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SYSTEM ANALYSIS OF TECHNOLOGICAL PROCESSES

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Abstract. The article discusses ways to solve engineering problems in the study of technological processes using methods of system analysis. The essence of this method is to study the technology as a cybernetic system with an assessment of the" reactions" of this system to external influences formed during an active experiment. At the same time, optimization problems are solved analytically. Analytical optimization is based on two main principles. The regression equations obtained as a result of processing experimental data and testing statistical hypotheses are models that adequately describe real processes. Each of these equations is an algebraic function of several variables, to which methods of mathematical analysis are applicable, including the study of extremums of functions in partial derivatives. The next step is to develop a process algorithm and develop computer programs that allow you to select the composition and predict the properties of the product. As an engineering interpretation, it is possible to construct optimized nomograms that allow solving both direct and inverse problems; that is, predicting the result or selecting technological factors. The research methods described in the article are implemented in the study of technologies of cellular concrete, foam concrete, cement-polymer concrete and products made of mineral wool and foam glass. As an example, the article considers the optimization of the selection of the composition of fine-grained concrete reinforced with chopped glass fiber. The implementation of the developed method allowed us to determine the optimal value of the determining parameters, including the consumption of fiber and plasticizer, as well as to form a method for studying the properties of products.

Keywords: concrete, composite material, technology, glass fiber, dispersed reinforcement, analytical optimization.

СИСТЕМНЫЙ АНАЛИЗ ТЕХНОЛОГИЧЕСКИХ ПРОЦЕССОВ

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Аннотация. В статье рассматриваются способы решения инженерных задач при исследовании технологических процессов с использованием методов системного анализа. Суть этого метода заключается в исследовании технологии как кибернетической системы с оценкой «реакций» этой системы на внешние воздействия, формируемые в процессе активного эксперимента. При этом решение оптимизационных задач осуществляется аналитически. Аналитическая оптимизация базируется на двух основных положениях. Полученные, в результате обработки экспериментальных данных и проверки статистических гипотез уравнения регрессии являются моделями, адекватно описывающими реальные процессы. Каждое из таких уравнений является алгебраической функцией нескольких переменных, к которому применимы методы математического анализа, в том числе исследование экстремумов функций в частных производных. Следующим шагом является разработка алгоритма процесса и разработка компьютерных программ, позволяющих осуществлять подбор состава и прогнозирование свойств продукта. В качестве инженерной интерпретации возможно построение оптимизированных номограмм, позволяющих решать как прямые, так и обратные задачи; то есть прогнозирование результата или выбор технологических факторов. Описанные в статье методы исследования реализованы при изучении технологий ячеистого бетона, пенобетона, цементно-полимербетона и изделий из минеральной ваты и пеностекла. В качестве примера в статье рассматривается оптимизация подбора состава мелкозернистого бетона, армированного рубленым стеклянным волокном. Реализация разработанной методики позволила определить оптимальное значение определяющих параметров, включая расход волокна и пластификатора, а также сформировать методику изучения свойств изделий.

Ключевые слова: бетон, композиционный материал, технология, стеклянное волокно, дисперсное армирование, аналитическая оптимизация.

1. INTRODUCTION

System analysis of technology and process modeling are aimed at solving three types of problems: development of composition selection methods; optimization of the composition or characteristics of the initial components; optimization of parameters that characterize the technology as a whole, or individual technological processes.

The object of research in this case is a technological process and to describe it, a cybernetic system is widely used, called a "black box", which has its own input parameters, control actions and outputs. Methods for studying technological processes by building cybernetic models and optimizing them are constantly being enriched and expanded. Implementation of the system analysis of technology involves addressing two types of technological problems: the development of methods for selecting the composition of the material and optimization of the technology of this material [1, 2].

Certain provisions of the system analysis are implemented in the study of recipes and technologies of building materials for various purposes and various material composition from heat-insulating products to heat-insulating and structural concrete. Modern realities, in which the construction complex is developing, suggest setting new tasks in related areas of research, including utilization of by-products of construction materials production and waste obtained as a result of demolition of construction objects [3-5].

Dispersed reinforcement with natural, synthetic, or mineral fibers can significantly modify the properties of the finished product [6-8]. In domestic and foreign practice, sufficient experience has been gained in the use of various types of fibers in the composition of concretes, building mixes or their analogues: steel fibers, fibers based on alkali-resistant glasses or basalts, polymer, cellulose, nanotubes, steel fibers, etc. [9-11]

The use of these by-products in the manufacture of construction products is a science-intensive method of recycling waste that appears as a result of the demolition of old buildings and structures, as well as waste from the production of building materials [12-14]. 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 a certain percentage of clinker minerals. As a result of fine grinding or mechanical or mechanochemical activation, this component ceases to be an inert filler and begins to exhibit astringent properties [15, 16].

Fine grinding of mineral components and the use of fibers with a diameter of 0.1...6 microns allows not only to modify the structure of concrete, with an increase in strength characteristics, and, first of all, Flexural strength, but also changes the nature of chemical and physico-chemical processes on the contact surfaces of the mineral matrix and fiber with the formation of ordered Microsystems qualified as nanostructures [17-20]. This suggests the emergence of a new subclass of building composites.

The purpose of the research presented in the article was to develop, using the methodology of system analysis, elements of the methodology for selecting the composition of a dispersed reinforced composite material based on fine-ground concrete scrap waste, mineral binder, alkali-resistant glass fiber and plasticizer.

2. MATERIALS AND METHODS

The system approach is one of the foundations of technological modeling. It consists in dividing the entire technological process into separate blocks that are adequate for technological processing; studying the functioning of each block separately; establishing the relationship between individual blocks and building a General scheme of the process as a set of blocks and links between them. The basis for the study is modeling, which can be carried out using both statistical methods (discussed above) and deterministic and conceptual (logical) models [21, 22].

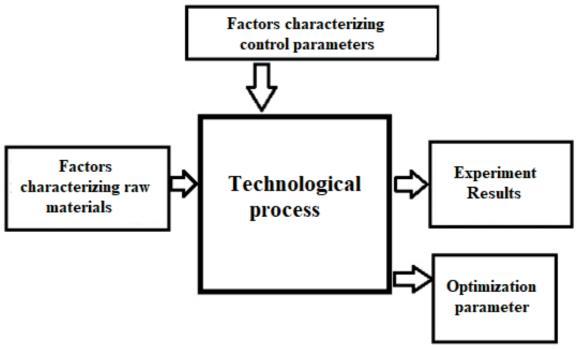


Figure 1. Technology as a cybernetic system

The "black box" (figure 1) can cover the technology as a whole. This technique is widely used when building models based on a "passive" experiment, when conclusions are drawn from observations and collecting statistical information. The "black box" can cover a separate technological conversion, that is, a separate process: selection of the composition, preparation of the mixture, molding, and heat treatment. The technology model, in this case, is obtained from individual bricks-blocks. The connection between individual" blocks "of technology is made through factors that are" outputs "for one block and" inputs” for another. This technique, which is widely used in the analysis of nonlinear technological processes, does not exclude the use of techniques used in the first method.

The cybernetic model, which is based on a flowchart, is a legitimate basis for conducting an experiment, further processing the results, and building its mathematical (statistical) model. A mathematical model of a separate technological process is formed from a set of polynomials describing individual fragments of this process.

If the "black box" covered the technology as a whole, the experiment covers dozens of factors. First, we consider the entire set of factors "involved" in the process of creating the material. Using special techniques, the most significant factors are identified, and then all the problems of technology optimization and simulation solutions are implemented based on the variation of significant factors.

The obtained regression equations are checked for all statistical hypotheses and the models ' adequacy is checked by the Fisher criterion. As a result of statistical checks, only significant factors are left out as a result of comparison with confidence intervals (Δbj), and as a result of checking by the Fisher criterion, a conclusion is made about the adequacy (or inadequacy) of the obtained models.

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

Interpolation of the results consists in calculating the strength and average density of the material depending on the values of the variable factors and is carried out by implementing computer programs. This program includes the following blocks: input data (values of factors in real terms), a block coding factors, calculation block, the output results on the display. Testing of statistical hypotheses, modeling, processing and optimization of results was carried out in accordance with the methods of processing the results of the experiment.

The equations are optimized using an analytical method. Which is based on the following provisions: the obtained regression equations adequately describe the technological process under study; each equation is an algebraic function of several variables (by the number of significant variable factors) and mathematical analysis methods are used to study this function. The experimental conditions are shown in table 1.

Table 1. The intervals of variation of factors

Name of the factor	Symbol X_i	Average value of the factor, Xi	The range of variation, ΔXi	The values of the factor levels	
				-1	+1
Consumption of Portland cement, kg / m^3	X_1	450	50	400	500
The consumption of plasticizer, %	X_2	0.6	0.2	0.4	0.8
Consumption of fine filler, kg / m^3	X_3	650	50	600	700
Consumption of the reinforcing component, %	X_4	1	0.5	0.5	1.5

The costs of cement, fine filler, plasticizer, and reinforcing component are taken as variable factors. The water flow rate is set in accordance with the required level of mobility of the mixture and is a dependent factor. The response function taken the strength of concrete in compression ($У_1$) and its average density ($У_2$).

As the parameter optimization in the third stage of the experiment adopted the coefficient of structural quality concrete (CCQ), equal to the ratio of compressive strength of concrete ($У_1$) to its average density ($У_2$):

$$CCQ = (У_1)/ (У_2)$$

3. RESULTS

Mathematical processing of the experimental results allowed us to obtain regression equations for compressive strength ($У_1$) and average density ($У_2$). The following mathematical models (polynomials):

- for compressive strength

$$У_1= 39.7 +3.9X_1+1.7X_2+1.9X_3 +2.2X_4 + 1.5X_1X_3 +1.2X_1X_4 -1.1X_2^2 -1.2X_4^2$$

- for medium density:

$$У_2 = 1960 + 52X_1 + 24X_2 + 33X_3 + 13X_4 + 11X_1X_3 - 6X_2^2 - 4X_4^2$$

The significance of the coefficient was checked by confidence intervals, respectively, the confidence interval for the density was Δb_1 = 0.8 MPa, and for the average density Δb_2 =3 kg/ m^3. The obtained models are checked for adequacy by the Fisher criterion. The calculated values of the Fischer criteria are equal for the average density model F_1=15.2 and for the compressive strength model F_2=15.7. Table of criteria values, respectively, equal to the 19.2 and 19.3. The calculated value of F-test does not exceed the table, and with the appropriate confidence level (98 %) model can be considered adequate. This fact will be taken into account in the analytical optimization of mathematical models.

Analysis of the coefficients of the equation $У_1 = f_1(X_1, X_2, X_3, X_4)$ shows that the strength increases with increasing expenditure of Portland cement, sand and screening in the intervals taken in the experiment (positive coefficients for X_1, X_2, X_3, X_4). When the polymer costs increase, first there is an increase in strength, and then at high costs – there is a decrease (coefficients at X_2 and X_2^2). This suggests that the function $У_1 = f_1(X_1, X_2, X_3)$ has a local extreme over X_4, and analytical optimization can be applied.

Analysis of the coefficients of the equation $У_2 = f_2(X_1, X_2, X_3, X_4)$ shows that the greatest influence on the increase in concrete density is exerted by an increase in the consumption of Portland cement and fine-ground filler (coefficients at X_1 and X_3). Increasing the consumption of the plasticizer and the reinforcing component increases the density: at first, intensive, and at high costs – insignificant.

Analytical optimization is based on the fact that the functions for strength and density $У_1 = f_1(X_1, X_2, X_3, X_4)$ and $У_2 = f_2(X_1, X_2, X_3, X_4)$ are mathematical and mathematical analysis methods can be applied to them, provided that the adequacy condition is not violated. In this case, the following scheme is adopted:

- The equation $У_1 = f_1(X_1, X_2, X_3, X_4)$ is differentiated by X_2 and equated to zero, determining the extreme of the function $У_1$ by X_2;
- the equation $У_1 = f_1(X_1, X_2, X_3, X_4)$ is differentiated by X_4 and equated to zero, determining the extreme of the function $У_1$ by X_4;
- solve the functions $У_1 = f_1(X_1, X_2, X_3, X_4)$ and $У_2 = f_2(X_1, X_2, X_3, X_4)$ with optimized values X_2 and X_4 ($X_2 = opt_2$ and $X_4 = opt_4$), then perform local optimization.

4. 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) for two of these variables, namely, the flow rate of the plasticizer (X_2) and the flow rate of the reinforcing component (X_4), has local extremes. Therefore, we can use the mathematical apparatus of analytical local optimization.

At the first stage, we perform analytical optimization based on the X4 factor.

$$\partial Y_1 / \partial X_4 = 2.2 - 2.4X_4 = 0 \rightarrow X_4 = \frac{2.2}{2.4} = 0.92$$

We solve the basic equations for $X_4 = 0.92$

-for compressive strength

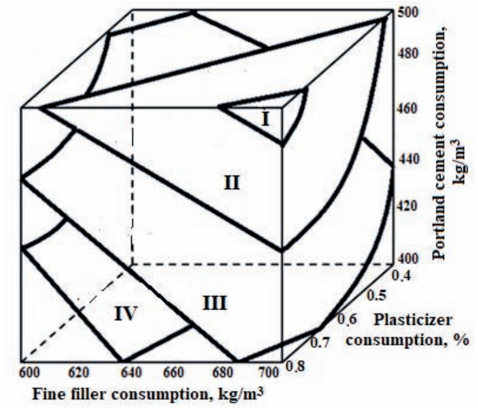
$$У_1 = 40.7 + 3.9X_1 + 1.7X_2 + 1.9X_3 + 1.5X_1X_3 + 1.1X_1 - 1.1X_2^2$$

- For average density:

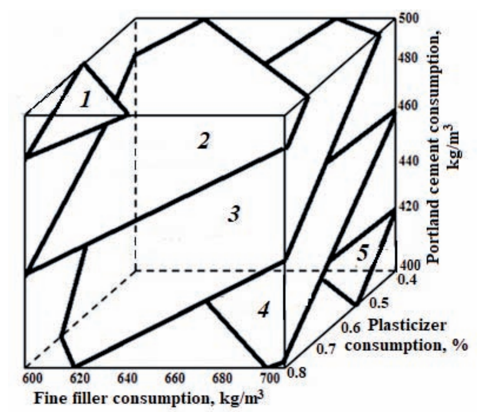
$$У_2 = 1969 + 52X_1 + 24X_2 + 33X_3 + 11X_1X_3 - 6X_2^2$$

In natural values, the consumption of chopped glass fiber is determined by decoding: $C_{gv} = 1 + 0.5 \times 0.92 = 1.46\%$.

Interpolation solutions for the entire range of changes in factors X_1, X_2, and X_3 can be represented graphically (Fig. 2).



a



b

Figure 2. Graphical interpretation of the response functions optimized for the consumption of the reinforcing component (consumption is Cgv = 1.46%): a – dependence of the concrete strength on variable factors; b – dependence of the average concrete density on variable factors: I – 40 MPa; II – 35 MPa; III – 30 MPa; IV – 25 MPa; 1 – 2000 kg/m³; 2 – 1950 kg/m³; 3 – 1900 kg/m³; 4 – 1850 kg/m³; 5 – 1800 kg/m³

At the second stage, we perform analytical optimization based on the X_2 factor

$$\partial У_1 / \partial X_2 = 1.7 - 2.2X_2 = 0 \rightarrow X_2 = \frac{1.7}{2.2} = 0.77$$

We solve the equations already optimized for X_4 at $X_2 = 0.77$

- For compressive strength

$$У_1 = 41.9 + 3.9X_1 \; 1.9X_3 + 1.5X_1X_3$$

- For medium density:

$$У_2 = 1984 + 52X_1 + 33X_3 + 11X_1X_3$$

In natural values, the consumption of chopped glass fiber is determined by decoding: $C_{gv} = 0.6 + 0.2 \times 0.77 = 0.75\%$

4) Form an analytical expression for the coefficient of structural quality of concrete (CCQ):

$$CCQ = \frac{У_1}{У_2} = \frac{41.9 + 3.9X_1 + 1.9X_3 + 1.5X_1X_3}{1984 + 52X_1 + 33X_3 + 11X_1X_3}$$

[MPa·м^3/кg]

A graphical interpretation of the resulting equation is shown in Fig. 3

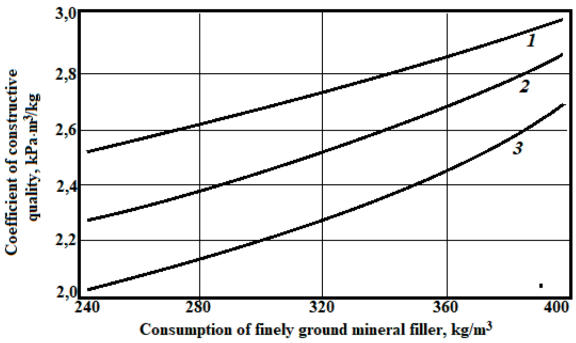


Figure 3. Dependence of the Coefficient of constructive quality on the consumption of fine-ground mineral filler and the consumption of Portland cement, taking into account the optimization of plasticizer consumption and the consumption of reinforcing fiber, kg / m^3: 1 – 500; 2 – 450; 3 – 400

Analyzing the graph of the dependence of the coefficient of structural quality (CCQ) on Portland cement and the consumption of mineral filler obtained by fine grinding of concrete scrap, we can state the following. First, it is an obvious fact that when the optimal values of plasticizer consumption (3.42 ± 0.2 kg/m^3) and the consumption of reinforcing fiber (1.44 ± 0.1%) are obtained analytically, the CCQ increases with the increase in the consumption of Portland cement. Second, it was found that in the intervals of variation of the factor provided for by the experimental conditions (table. 1) there is a tendency for additional CCQ growth with increasing filler costs. This may well be explained by its hydraulic activity, but requires additional research.

Using the methods of system analysis and the approach to technology as a cybernetic system allows you to create a mathematical model of the technology as a whole, or its individual blocks. In particular, to develop methods for selecting the composition and predicting the properties of the product. It is also important to be able to obtain information on the direction and significance of the influence of factors or pair interactions on the result (by the sign and absolute value of the coefficient or pair interaction.

Analysis of regression equations also provides information on the possible appearance of a synergistic or antagonistic joint influence of a group of factors on the result (coefficients for paired or triple interactions). Here it is necessary to emphasize that only the fact of interaction can be registered, since the factors in the equations are represented in encoded form. To estimate the amount of influence, the equations must be converted to the natural values of the factors.

The results of studies of technological processes using system analysis methods are also considered as a basis for further research with the solution of problems of materials science, heat and mass transfer in materials, and the study of phase transformations in the process of technological processing.

5. CONCLUSION

As a result of the research, elements of the methodology for selecting the composition of a dispersed reinforced composite material based on fine-ground concrete scrap waste, mineral binder, alkali-resistant glass fiber and plasticizer were developed. The research was based on the method of system analysis, the essence of which was to study technology as a cybernetic system with an assessment of the" reactions” of this system to external influences formed during an active experiment. At the same time, the solution of optimization problems was carried out within the framework of the General methodology of analytical optimization.

The research methods described in the article were previously implemented in the study of technologies for cellular concrete, foam concrete, cement-polymer concrete, and products made of mineral wool and foam glass. As an example, the article considers the optimization of the selection of the composition of fine-grained concrete reinforced with chopped glass fiber.

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