | 1.25  | 1.25  |
| Blur not less than, cm        | 17   | 17    | 14÷25| 10÷17 | 8÷18  | 8÷17  |
| Compressive strength, mPa     |      |       | 3÷8  | ≥ 9   | ≥ 11  | ≥ 10  |
| after 3 days                  |      |       |      |       |       |       |
| after 28 days                 | 7    | 10    | 19÷25| 26÷32 | 22÷33 | 19÷36 |
| Bending strength, mPa         | 5.0  | 5.0   | 4.5÷7| 7.5÷9.5| 7÷12 | 7.5÷10|
| after 28 days                 |      |       |      |       |       |       |
| Strength of adhesion with concrete base after keeping in air under dry conditions mPa. Not less than | 1.0  | 1.0   | 1.1  | 1÷1.4÷1.9 | – | 1÷1.6÷1.9 |
| Abrasion g/cm<sup>2</sup>, no more | –    | 0.7   | <0.7 | <0.7  | <0.7  | <0.7  |
| Shrinkage, no more mm/m       | –    | 1.4   | 1.5  | 1.6   | 1.7   |       |
| Frost resistance cycles       | –    | 75    | 75   | 75    | 75    | 75    |
| Additional requirements       |      |       |      |       |       |       |
| Mortar separation, no more    | tga ≥ 0.25<sup>(4%)</sup> | tga ≥ 0.25<sup>(4%)</sup> | tga > 0.5 | tga ≥ 0.3 | tga ≥ 0.3 | tga ≥ 0.25 |
| Segregation, %, no more        | 5    | 5     | <5   | <5    | <5    | <5    |
| Mixture density, kg/m<sup>3</sup> | –    | –     | 1760÷ | 1780÷ | 1840÷ | 2080÷ |
| Mortar density, kg/m<sup>3</sup> | –    | –     | 2100  | 2230  | 1980  | 2210  |

<sup>a</sup> Compounds with S-3.
<sup>b</sup> Values based on Melflux.
Table 3. Compositions of repair, masonry and installation mortars based on activated and non-activated mortar mixtures.

| Name                              | Standard norms requirements | Properties of masonry compounds | Properties of repair and mounting compounds |
|-----------------------------------|----------------------------|--------------------------------|---------------------------------------------|
|                                   |                            | AM-T | AM-T | NAM-S | NAM-S |
| Mortar brand                      | MS2                        | MS3  | RC3  | MN1   | MS2   | MS3   | MS1   |
| Filler fineness                   | 1.25                       | 1.25 | 1.25 | -     | 1.25  | 1.25  | 1.25  |
| Workability not less than, cm     | 5                          | 7    | -    | -     | >5    | >7    | -     |
| Pot life not less than, min       | 120                        | 90   | 30   | 30    | 90÷300| 90÷300| 80÷260| 80÷260|
| Compressive strength, mPa         | 40                         | 25   | 25   | 36/70a| 45b   | 36/70a|
| after 3 days                      | 5                          | 5    | 20   | 60    | 12/12a| 12/12a|
| after 28 days                     |                            |      |      |       |       |       |
| Bending strength, mPa, not less than: | -                        | 5    | 7    | 8     | 8     | 12/12a|
| Frost resistance cycles           | 25-75                      | -    | -    | 50    | 50÷75 | 50÷75 | -     | 75    |
| Shrinkage, mm/m, no more          | -                         | -    | 2.0  | 1.5   | -     | -     | <2.0  | <1.5  |
| Strength of adhesion with concrete base, mPa, not less than | 0.2                       | 0.2  | 0.8  | -     | 1.1   | 1.1   | -/1.6÷1.9 |
| Additional requirements            |                            |      |      |       |       |       |       |
| Water resistance                   | -                         | -    | -    | -     | 1     | 1     | 1/1   | 1/1   |
| Water absorption %                 | -                         | -    | -    | -     | 6     | 6     | 3/3   | 3/3   |

* Before / compounds with S-3, after / values based on Melflux.
  *b With the addition of an accelerator.

4. Development of a Decision Support System structure

To vary the analysis algorithms, mathematical or statistical software packages are usually used. However, work with them demands additional efforts on integration with the data storage - importing data into the software package, analyzing the data by means of the package, exporting the analysis results to the data storage. On the other hand, popular database management systems (DBMS) incorporate services of data analysis and standard algorithms of statistical processing and neural network modeling long ago. Of these, Microsoft (Ms) SQL Server has the most comprehensive list of capabilities for designing information analytical systems. The implementation of the Ms SQL Server Analysis Service project allows the use of data analysis tools by various methods and tabular data visualization tools based on queries to the storage in the SQL language or in the multidimensional expressions language. The Ms SQL Server Integration Service project allows organizing the collection of information from third-party data sources on entity-relationship (ER) modeling, taking into account their possible heterogeneity. Graphic visualization of data analysis results can be implemented by means of the MS SQL Server Reporting Service project.

Thus, the multifunctionality of user tasks that can be implemented using the package of services of Ms SQL Server allows us to consider this DBMS also as the main tool for designing a data storage. It is customary to use a multidimensional space with a discrete number of values in each dimension as a model of the repository of experimental data and analytical processing data. In dimensional modeling, each particular model consists of one table in which the facts are stored, and several other tables in
which the measurements are described. The first table is called the fact table, and the second is called the dimension table. In the model we selected (Figure 1), the materials of additives, the specific surface area, and the percentage of the additive content were taken as measurements. As measures or facts, the properties of composites were used: strength, frost resistance, shrinkage, water resistance. Introduction of additional hierarchical level in the form of the table "Reference Weight" allows to expand versions of the description of additive mass value.

Figure 1. Data storage information model for ER modeling.

The resulting model differs from the standard models of analysis of “stars” and “snowflakes”. In typical models, there is a one-to-many relationship between dimension tables and a fact table. In the developed ER repository model, the form of this connection is “many – to – many”.

The reason is that the object of analysis may be the parameter of a particular additive in the composition of the composite, and the real argument is the collection of additives. This forces to introduce an additional level of the dimension tables hierarchy in the form of a relationship table. In figure 1, this is the “Additives” table, the row of which represents a separate additive as the part of a composite. Accordingly, when forming analytical queries, it is impractical to use the default values for fixed parameters.

5. Conclusion

Natural experiments are implemented and the analysis of the received experimental statistical regularities is carried out. The obtained dependencies describe a change in the properties of mixtures and fine-grained concrete under the influence of silica-containing macro- and micro-fillers of various nature and dispersion together with organic superplasticizers.

Based on the results obtained, optimal MFM compositions are recommended for activated and non-activated mixtures, which differ in the quantitative ratio of components with the same qualitative composition. The proposed MFM compositions provide improved quality indicators and comfort conditions for various structural elements in comparison with standard norms.

The multiplicity and versatility of the MFM compositions obtained by the authors on the basis of identical in quality and different in quantitative compositions of organic-mineral modifiers determines the expediency and relevance of the automation of analytical studies using DSS. The main objective of the DSS is to provide information on existing MFM. This will expand the selection field and evaluate the competitiveness of the composition.
It is recommended to use the integration, analysis and reporting services of modern DBMS as tools for implementing multifunctional DSS. The list of standard projects recommended for the building of DSS assembly intended for the ER-simulation of fine-grained concrete of multifunctional purpose is determined, and an information model of the DSS data storage is developed.

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