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Optimisation of the composition of comprehensively modified self-compacting fine-grained concrete mixtures for vibration-free and low-vibration construction technologies

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Abstract: The article presents the results of research on optimising the composition of complex modified self-compacting fine-grained concrete mixtures intended for vibration-free and low-vibration construction technologies. The aim of the work was to establish rational component ratios that ensure an optimal balance between the rheological and strength characteristics of concrete. The parameters considered for optimisation were compressive strength at 1, 7 and 28 days, flexural strength, average density, and water-cement ratio. It was found that the use of a complex modifier, including mineral and chemical additives, contributes to a reduction in the water-cement ratio while maintaining the necessary mobility, increases early and final strength, and ensures the formation of a dense and homogeneous material structure without the use of vibration compaction. The results obtained can be used in the development of energy-efficient technologies for monolithic construction using self-compacting fine-grained concretes.

Keywords: self-compacting concrete; fine-grained concrete mix; complex modifier; composition optimisation; vibration-free technology; compressive strength; flexural strength; density; water-cement ratio; burnt mould waste; polycarboxylate superplasticiser

1. Introduction

The modern construction industry is characterised by rapid development and increasing demands on the quality, strength, durability and technological properties of structural materials. In these conditions, cement concrete retains its leading position as the most versatile and effective material with a wide range of properties that can be adjusted. One of the priority areas for the development of concrete technologies is the creation of self-compacting compositions that ensure high structural density and uniformity without the use of vibration [1].

In global practice, the introduction of self-compacting fine-grained concrete (SCFC) has become an important step in the improvement of monolithic construction technologies. Such mixtures are characterised by increased mobility, the ability to self-compact under their own weight, and structural stability, which improves the operational properties of the finished material and increases the energy efficiency of construction processes [2].

The required set of properties for self-compacting fine-grained concrete is achieved through the rational selection of components, optimisation of the particle size distribution of the aggregate structure, and the use of complex modifying additives. The most effective approach in this direction is recognised to be the use of chemical plasticising additives with mineral microfillers. Their combined action reduces the water-cement ratio while maintaining the necessary mobility, contributes to the intensification of hydration processes and the formation of a dense, low-porosity cement stone structure [3].

Previous studies have shown that the use of complex modifiers can significantly improve the technological and physical-mechanical properties of self-compacting concrete, as well as ensure its stable formation with minimal energy consumption. This opens up opportunities for the widespread introduction of vibration-free and low-vibration technologies into construction practice, which is particularly relevant in the context of the need to reduce labour intensity, energy consumption and negative environmental impact [4-8].

Taking into account the priority areas of development of the construction industry in the Republic of Uzbekistan, including within the framework of the implementation of the 'Strategy for the Development of New Uzbekistan for 2022-2026', the development of energy-efficient, technologically advanced and environmentally friendly building materials based on local raw materials is of particular importance. The creation of self-compacting fine-grained concretes with the necessary set of properties meets the objectives of improving the quality, reliability and seismic resistance of structures under construction, as well as contributing to a reduction in construction costs.

The aim of the study is to optimise the composition of complex modified self-compacting fine-grained concrete mixtures for vibration-free and low-vibration construction technologies based on an analysis of the influence of chemical and mineral additives on the water-cement ratio,

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strength, rheological and physical-technical characteristics of concrete.

The relevance of the research is determined by the need to develop effective compositions of self-compacting fine-grained concretes that ensure high performance properties when using local mineral resources and modern modifying systems. The scientific novelty of the work lies in establishing the patterns of influence of complex additives of various nature on the structure and properties of self-compacting fine-grained concretes, as well as optimising the composition parameters for the implementation of vibration-free moulding technologies.

2. Research Methodology

Materials widely available in the Republic of Uzbekistan were used to conduct experimental research on the development of self-compacting fine-grained concrete. The main binder was Portland cement grade CEMI 32.5N, produced by "Kizilkumcement" LLC.

The mineral filler used was metallurgical waste from "Uzbekistan Temir Yollari" JSC, which is a finely dispersed grey-brown material with a high specific surface area and the presence of amorphous phases. Before use, the filler was dried at a temperature of (105±5)°C to a constant mass and then ground in a ШЛМ-100 laboratory ball mill. The grinding time and load were determined experimentally in order to achieve optimal dispersion.

The dispersion of the mineral filler was controlled by the specific surface area using the Kozeni-Karmann air permeability method with the ПСХ-11А device, which allowed quantitative assessment of the degree of fineness of grinding. In addition, the morphology of the particles and the degree of aggregation were assessed using a sieve No. 008.

The chemical additive used was PRO500 superplasticiser based on polycarboxylate esters, which has a high water-reducing capacity (up to 25–30%) and provides the required mobility of cement systems with minimum water consumption.

To assess the physical and mechanical characteristics of self-compacting fine-grained concrete mixtures, a series of experimental studies was conducted to determine compressive strength, flexural strength, average density, and optimisation of the water-cement ratio.

The compressive strength of concrete was determined in accordance with the requirements of GOST 10180–2012 'Concrete. Methods for determining strength using control samples'. Cubes measuring 100×100×100 mm were made for testing and were tested at 1, 7 and 28 days of age. The tests were carried out on a hydraulic press with load control until the sample failed, after which the average strength of the series was calculated.

Bending strength was determined in accordance with GOST 310.4–2012 'Cements. Methods for determining strength' and GOST 24452–2015 "Concretes. Methods for determining flexural strength." For this purpose, 40×40×160 mm beams made of the same concrete mixture as the cubes were used. The tests were performed on a tensile testing machine using a three-point bending scheme, with the maximum load causing sample failure being recorded.

The average density of the hardened concrete was determined by the hydrostatic weighing method in accordance with GOST 12730.1–2020 'Concrete. Methods for determining density.' For each composition, the average density value was determined from three samples, which ensured the representativeness of the data.

The data obtained served as the basis for statistical processing and further optimisation of the composition of self-compacting fine-grained concretes using complex modifying additives.

The experimental campaign was planned as a two-factor central composite design, providing an assessment of linear, quadratic and interactive effects with the minimum number of experiments required [10]. The following factor variables were selected:

- x_1 — consumption of polycarboxylate superplasticiser (range 0.60–1.40 wt.% of cement mass);
- x_2 — consumption of burnt moulding waste (range 20–30 wt.% of filler).

All experiments are performed in random order (randomisation) to minimise temporal and systematic effects. Centre replicates are evenly distributed throughout the overall sequence of experiments, which allows for a correct assessment of intra-pair variability and the adequacy of the quadratic model.

$$Y = c + a_1x_1^2 + b_1x_1 + a_2x_2^2 + b_2x_2 + a_3x_3^2 + b_3x_3 + \dots + a_nx_n^2 + b_nx_n \quad (1)$$

For each point in the plan, a sufficient number of parallel samples (at least three for each key test) are to be produced, which ensures the statistical reliability of the average response values. After the experiments are completed, the data serves as the basis for approximating a second-order quadratic regression model (1) with an assessment of the main effects, quadratic terms, and the interaction between x_1 and x_2.

The plan concludes with a phase of confirmatory experiments: at least three independent repetitions are performed for the optimal combination of factors found to verify the model's predictions and check the reproducibility of the results.

3. Results and Discussion

To optimise the performance properties of fine-grained concretes with complex additives, a series of experimental studies was conducted to establish the patterns of influence of the composition of modifying components on the physical, mechanical and structural characteristics of materials. The main objective of the experiments was to determine and justify the most effective composition of the complex additive, ensuring an optimal combination of strength, density, workability and durability of fine-grained concrete.

A key aspect of the research was the study of the synergistic interaction between the superplasticiser (SP) and the component of the complex additive based on burnt moulding waste (BWS), which has a combined effect on the formation of the microstructure and pore space of the cement stone. Previous studies [9–15] have confirmed that the combined use of these components not only reduces the

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water demand of the system, but also contributes to the formation of a dense structure with uniform pore distribution, which significantly improves the strength and durability of self-compacting mixtures.

From a practical point of view, the relevance of this approach is due to the need to create concrete mixtures with high self-compaction without external vibration compaction, while maintaining resistance to delamination and uniformity of structure. Such concretes are especially in demand in the construction of monolithic and reinforced structures of complex configuration, where the use of traditional compaction is impossible.

The research was conducted on fine-grained concrete mixtures prepared with a constant cement-to-sand ratio (C:S = 1:2.5), which minimised the influence of the aggregate composition on the physical and mechanical properties of the concrete (Table 1).

The amount of mixing water in all series was selected taking into account the preservation of equal mobility of the mixtures in order to exclude the influence of differences in consistency on the physical and mechanical indicators. The mobility of the mixtures was assessed by the Hagerman cone spread, determined on a shaking table in accordance with GOST 310.4-81. The spread values were maintained within the range of 260–280 mm, which meets the requirements for self-compacting mixtures.

Table 1

Experiment plan and test results for fine-grained concrete

№	Composition of the complex supplement		Cone spread, mm	Average value of the response function					
	SP, %	BWS, %		W/C	R_1, MPa	R_7, MPa	R_{28}, MPa	R_{bend}, MPa	ρ, kg/m³
	X_1	X_2		Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
1	-	-	200	0,64	30,7	31,6	50,7	5,1	2047
2		20	195	0,72	6,6	10,5	21,4	4,1	1835
3		25	195	0,88	5,8	9,1	17,9	3,4	1804
4		30	190	0,97	4,2	7,5	15,7	2,6	1752
5	0,6	-	280	0,46	27,8	42,3	49,1	7,2	2166
6		20	270	0,5	28,8	40,2	48,1	7,1	2134
7		25	270	0,54	24,4	37,3	46,1	6,8	2071
8		30	270	0,58	21,1	34,3	44,7	6,2	2035
9	1,0	-	280	0,34	37,6	44,2	50,1	8,0	2215
10		20	280	0,34	36,5	46,1	51,1	8,9	2207
11		25	280	0,34	34,8	42,1	51,0	8,1	2189
12		30	275	0,38	30,1	39,8	49,2	7,7	2134
13	1,4	-	280	0,34	37,7	44,2	50,0	7,6	2214
14		20	280	0,34	36,4	46,1	50,1	8,8	2208
15		25	280	0,34	34,7	42,1	49,1	8,2	2188
16		30	280	0,38	30,2	39,8	48,1	7,6	2131

Analysis of the experimental data obtained showed that the use of a superplasticiser is a decisive factor determining the self-compacting ability of fine-grained mixtures. In compositions not containing SP, it was not possible to achieve the required mobility even with an increase in W/C, which led to delamination and water separation when spreading less than 210 mm. Such mixtures formed a heterogeneous structure with increased porosity, which negatively affected the strength characteristics of hardened concrete [16].

After processing the results and filtering out insignificant coefficients from the regression equation, mathematical models were obtained [17-20]. With a statistical reliability level of 94–98%, the obtained regression models describing the dependence of the studied indicators of self-compacting fine-grained concretes on the content of superplasticiser (SP) and burnt moulding waste (BWS) are as follows:

$$W/C = 0.72 - 0.63X_1 + 0.25{X_1}^2 - 0.0026X_2 + 0.026{X_2}^2$$

$$R_1 = 9.61 + 42.94X^1 - 16.12X^{12} + 0.27X^2 - 0.01X^{22} + 0.037X^1X^2$$

$$R_7 = 28.03 + 42.09X^1 - 22.90X^{12} - 0.46X^2 - 0.091X^{22} + 0.52X^1X^2$$

$$R_{28} = 45.23 + 29.02X^1 - 19.82X^{12} - 1.025X^2 - 0.012X^{22} + 0.84X^1X^2$$

$$R\_{bend} = 4.91 + 5.74X^1 - 2.76X^{12} + 0.051X^2 - 0.04X^{22} + 0.064X^1X^2$$

$$\rho = 1932 + 543.5X_1 - 248.1{X_1}^2 + 0.25X_2 - 0.21{X_2}^2 + 2.99X_1X_2$$

Figures 1–6 show isographic dependencies reflecting changes in the main physical and mechanical properties of self-compacting fine-grained concrete mixtures under the influence of varying factors — the amount of superplasticiser (SP) and burnt moulding waste (BWS). The diagrams show the patterns of change in the water-cement ratio, compressive strength at 1, 7 and 28 days, flexural strength, and average concrete density. The resulting isographic surfaces allow visualisation of the complex influence of the factors under study and determination of the areas of optimal combinations that ensure the achievement of the required operational properties of the material.

Mathematical models based on experimental data made it possible to comprehensively analyses the influence of variable factors — SP and BWS content — on the formation of the physical and mechanical properties of self-compacting fine-grained concretes. The regression equations obtained are characterised by a high degree of adequacy and reproducibility, which confirms the reliability of the developed models and their applicability for engineering calculations in the design of compositions of similar materials.

The results of the analysis showed that changes in the content of the components of the complex additive have a non-linear effect on the strength characteristics of concrete. At the same time, it was found that optimal operational properties are achieved with a rational ratio of the parameters under study, ensuring a balance between the mobility of the mixture and the density of the cement stone structure. In particular, it was established that the maximum compressive and flexural strength values are observed when the superplasticiser content is 1.0% and the burnt moulding waste content is 25% of the cement mass.

This combination of components contributes to the formation of a denser and more uniform microstructure of cement stone, a reduction in capillary porosity, and an increase in the degree of hydration of clinker minerals. Together, these factors increase the strength, durability and structural stability of fine-grained concrete, confirming the effectiveness of the proposed complex additive in non-vibration concrete technologies.

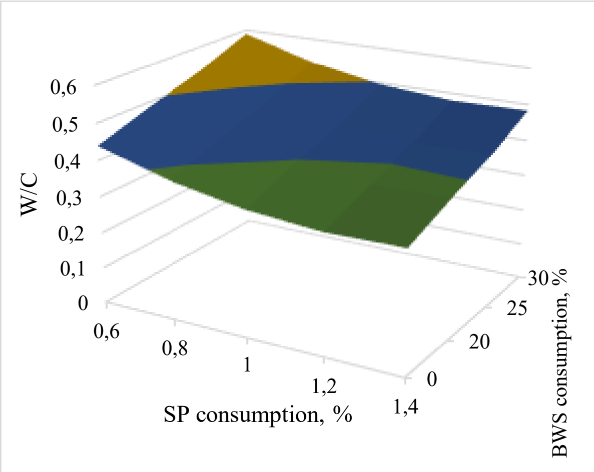

Fig. 1. Water-cement ratio of self-compacting fine-grained concrete mixtures depending on the content of SP and BWS in the complex additive

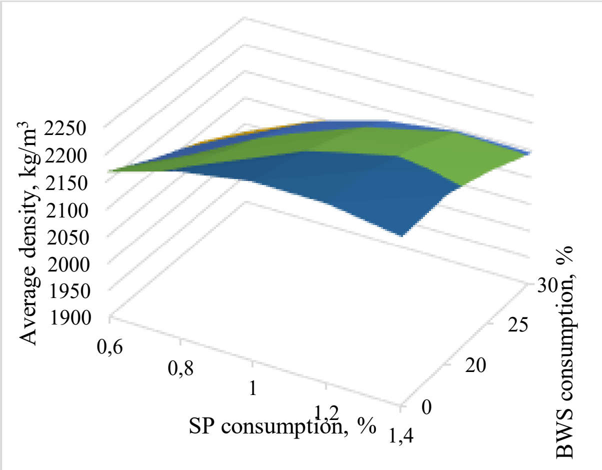

Fig. 2. Average density of self-compacting fine-grained concrete mixtures depending on the content of SP and BWS in the complex additive

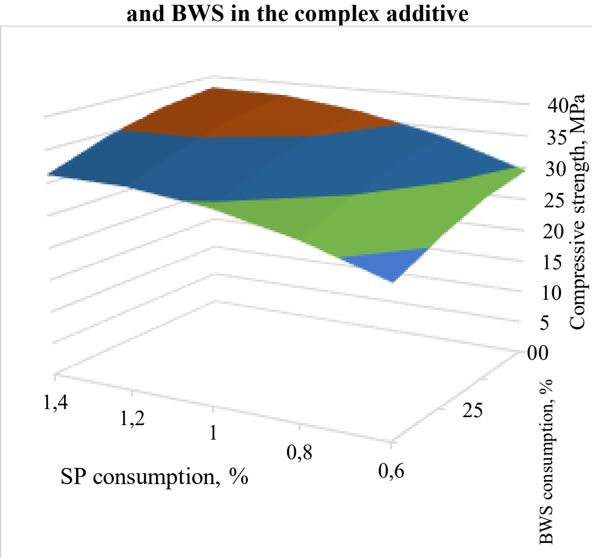

Fig. 3. Compressive strength of fine-grained concrete at 1 day of age depending on the content of SP and BWS in the complex additive

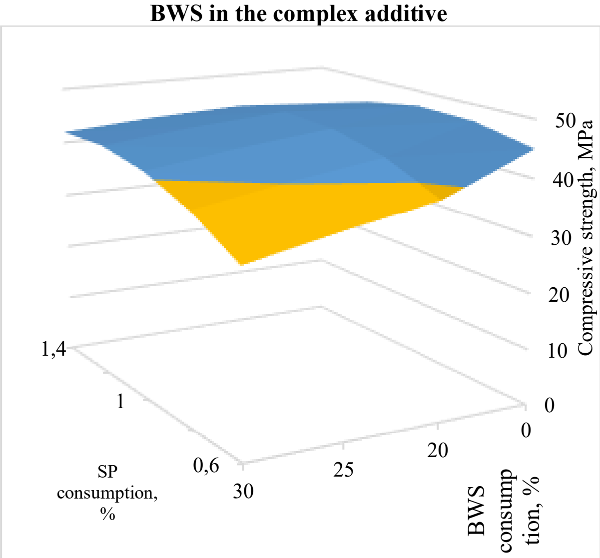

Fig. 4. Compressive strength of fine-grained concrete at 7 days of age depending on the content of SP and BWS in the complex additive

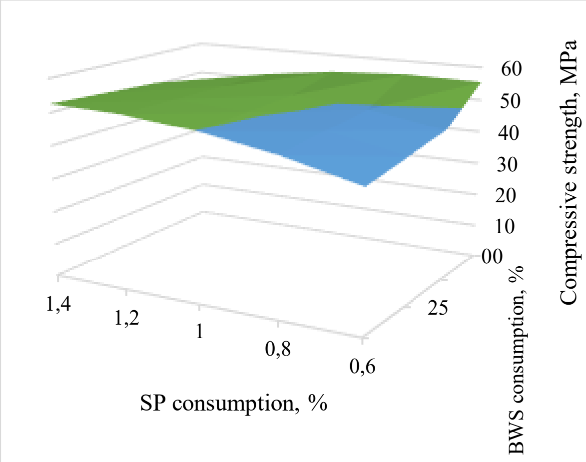

Fig. 5. Compressive strength of fine-grained concrete at 28 days of age depending on the content of SP and BWS in the complex additive

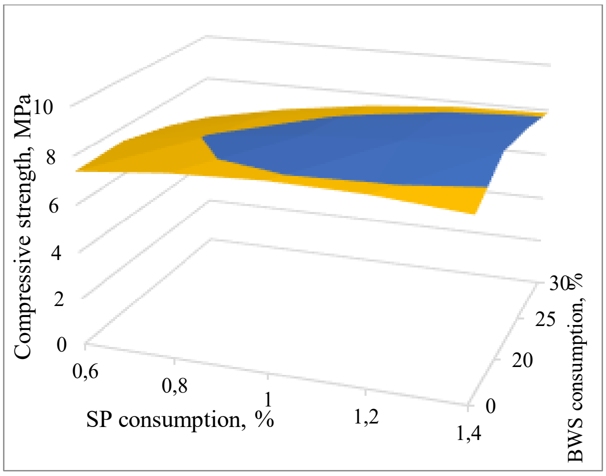

Fig. 6. Flexural strength of fine-grained concrete at 28 days of age depending on the content of SP and BWS in the complex additive

4. Conclusion

The studies conducted made it possible to establish the patterns of influence of a complex additive, including SP and BWS, on the formation of the structure and physical and mechanical properties of self-compacting fine-grained concretes. Based on the results of two-factor experimental design and subsequent mathematical modelling, regression relationships were developed to describe the influence of variable factors on the main property indicators: water-cement ratio, compressive and flexural strength, and concrete density.

The constructed models have a high degree of adequacy (confidence level of 94–98%) and allow predicting changes in the operational properties of the material depending on the composition of the complex additive. Analysis of response surfaces showed that varying the content of SP and BWS has a pronounced synergistic effect, improving the rheological characteristics and structural density of concrete.

It has been established that the optimal ratio of components ensuring the best physical and mechanical properties corresponds to a superplasticiser content of 1.0% and burnt moulding waste of 25% of the cement mass. With these parameters, a dense and uniform microstructure of cement stone is formed, capillary porosity is reduced, compressive and flexural strength is increased, and the overall homogeneity of the material is improved.

Thus, the results of the study confirm the effectiveness of using complex additives based on SP and BWS in the production of self-compacting fine-grained concretes. The proposed optimal component ratios can be used in the design of concrete compositions for vibration-free and low-vibration construction technologies, ensuring an increase in their strength, durability and manufacturability.

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