Developing design methods of concrete mix with microsilica additives for road construction

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Abstract. Based on the laboratory test results, regression equations having standard cone and concrete strength, to determine the available amount of cement, water and microsilica were obtained. The joint solution of these equations allowed the researchers to develop the algorithm of designing heavy concrete compositions with microsilica additives for road construction.

1. Introduction
Concrete has one of the leading places in the construction industry. A significant increase in the share of monolithic structures in modern construction leads to using mobile concrete mixtures, characterized by high values of water-cement ratio. However, increasing the height of buildings requires increasing the compression strength of concrete, leading to increase in cement consumption. Heavy concrete with an increased content of aggregate-rubble and a reduced weight percentage of cement is used in the construction of the road base to ensure the reliability and longevity of highways and city roads that allows reducing expenses on manufacture of a concrete mix. However, the frost-resistance of concrete and, consequently, the reliability of the foundation of the road surface are substantially reduced.

The process of obtaining high-strength concrete involves using highly active binders and high quality fillers. However, limited production of high quality cement, and shortage of high quality fillers greatly complicate the process of producing high strength concrete. Therefore, the task of increasing the concrete strength by means of mobile mixtures is very important nowadays.

2. Research direction
Modern researches conducted in the field of high-strength concrete production, let the researchers point out that the process of obtaining high-strength and frost-resistant concrete is possible only at maximum concentration of Portland cement minerals in hydration processes by means of using chemical activation of hardening systems as well as using super plasticizers and micro fillers [1, 2]. Therefore, in modern construction industry, modified compositions are widely used. Complex additives are the most popular in obtaining concretes with high performance properties [3].

Modern technologies allow mastering high-strength concrete production, but the process of achieving high design qualities of mixtures and hardening properties of concrete, is associated with a significant increase in concrete mix cost. Therefore, the choice of technological and economically optimal concrete composition requires serious scientific and practical preparation.

In some cases, the desired concrete properties can be achieved with the help of very simple productive means. Silica fume has got wide popularity (MS) as being generated in smelting process of...
ferrosilicon. MS is an extremely fine product existed in the form of spherical particles of silicon monoxide [4].

The popularity of MS in the world remains to this day, which is explained by its positive influence on strength, frost resistance, permeability, sulfate resistance, etc. However, despite the conclusive advantages of concretes with MS additives, confirmed by numerous studies abroad and in this country [3-5], they have not received wide application in the construction industry of our region.

In our opinion, this situation is explained by the fact that most researches of modified concrete are aimed at determining the dosage of modifiers providing compositions with the highest strength characteristics. And high quality fillers are often used in the researches.

It is necessary to ensure design solutions in production conditions it means that it is necessary to use concrete of some classes at the site. In this case, it is hardly possible to design modified compositions with specified properties due to the lack of design methodology. Experimental choice of modified concrete compositions required great deal of labor expenditure and laboratory testing time.

Paying attention to complex nature of concrete mixture component influence on modified concrete properties, it should be noted that the tasks of developing methods for designing modified concrete are relevant at the present time.

3. Methods and materials
Numerous studies have proved high efficiency of poly-functional action additives to produce concretes with high performance characteristics, but in this case the cost of the mixture is significantly increased, so the concrete producers are reluctant to introduce new compositions. However, it is easy to achieve the desired properties of concrete.

At the department “Construction and Technosphere Security” a lot of complex studies of concrete with various additives including super plasticizers and MS, have been carried out for many years.

To compose models describing multi component system behavior it is necessary to establish the dependency of mixture mobility and concrete strength on the basic mixture component numbers. It is quite difficult and tiresome task. In this case, it is better to use rational methods of experiment planning [6-7].

Since the main task of designing concrete is to obtain required concrete strength at given mixture mobility, the following response functions are taken into account: standard cone mixture draft, sm and concrete compression strength at various time of hardening. Experimental studies have proved that workability and strength of concrete with MS additives can be determined by the three components ratio: cement; water and MS additives. This reduces the number of managed factors to three, and greatly simplifies the experiment design matrix. For a long time, when conducting laboratory studies and results processing, a rational method of planning experiments by Brandon was used at the department. The use of this method allows, if it is necessary, to adjust promptly factor space and the step of varying factors. In addition, the model is not constructed as a polynomial, but as a product of functions being independent factors, so it has fine physical meaning. It ensures transformation of a constructed model which is relative to variables, and this fact is especially important in the development of design techniques.

The variation levels of the independent factors are selected on the basis of analysis of concrete mixture compositions produced by different enterprises of the town. As a result, to reduce the costs, the following values of variation of components: cement 300, 330 and 360 kg; MS 20, 30 and 40 kg water 190, 210, and 230 kg per 1 m$^3$ of mixture are proposed. The amount of gravel or break stone and sand remains the same for the concrete design class.

Based on three variables, the experiment design matrix was consisted of nine compositions. For testing the samples with 100 mm cube edge were used. Sand with fine modulus of 1,61 – 1,67 taken from Persianovaskiy career, gravel or break stone fraction 10 – 20 with compressive strength 90 – 110 MPa, being used during the tests as they are supposed to be usual components at all concrete town cites. Sand and stone break contents in all compositions remained unchanged. Portland cement produced by Sebryakovsky plant of M500-D0 was used as a binder.
The tests of each nine compositions were aimed at determining slump and strength of the samples for 1, 3, 7, 14 and 28 days of concreting.

Statistical processing of test results allowed establishing the dependence of the concrete strength on the cement amount, MS, water and mixture of draft cone presented in figure 1. Within the chosen factor space, the dependent variable (cone draft) is well described by linear equations, which greatly simplifies the calculations.

According to private approximation results the equations for calculation of cone draft was received

\[ O = (1.13 - 0.042C)(2.07 - 0.33Si)(32.83W - 54.37) \]

Similarly, the equation to calculate the strength of concrete for 28 days of concreting or hardening was obtained

\[ R_{28} = (13.70C - 15.72)(0.96Si + 0.71)(2.34 - 0.71W), \]

where: C – cement consumption; Si – MS; W – water, to 0.01 m³ of mixture.

Considering that, the optimal dosage of MS in the mix for the studied compounds, is 8 to 11% of cement weight having 10%, a system of equations can be obtained

\[
\begin{align*}
O &= (1.13 - 0.042C)(2.07 - 0.33Si)(32.83W - 54.37) \\
R_{28} &= (13.70C - 15.72)(0.96Si + 0.71)(2.34 - 0.71W).
\end{align*}
\]

The solution of the equation let to determine cement and water quantity in concrete mix in concrete draft and strength.

Having determined a range of acceptable quantity of cement and water, and the maximum value of water-cement ratio, the system of equations and inequalities with unknowns C and W is obtained:

\[
\begin{align*}
(13.67C - 15.72)(0.096C + 0.71)(2.34 - 0.71W) &= R_{28} \\
(1.13 - 0.042C)(2.07 - 0.33C)(32.83W - 54.37) &= O \\
2.5 &\leq C \leq 4.5 \\
1.8 &\leq W \leq 2.3 \\
\frac{W}{C} &\leq 0.7.
\end{align*}
\]
For convenience, variables C and W are replaced by x and y and letter symbols for the numerical coefficients in parentheses are introduced:

\[ a_1 = 13.67; a_2 = 0.096; a_3 = b_2 = 0.71; a_4 = 0.042; a_5 = 0.33; \]
\[ a_6 = 32.83; b_1 = 15.72; b_3 = 2.34; b_4 = 1.13; b_5 = 2.07; b_6 = 54.37. \]

Expressing y in terms of x from (1), (2) we have obtained:

\[ y = \frac{b_3}{a_3} - \frac{R_{28}}{a_3(a_1x - b_1)(a_2x + b_2)}, \]
\[ y = \frac{b_5}{a_6} + \frac{F}{a_6(b_4 - a_4x)(b_5 - a_5x)}. \]

Equating the obtained expressions and multiplying both parts of the last equality by the product of denominators of fractions with numerators \( R_{28}, F \) in it, we obtain

\[ a_6b_5(a_4x - b_4)(a_2x + b_2)(b_4 - a_4x)(b_5 - a_5x) - R_{28}a_6(b_4 - a_4x)(b_5 - a_5x) = a_3b_6(a_1x - b_1). (a_2x + b_2)(b_4 - a_4x)(b_5 - a_5x) + Fa_5(a_1x - b_1)(a_2x + b_2). \]

Expand all brackets and bring similar terms in the resulting equation, transform it to the form

\[ A_4x^4 + A_3x^3 + A_2x^2 + A_1x + A_0 = 0, \tag{6} \]

where

\[ A = a_6b_3 - a_3b_6 = 38,2195; A_4 = Aa_1a_2a_4a_5 = 0.6951651293664; \]
\[ A_3 = A((a_1b_2 - a_2b_1)a_4a_5 - (a_4b_5 + a_5b_4)a_3a_2) = -18.721922592285; \]
\[ A_2 = A((a_2b_4 - a_4b_2)a_1b_3 + (a_2b_1 - a_1b_2)a_5b_4 + (a_2b_5 - a_5b_2)a_4b_1) - a_4a_5a_6R_{28} - a_1a_2a_3F = -32,45656394834504 - 0.4550238R_{28} - 0.9317472F; \]
\[ A_1 = A((a_4b_2 - a_2b_4)a_1b_5 + (a_2b_5 - a_5b_2)a_1b_3) + a_5(a_4b_5 + a_5b_4)R_{28} + a_3(a_2b_1 - a_1b_2)F = 928,924431001677 + 15,0965472R_{28} - 5.8195718F; \]
\[ A_0 = -Ab_1b_2b_4b_5 + a_6b_4b_5R_{28} + a_3b_1b_2F = -997.80271322094 - 76.792653R_{28} + 7.924452F. \]

By the basic theorem of algebra, equation (6) has four complex roots. These roots are easy to find with a very high degree of accuracy, using one of the available in the Internet calculators for solving algebraic equations.

From (4), (5) is obtained inequality

\[ x \geq y/0.7 \geq 1.8/0.7 = 2.571 \]

If equation (6) has real roots in the interval \([2.571; 4.5]\), then it is necessary for each of them to calculate the corresponding value of y by formula

\[ y = 3,296 - \frac{R_{28}}{0.932x^2 + 5.820x - 7.924} \tag{7} \]

Further, it is necessary to verify the fulfillment of the inequalities \(1.8 \leq y \leq 2.3; \ Y \leq 0.7x\). When they are fulfilled (and only in this case), the pair (x, y) is a solution of system (1) - (5).
Restoring the variables, after transforming and calculating the coefficients and free terms from equation (6), we obtain expression

\[ 0.695C^4 - 18.722C^3 - (32.646 + 0.455R_{28} + 0.932O)C^2 + 
+ (928.924 + 15.097R_{28} - 5.8200)C - (997.803 + 76.793R_{28} - 7.924O) = 0 \] (8)

Substituting the designed value of concrete strength \( R_{28} \) and draft in this equation \( O \) the roots are determined. Equation (8) has four roots, but the only one satisfies the inequality (3), it will match the cement consumption to prepare 0.01 \( m^3 \) of the mixture. Substituting the obtained value of cement consumption in the expression (7), the necessary amount of water can be calculated.

Despite the cumbersome expression (8), usage of modern mathematical apparatus, namely, the calculator, "Solution of algebraic equations online" by Laguerre’s method, the roots of the equation can be easily found.

Paying attention to high dispersion of MS and its low content in the mixture, changes in volume with MS additives can be neglected. Therefore, the consumption of fine and coarse fillers is performed according to a well known method of "absolute volume”.

4. Conclusion

Based on the processing results of laboratory studies of the concrete composition with additives MS performed by means of using experimental design, particular relationships of cone draft of the mix and strength of concrete compression dependence from the cement content, water and MS are obtained. Based on these dependencies, the equations (1-2), a joint decision which allowed obtaining the expression (6-7) to calculate amount of cement and water of the designed concrete mix.

The proposed algorithm is used to calculate the preliminary composition of the modified MS concrete for the construction of a monolithic framework of the retaining wall 5.5 m high on the section of the bulk ground of one of the main roads of the city of Shakhty in the Rostov Region. This algorithm allows to significantly reduce the testing attempts for approving concrete composition choice.

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