Analytical optimization of the dispersion-reinforced fine-grained concrete composition

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Abstract. The article presents the results of studying the problem of the concrete scrap accumulation and disposal. It is noted that after the implementation of comprehensive programs, including the renovation and modernization of the housing stock, a significant amount of concrete scrap has already been accumulated, and its amount will only increase. The results of scientific research on the compositions development of composite binder and fine-grained dispersed reinforced concrete based on this binder are presented. The purpose of the research described in the article was to develop the elements of a methodology for selecting the dispersed reinforced composite material composition based on finely ground waste of concrete scrap, mineral binder, thin basalt fiber and superplasticizers. The goal was solved using the methodology of technological processes system analysis and, in particular, mathematical planning, processing the experimental results and applying the analytical optimization method. It is noted that fine grinding of mineral components and the use of fibers with a diameter of 0.1 ... 6 microns allows not only to modify the concrete structure with an increase in strength characteristics, but also changes the chemical and physicochemical processes’ nature on the contact surfaces of the mineral matrix and fiber, as well as the same binder and finely ground reactive mineral particles with the formation of microsystems qualified as nanostructures.

Introduction
Technology development in modern society presupposes the emergence of many challenges and the formation of new problems associated with an excessive load on technology. Since the 1950s, the need to recycle industrial waste, including construction industries has become one of the serious problems [1-3]. For Russia, this problem is exacerbated by the renovation of the housing stock and the demolition of dilapidated housing. As a result of the comprehensive housing programs implementation, a huge amount of construction (including concrete) scrap has already been accumulated at the relevant facilities. The need for its use arises both from the fact of alienation of territories for the storage of these wastes, and from the additional burden on the environment. Disposal of this waste is necessary and will become mandatory in the near future.

The most technologically advanced way of recycling waste generated both as a result of the old buildings and structures’ demolition and waste from the building materials’ production is the use of these by-products in building products’ manufacturing [4–6]. It should be noted here that any by-products of the production of mineral binders, Portland cement, concrete, or their derivatives, classified
as waste, contain some percentage of clinker minerals. As a result of fine grinding or mechanical or mechanochemical activation, this component ceases to be an inert filler and starts exhibiting astringent properties [7–9].

The introduction of fibers or thread lines into the composition of raw mixtures also makes possible to significantly modify the properties of the finished product. In domestic and foreign practice, sufficient experience has been accumulated in the use of fibers of various natures in the composition of concretes, building mixtures or their analogues: steel, fibers based on alkali-resistant glasses or basalts, polymer, cellulose, nanotubes, etc. [10–12].

Fine grinding of mineral components and the use of fibers with a diameter of 0.1 ... 6 microns allows not only to modify the concrete structure, with an increase in strength characteristics, and, first of all, bending strength, but also changes the nature of chemical and physicochemical processes on the contact surfaces of the mineral matrices and fibers with the formation of ordered microsystems classified as nanostructures [13–15]. This suggests the emergence of a new subclass of building composites.

The purpose of the research described in the article was to develop elements of a methodology for selecting the composition of a dispersed reinforced composite material based on finely ground waste of concrete scrap, mineral binder, thin basalt fiber and superplasticizers.

**Materials and Methods**

System analysis of technological processes on the provisions of which the developed technique is based is predicated on considering technology as a cybernetic system. This system is divided into blocks adequate to technological advancements, for each of which the "black box" model is implemented. In the classical system chain, there are blocks of dosage (consumption) of components, their preparation and pretreatment, grinding, mixture preparation, molding, heat treatment [16–19].

The article presents the results of studying the first block. It is associated with the concrete mixture main components’ consumption optimization.

As variable factors, the costs of cement, fine waste, screening, plasticizer and reinforcing component are taken. The experimental conditions are shown in Table 1. The sand consumption is taken equal to 300 kg/m$^3$. Water consumption is set in accordance with W / C and is not an independent factor. The response functions are the compressive strength of concrete ($Y_1$) and its average density ($Y_2$).

As an optimization parameter at the third stage of the experiment, the coefficient of constructive concrete quality (CCQ), equal to the ratio of the compressive strength of concrete ($Y_1$) to its average density ($Y_2$): 

$$CCQ = \frac{Y_1}{Y_2}$$

The obtained regression equations are checked for all statistical hypotheses and the models’ adequacy is checked by the Fisher’s criterion. As a result of statistical tests as a result of comparison with confidence intervals ($\Delta bj$) only significant factors are left, and as a result of the Fisher test, a conclusion about the adequacy (or inadequacy) of the obtained models is made.

Evaluation of each factor’s influence on the result is carried out according to the value and sign of the coefficient facing the factor (its linear value or quadratic function) or their paired interaction. It should be noted that the experiment is carried out in the coded values of the factors (reduced to the interval $[-1, +1]$).

The interpolation of the results consists in determining the strength and average density of the material by calculation, depending on the variable factors’ values and is carried out by implementing the programs for electronic computer. Such a program includes data input blocks (values of factors in natural terms), a factor coding block, a calculation block, and a block for outputting results to the display. Testing of statistical hypotheses, modeling, processing and optimization of the results was carried out in accordance with the methods of the software package G-BAT-2011.

The equations are optimized using the analytical method, which is based on the following provisions: the obtained regression equations adequately describe the studied technological process; each equation
is an algebraic function of several variables (according to the number of significant variable factors) and methods of mathematical analysis are applicable to study this function [18–20].

### Table 1. Factor variation intervals.

| Factor name                              | Symbol X₀ | Average factor, \(\bar{X}_i\) | Variation interval, \(\Delta X_i\) | Factor values at the levels |
|------------------------------------------|------------|--------------------------------|-----------------------------------|----------------------------|
| Portland cement consumption, [kg/m³]     | X₁         | 450                            | 50                                | 400 500                    |
| Plasticizer consumption, [kg/m³]         | X₂         | 3                               | 0.5                               | 2.5 3.5                    |
| Consumption of finely ground waste, [%]  | X₃         | 320                            | 80                                | 240 400                    |
| Reinforcing component consumption, [%]   | X₄         | 1                               | 0.5                               | 0.5 1.5                    |

Sand consumption 200 [kg/m³]

### Results

Mathematical processing of the experimental results made it possible to obtain the regression equations for the compressive strength \((Y_1)\) and average density \((Y_2)\). The following mathematical models (polynomials) are obtained:

- for compressive strength

\[
Y_1 = 41.7 + 5.2X_1 + 2.7X_2 + 2.3X_3 + 3.0X_4 + 1.7X_1X_3 - 1.6X_2^2 - 1.7X_4^2
\]

- for average density:

\[
Y_2 = 1920 + 52X_1 + 34X_2 + 43X_3 + 13X_4 + 11X_1X_3 - 6X_2^2 - 4X_4^2
\]

The significance of the coefficient was checked by confidence intervals, respectively, the confidence interval for strength was \(\Delta b_1 = 0.8\) MPa, and for average density \(\Delta b_1 = 3\) kg/m³.

The resulting models were tested for adequacy according to the Fisher’s criterion. The calculated values of the Fisher criteria are equal for the average density model \(F_2=15.1\) and for the compressive strength model \(F_1=16.7\). The table values of the criteria are 19.2 and 19.3, respectively. The calculated values of the F-criterion do not exceed the tabular one, and with the corresponding confidence level (98%) the model can be considered adequate.

Analysis of the equation coefficients \(Y_1 = f_1(X_1, X_2, X_3, X_4)\) shows that the strength increases with an increase in the Portland cement and finely ground filler consumption in the intervals adopted in the experiment (positive coefficients at \(X_1, X_3\). With an increase in the consumption of the plasticizer, first there is an increase in strength, and then, at high consumption, a decrease is observed (coefficients at \(X_2\) and \(X_4^2\)). A similar picture takes place with an increase in the consumption of the reinforcing component (coefficients at \(X_4\) and \(X_4^2\)). This suggests that the function \(Y_1 = f_1(X_1, X_2, X_3, X_4)\) has local extrema in \(X_2\) and by \(X_4\), and it is possible to use analytical optimization.

Analysis of the equation coefficients \(Y_2 = f_2(X_1, X_2, X_3, X_4)\) shows that an increase in the consumption of Portland cement and finely ground filler (coefficients at \(X_1\) and \(X_3\)). An increase in the plasticizer and the reinforcing component consumption contributes to an increase in density: at first intensive, and at high costs - insignificant.

Analytical optimization is based on the fact that the functions for strength and density \(Y_1 = f_1(X_1, X_2, X_3, X_4)\) and \(Y_2 = f_2(X_1, X_2, X_3, X_4)\) – are the mathematical methods and it is permissible to apply the methods of mathematical analysis to them, provided that the condition of adequacy is not violated. In the case under consideration, the following scheme is adopted:

- the equation \(Y_1 = f_1(X_1, X_2, X_3, X_4)\) is differentiated by \(X_2\) and equate to zero, determining the extremum of the function \(Y_1\) by \(X_2\);
- the equation \(Y_1 = f_1(X_1, X_2, X_3, X_4)\) is differentiated by \(X_4\) and equate to zero, determining the extremum of the function \(Y_1\) by \(X_4\);
the functions \( Y_1 = f_1(\mathbf{X}), Y_2 = f_2(\mathbf{X}) \) are solved at the optimized values \( X_2 = \text{opt}_2 \) and \( X_4 = \text{opt}_4 \), then local optimization is carried out.

**Discussions**

Analysis of the polynomial describing the relationship between compressive strength and variable factors shows that this function (which is essentially a function of several variables) in two of these variables, namely, the consumption of the plasticizer \( X_2 \) and the consumption of the reinforcing component \( X_4 \), has local extrema. Therefore, we can use the mathematical apparatus of analytical local optimization.

The methodology of analytical local optimization is based on the fact that the nonlinear dependences obtained as a result of mathematical processing of the statistical analysis results are, on the one hand, mathematical models that adequately describe the phenomenon under study, and this adequacy is confirmed by testing the statistical hypotheses.

On the other hand, these dependences are the second-order polynomials and mathematical functions of several variables, to which the methods of algebraic analysis of such functions in general and, in particular, the determination of their local extrema can be applied. The local extremum of such functions is determined by differentiating the function with respect to the parameter of interest to us (in this case, \( X_2 \)) and setting the result to zero. The subsequent solution of the linear dependence gives a possibility to find the factor value corresponding to the extremum in the domain of this factor.

In the optimization process, we perform the following sequence of actions:

1) Determine the local extrema of the function \( Y_1 \) by \( X_2 \) and \( X_4 \):

\[
\frac{\partial Y_1}{\partial X_2} = 2.7 - 3.2 X_2 = 0 \rightarrow X_2 = \frac{2.7}{3.2} = 0.84
\]

\[
\frac{\partial Y_1}{\partial X_4} = 3.0 - 3.4 X_4 = 0 \rightarrow X_4 = \frac{3.0}{3.4} = 0.88
\]

2) Solve the functions \( Y_1 = f_1(\mathbf{X}), Y_2 = f_2(\mathbf{X}) \) at the optimized values \( X_2 = 0.84 \) and \( X_4 = 0.88 \)

- for compressive strength

\( Y_1 = 46.7 +4.9X_1+2.3X_3 +1.5X_1X_3 \)

- for average density:

\( Y_2 = 1953+ 52X_1 + 43X_3 + 11X_1X_3 \)

3) Determine the natural values of the optimized factors, taking into account the data in Table. 1:

Plasticizer consumption: \( 3 + 0.5 \times 0.84 = 3.42 \pm 0.2 \) kg/m³
Reinforcing component consumption: \( 1 + 0.5 \times 0.88 = 1.44 \pm 0.1\%

4) Form the analytical expressions for the coefficient of concrete constructive quality (CCQ):

\[
CCQ = \frac{Y_1}{Y_2} = \frac{46.7 +4.9X_1+2.3X_3 +1.5X_1X_3}{1953+ 52X_1 + 43X_3 + 11X_1X_3}, \text{ [MPa·m³/kg]}
\]

The graphical interpretation of the obtained equation is shown in Figure 1.
Analyzing the graph of the coefficient of constructive quality (CCQ) dependence from Portland cement and the consumption of mineral filler obtained by fine crushing of concrete scrap, the following can be stated. First, the obvious fact that with the analytically obtained optimal values of the plasticizer consumption (3,42 ± 0,2 kg/m³) and consumption of reinforcing fiber (1,44 ± 0,1%) with an increase in the Portland cement consumption CCQ increases. Second, it was found that in the intervals of factor variation provided by the experimental conditions (Table 1), there is a tendency for additional CCQ growth with an increase in filler costs. This may well be explained by its hydraulic activity, but requires additional research.

Summary
In connection with the increasing volumes of construction waste accumulation in the process of housing renovation, demolition of dilapidated ones, replacement of bridge structures and road surfaces, the problems of processing elements of the destroyed structures and buildings in order to obtain secondary nonmetallic building materials become extremely urgent. The research results presented in the article show the possibility of using a fine-grained waste concrete scrap as an active filler for composite binder and structural concrete based on it.

The experimental technique based on the system analysis of technological processes allows obtaining adequate mathematical models, the engineering interpretation of which allows solving technological problems, including the selection of the composition of fine-grained concrete with dispersed reinforcement, as well as obtaining the optimization solutions in the process of processing the experimental data.

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