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Development of compositions of modified concrete with improved water-repellent properties for underground parts of buildings

V D Tukhareli, A V Tukhareli, T F Cherednichenko
Institute of architecture and construction, Volgograd State Technical University, 28, Lenin avenue, 400005 Volgograd, Russia
E-mail: mr-reb@mail.ru

Abstract. In building of various underground structures, one of the main tasks is to ensure the durability and reliability of concrete structures, as well as the resistance to ground and aggressive water, which, in its turn, should be taken into account in the development of concrete compositions. The wastes from the chemical and processing industry are used as additives to concrete to regulate various properties of composites. This study shows that the use of a modifier from the organic fraction of oil waste make a material with improved characteristics for its use in underground parts of structures. When solving the problem of selecting the composition of a sulfate-resistant composite with water-repellent properties, the methodology of mathematical design of the experiment was used on the basis of a polynomial model linking the optimization parameter of the compressive strength limit with independent technological factors having three levels of variation. The analysis of the results of the experiment made it possible to determine the admissible limits of the oscillations of the independent variable factors, which ensure that the optimization parameter is found not only at the extreme point, but also in the region of given values.

1. Introduction
One of the main tasks during the construction of various buried structures and hydraulic engineering objects is to ensure the durability and reliability of concrete structures. As a rule, waterproof concrete is used for the construction of such facilities. Various types of protective coatings are easily damaged during operation, their tightness is degraded. The service life of such materials differs significantly from the service life of concrete structures. In order to avoid large financial expenses, the production of concrete with water-repellent properties becomes relevant. This concrete is able to resist the penetration of water, including under high pressure, which is achieved by introduction of multifunctional admixtures based on the chemical substances [1-6].

In modern practice various chemical compounds of domestic and foreign production are used as additives to concrete, and waste of the pulp and paper industry, fat-and-oil production, waste of petrochemical synthesis are also used, but deficiency of these products limits their application [7-9]. Chemical additives are not scarce, but on a scale of mass production of the basic building material of concrete with improved technological and operational characteristics, the idea of using industry-related waste as highly effective admixtures of complex and multifunctional action has always been and remains relevant nowadays. The maximum technical effect of the action of chemical additives in
the form of petrochemical synthesis waste reveals individually, so the analysis of the mechanism of complex action should be considered in each individual.

2. Relevance and scientific merit of the subject
Mineral additives not only provide resource saving, but also significantly affect the properties of composites, increasing their performance and life of the structures. Strength and crack resistance take pride of place among the physical and mechanical characteristics, being the main indicators of cement concrete quality, which is directly related to the structural features of the composite material. Improving the quality of cement concrete is most closely related to a decrease in the defect of the initial materials, an increase in the bonding strength in the contact layer of cement stone and aggregate, elastic-plastic properties, the characteristics of the capillary-porous structure.

Natural products (e.g. oleinic acid) or some industrial wastes (napthenate soap) were mainly used as technical waterproofing admixtures in cement concrete technology. However, based on the economic feasibility while maintaining the properties of modified compositions, nowadays products, materials and waste of petrochemical synthesis are increasingly used for the manufacture of waterproofing admixtures [10-14]. All these technical materials differ from each other in chemical composition and in their origin according to the production technology, but all of them are characterized by the presence of molecules with a distinct asymmetric-polar structure. Waterproofing admixtures are introduced into concrete and mortar mixes to reduce wetting of the pore walls, capillaries and the surface of structures.

Indeed, the purpose of the study is to develop the foundations of deriving concrete for underground construction. Moreover, depending on the percentage, the type of waterproofing admixture and modification goals, it is possible to enhance certain performance characteristics of cement compositions [15,16].

3. Research objective and theoretical part
Selection of concrete composition for monolithic structures of underground parts of buildings is a demanding challenge. The peculiarity of the concrete technology provides for the production of concrete with average strength characteristics equal to the brand of concrete used at a coefficient of strength variation of 13.5%, and in some cases exceeding this brand. This effect can be achieved not only by using materials that fully meet the highest requirements, but also by creating the optimal, most compact structure of concrete.

Taking into account these requirements, the technological process can be represented with a certain degree of reliability as a sequence of states of the multifaceted system. The degree of reliability of the actual technological process depends on the final goal of the study and the choice from the set of independent factors the most significant ones determining the function of the system response and allowing them to be controlled. This relationship can be represented as equations that make it possible to analyze the influence of factors on the output capacity and can be used as a basis for describing the quality of the processes under study.

Methodology, involving the use of mathematical statistics equations binding specified index of composite properties with a combination of any particular technological factors has gained widespread when solving problems of designing composite structures with different combination of properties. The study of the influence of various factors on the properties of constructional materials was carried out using the method of mathematical planning of the experiment on the basis of a polynomial model.

In order to select the composition and optimize the performance characteristics of the modified cement composite, the organic fraction of oil refinery wastes (OFW) was used in the research work, after the extraction of aromatic hydrocarbons from oil, containing paraffin, naphthenic and aromatic hydrocarbons, from light to heavy, in a certain ratio [17]. The choice of optimization factors for the concrete composition modified by hydrophobic-plasticizing admix OFW was made on the basis of technological feasibility of obtaining a material with improved performance for its use in underground parts of structures.
In construction and technological practice the most widespread are the methods of designing concrete compositions with the required strength of compression. Firstly, this is due to the fact that the concrete strength is the main parameter of dimensioning calculations, and, secondly, the strength is uniquely related to the other necessary concrete properties [18-20].

4. Results of the experiment
The composition analysis of the modified concrete mixture was determined on the basis of the dependence of the strength of the concrete on the most significant, independent and controlled factors, such as: the amount of cement, the amount of the modification admix and the water-cement ratio. To obtain the specified properties of the concrete composition, preliminary tests were carried out using mathematical methods for planning the experiment and processing its results. The most common for finding the optimal values of the output value, for example, the strength of concrete, is a multi-factor planning model, which must have insensitivity to small random effects and minimal reproducibility errors for parallel experiments. Since, according to preliminary research, the response surfaces for the cement concrete compositions are not linear [10,17], the factors had three levels of variation (table.1).

Table 1. Variability intervals of independent variable factors.

| Name of the levels of variation of the factors | Code value of the factors | Variability interval | Levels of the factors | Name of a factor |
|----------------------------------------------|--------------------------|----------------------|-----------------------|------------------|
| C                                            | x1                       | 50                   | 600 550 500           | x1 – the mass of sulfate-resistant cement, kg/m3; |
| OFW                                          | x2                       | 0.2                  | 0.8 0.6 0.4           | x2 – OFW admixture in % of the mass of cement; |
| W/C                                          | x3                       | 0.05                 | 0.45 0.4 0.35         | x3 – W/C ratio   |

The mathematical model of the process is a function that relates the parameter of optimization of the compressive strength \( R_{com} \) with variable factors \( x_1, x_2, x_3 \). After statistical processing of experimental data using the matrix of the central-composition plan of the second order corresponding to the orthogonality condition, the basic regression model was obtained:

\[
Y(R_{com}) = 52.09 - 0.92\cdot(x_1) - 4.11\cdot(x_2) + 0.6\cdot(x_3) - 1.75\cdot(x_1)\cdot(x_2) - 1.28\cdot(x_1)\cdot(x_3) - \\
-0.11\cdot(x_2)\cdot(x_3) - 1.73\cdot(x_1)\cdot(x_2)\cdot(x_3) - 1.47\cdot(x_1)^2 - 1.25\cdot(x_2)^2 - 1.89\cdot(x_3)^2
\]

The analytical method of the response function analysis makes it possible to estimate the quality and adequacy of the quadratic regression equation. At the same time, an important requirement is to check the reliability of the available data in order to make a conclusion about the properties of the general population with the highest possible probability. Therefore, the analysis of the considered mathematical model was performed to assess its representativeness using various criteria of approximation accuracy.

The coefficient of multiple determination \( R^2=82.6 \) was obtained when approximating the experimental data using the quadratic polynomial of multiple regression. This indicates a very close relationship of variables with the referable variable \( Y(R_{com}) \), so 82.6% of the variation in compressive strength is due to the variation of factors \( x_1, x_2, x_3 \) and only 17.4% is due to the action of other factors not included in the model. The estimation of tightness of joint effect of factors on the final outcome was identified by aggregate correlation index \( \rho =0.91 \to 1 \), which depends not only on the correlation of the results with each of the factors separately, but also on the inter-factor correlation. The estimation of the model accuracy by the average relative approximation error \( \bar{A}=1.2\% \) within the range of less than 8-10% indicates a good selection of the model to the initial data, which also indicates the reliability and adequacy of the model to the real process. Thus, the analysis of the characteristics of the models shows that the constructed model as a whole is quite accurate and significant. All its coefficients are significant and technologically interpretive.
In order to find the optimal composition of sulfate-resistant concrete, modified by the admix OFW, within the investigated area of variation of the variables $x_1, x_2, x_3$, the graphical construction of the response surfaces of the multi-factorial experiment was performed. The graphical interpretation of the obtained mathematical dependence allows us to visualize the regression equation, in which only two of the three factors and their combinations remain variable; the third factor of the equation is fixed at the zero coded level. In this research method, the terms of the equations with three combinations of factors are equal to zero. The response surfaces constructed by the obtained equations are shown in Figure 1-2.

**Figure 1.**
A - The response surface of the values of the compressive strength $Y (R_{com})$ variation coefficients as a function of the weight of the sulfate-resistant cement ($x_1$) and the addition of the OFW ($x_2$); B - contour lines of variation of compressive strength from the interaction of factors ($x_1$) and ($x_2$).

**Figure 2.**
C - The response surface of the values of the compressive strength $Y (R_{com})$ variation coefficients as a function of the weight of the sulfate-resistant cement ($x_1$) and water-cement ratio ($x_3$); D - contour lines of variation of compressive strength from the interaction of factors ($x_1$) and ($x_3$).
One of the advantages of graphical visualization of regression equations is the response surface in axonometric perspective. We take the minimum projection from all projections of the given area of the defined range of values of optimization parameter on the axis of the same factor for the permissible variation limit of the studied factors. From Figure 1B, 2D we determine the variation limits of the independent variable factors in the field of given values: the mass of cement \( x_1 = 547-575 \text{ kg/m}^3 \); admixture (% of the mass of cement) \( x_2 = 0.645-0.72 \); water-cement ratio \( x_3 = 0.39-0.43 \).

When the values of the variable factors are: \( x_1 = 562.5 \text{ kg/m}^3 \), \( x_2 = 0.66 \) (% of the mass of cement), \( x_3 = 0.415 \) the optimization parameter \( Y(R_{com}) = 52.11 \text{ MPa} \) has an extreme value in the range of set values. The coefficient of variation of strength with the factors \( x_1 = 562.5 \pm 14 \text{ kg/m}^3 \); \( x_2 = 0.65 \pm 0.0375 \) (% of the mass of cement), \( x_3 = 0.415 \pm 0.02 \) does not exceed an average of 5%, which is within the 95% of confidence interval of the regression coefficient assessment by the level of their significance (a Student's criterion).

Consequently, the joint (analytical and graphical) method of analysis of the results of the multivariate experiment was used: to study the regression equation properly describing the response function; to determine the permissible margin of the variation limits of the independent variable factors, providing the finding of optimization parameter – the compression resistance of the modified sulfate-resistant concrete, in a given range of values.

5. Conclusion

In recent decades, new effective binders, modifiers, new technological methods and methods of obtaining constructional composites have become widespread. Use of products and oil-processing materials from the enterprises in the region allowed expanding the list of highly effective integrated admixtures, raw base of construction materials, to reduce the production cost of the items, and to contribute to a solution of such ecological problem as recycling of wastes.

When optimizing the compositions of modified concrete, their physical and mechanical properties improve, which increases the longevity of concrete. To obtain concrete with different properties, it is necessary to purposefully control their structure formation, since the structure of the material determines its properties. Computer-aided design of composites compositions allows creating and mastering production of new types of concrete that gives an additional impulse for creation of new-generation building structures.

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