Development of the Composition of Steel Fiber Reinforced Concrete for the Repair of Bridge Structures

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Abstract. The article is devoted to the problem of increasing the service life of road networks, which, with an increasing flow of vehicles in harsh climatic conditions, becomes even more urgent. In such conditions, with the traditional approach to the reinforcement of the roadway of bridge structures, defects often appear on the concrete surface in the form of macrocracks and potholes in the protective layer. As one of the ways to solve this problem, the use of concrete with dispersed reinforcement with steel fibers for the upper layer of the pavement is considered, which makes it possible to increase its strength and impact strength. To determine the required amount of concrete mixture components with specified performance characteristics, a two-factor experiment was carried out, which made it possible to obtain a regression dependence of the ultimate compressive strength of steel fiber reinforced concrete at the design age, depending on the proportion of the mass of steel fiber on the mass of solid components and the proportion of the mass of organo-mineral additives from the mass of cement. The recipe of steel fiber reinforced concrete, developed on the basis of the experimental data, was tested during the reconstruction of one of the bridges of the A360 Lena federal highway.

1. Introduction

The increased wear and tear of the road infrastructure of the Republic of Sakha (Yakutia) is associated, first of all, with regional climatic features, as well as an annual increase in the number of vehicles. In this regard, in Yakutia, in comparison with other constituent entities of the Russian Federation, the modernization, repair and reconstruction of the road network is carried out quite often. To solve this problem, complex measures should be taken, including the use of structural materials with increased operational characteristics.

Traditional reinforcement of the roadway of bridge structures is usually made with a reinforcing mesh, over which a concrete mixture of the required thickness and with the specified quality indicators is poured [1, 2]. However, the authors of [1-3] found that with such a constructive solution, concrete does not enter the zone of influence of tensile and bending stresses. As a result, when exposed to external mechanical loads emanating from large vehicles, defects are formed on the concrete surface in the form of macrocracks and potholes in the protective layer [3]. This process is especially intense in harsh climatic conditions, since large temperature and humidity drops cause deformations and settlements of the subgrade. The most effective method of preventing such a situation is dispersed concrete reinforcement with discrete fiber-fibers [4-6].

A variety of heavy concrete, dispersed-reinforced with steel fibers, is called steel fiber concrete (hereinafter referred to as SFRC) [7-9]. Replacing conventional heavy concrete with SFRC leads to an
increase in the strength of sections of compressed, tensioned and bent structural elements of the bridge. In addition, the introduction of fiber into the brittle cement matrix of concrete greatly increases its crack resistance and impact strength [10].

The development and implementation of a modified SFRC based on local raw materials will significantly extend the useful life of road pavements, including bridges. On the basis of the above provisions, the purpose of the research work is to design the composition of an operationally resistant SFRC with the specified physical and mechanical parameters for the repair and reconstruction of the bridge.

2. Materials and methods

The following raw materials were used in the experimental studies: Portland cement of the CEM I 42.5N class in accordance with GOST 31108-2016 produced by SpaskCement JSC; sand according to GOST 8736-2014; crushed granite fr. 5-20 in accordance with GOST 8267-93; steel fiber "Chelyabinka" (hereinafter fiber) according to TU 1231-001-70832021-2010; complex organo-mineral additive CMID-4 (hereinafter additive) according to TU 5745-002-53268843-00; industrial water according to GOST 23732-2011.

The selection of the composition of the SFRC is made in accordance with the requirements of GOST 27006-86. Tests of SFRC samples were carried out using standard methods, equipment and measuring instruments, certified and verified in the prescribed manner. Regression coefficients, statistical data, as well as the response surface and nomogram were obtained using the MathCAD 2018.

3. Experiment results

The bridge structure is subjected to simultaneous cyclic action of mechanical loads (static and dynamic) and climatic factors (precipitation, temperature drops, etc.). In this regard, the concrete in the structure of the bridge should have increased physical and mechanical properties, as well as high operational resistance. These requirements fully comply with the SFRC class in compressive strength B35, frost resistance grade F300 and water impermeability W12. The calculation of the SFRC composition was carried out by the method of absolute volumes. The method is based on the assumption that the concrete mixture immediately after molding and vibration compaction is in the so-called absolutely dense state without internal pores and voids.

According to the results of calculating the composition, for the manufacture of 1 m3 of SFRC mixture, you will need: cement 502 kg, sand 691 kg, crushed stone 1044 kg. To determine the required amount of additive and fiber at the given values of quality indicators, the method of mathematical planning of the experiment was used. The following factors were taken as input factors: \( x_1 \) is the content of steel fiber (the proportion of the mass of fiber in the total mass of solid components,%) and \( x_2 \) is the content of the CMID-4 additive (the proportion of the mass of the additive to the mass of cement,%). The selected factors varied at three levels. The values of the levels of variation of factors are established on the basis of preliminary experiments, as well as the results of works [10-13]. Compressive strength at 28 days of hardening was chosen as the output parameter. The levels of variation of the factors are given in Table 1.

| №  | Name factor                      | Designation | Factor variation levels | Variation step |
|----|----------------------------------|-------------|-------------------------|---------------|
| 1  | Steel fiber content [kg]         | \( x_1 \)  | 1 1.5 2                | 0.5           |
| 2  | Content of CMID-4 additive [kg]  | \( x_2 \)  | 3 5 7                 | 2             |

To quantify the effect of additives and fiber consumption on changes in strength, we carried out a full two-factor experiment, consisting of three levels and nine experiments \((n^1 \times n^2 = 9)\). When choosing
an experimental design, the need to obtain an adequate mathematical description of the considered
dependence was taken into account. After manufacturing, the specimens gained strength under normal
hardening conditions \((t = 20 \pm 2 \degree C, w = 95-100\%)\). The planning matrix and the results of the
experiment are presented in Table 2.

The regression coefficients were determined by the least squares method (Eq. 1), the calculation
formulas are given in [14-16]. To increase the accuracy of the approximation, the number of equation
coefficients was increased to six units (taking into account \(b^6\)).

\[
\begin{align*}
b_1 &= \frac{1}{6} \sum_{i=1}^{9} x_1 Y_i = \frac{1}{6} 9.87 = 1.64 \\
b_2 &= \frac{1}{6} \sum_{i=1}^{9} x_2 Y_i = \frac{1}{6} (-1.06) = -0.18 \\
b_{11} &= \frac{1}{2} \sum_{i=1}^{9} x_1^2 Y_i - \frac{1}{3} \sum_{i=1}^{9} x_1 Y_i = \frac{1}{2} 267.17 - \frac{1}{3} 407.43 = -2.22 \\
b_{22} &= \frac{1}{2} \sum_{i=1}^{9} x_2^2 Y_i - \frac{1}{3} \sum_{i=1}^{9} x_2 Y_i = \frac{1}{2} 282.88 - \frac{1}{3} 407.43 = 5.63 \\
b_{12} &= \frac{1}{4} \sum_{i=1}^{9} x_1 x_2 Y_i = 0.66
\end{align*}
\] (1)

The significance of the regression coefficients was assessed using the Student's test. At the same
time, it was taken into account that at each point of the plan, two parallel experiments were carried out.
According to the results of assessing the significance at a confidence level of \(P = 0.95\), it turned out that all the regression coefficients of the analyzed model are statistically significant. Based on the
calculations performed, the regression equation takes the following form:

\[Y(x_1, x_2) = 43 + 1.64 x_1 - 0.18 x_2 - 2.22 x_1^2 + 5.63 x_2^2 + 0.66 x_1 x_2.\] (2)

The adequacy of the resulting model was assessed using the Fisher test. In accordance with the
technique described in [17-19], the sum of the squares of the residuals \(S_i^2\), as well as the residual
variance \(S^2\), were analyzed. With a significance level equal to \(\alpha = 0.05\) and the number of degrees of
freedom \(f_1 = 3, f_2 = 9\), it turned out that the calculated value of the Fisher criterion \(F_c\) does not exceed
its table value \(F_t\). This result confirms that the scatter relative to the obtained regression equation is
significantly less than the scatter of the mean. Based on the foregoing, it can be assumed that the
developed model adequately interpolates the experimental data and can be used for further analysis. The
details of calculations to assess the adequacy of the model according to the Fisher criterion are given in
equations (Eq. 3).
\( S^2_a = \frac{m \sum (Y_i - \bar{Y})^2}{n-l} = \frac{2 \times 12.03}{9-6} = 8.019 \)
\( S^2_p = \frac{\sum_{i=1}^{n} s^2_i}{n} = \frac{23.71}{9} = 2.634 \)
\( F_e = \frac{S^2_a}{S^2_p} = \frac{8.019}{2.634} = 3.04 < \{ F_t = 3.86 \} \) 

(3)

The interpretation of the influence of the selected factors on the change in the compressive strength of the CFB was made based on the analysis of the regression equation. (Eq. 1) is used to construct a three-dimensional graph (response surface) and a nomogram of the change in compressive strength versus the consumption of additive and fiber. Graphical interpretation of (Eq. 3) is shown in Fig. 1.

![Graph showing the influence of factors on compressive strength](image)

**Figure 1.** Relationship between compressive strength and additive and fiber content

Analysis of the graphs shown in Fig. 1 shows that the factor \( x^1 \) has the strongest effect on the compressive strength. Positive linear and negative quadratic effects of this factor have been revealed, which indicates an increase in compressive strength from 39.14 to 48.73 MPa with a fiber content from 1 to 1.5%. However, when the fiber content is from 1.5 to 2%, a decrease in strength is observed to 42.42 MPa. A negative linear and positive quadratic influence of the factor \( x^2 \) was established. This is due to the fact that when the amount of additive is from 3 to 5%, the compressive strength decreases from 45.61 to 43 MPa. With an additive content of 5 to 7%, the compressive strength rises to 48.53 MPa. The nature and strength of the influence of the factor \( x^2 \) is significantly influenced by its linear interaction with \( x^1 \). It should be noted that the pair interaction \( x^1 x^2 \) has a positive sign, and in terms of the force of impact on increasing the strength, it exceeds \( x^2 \) by 3.7 times. Most likely, with such a combination of factors, the maximum value of the strength of the cement stone is achieved, which in turn contributes to an increase in the strength of mechanical adhesion of the fiber to the composite matrix. When ensuring good adhesion of the fiber and the cement matrix, the SFRC works most efficiently, namely, the load is transferred through the cement stone to the fiber during shear deformation in the contact zone. The increase in strength is also explained by an increase in the fracture toughness of the composite as a result of “inhibition” of cracking and the perception of tensile stresses by the fiber.

Based on the data obtained, an SFRC recipe was compiled, which was tested during the reconstruction of a three-span reinforced concrete bridge (47 m long) across the river. "Khamagan" of the Aldan ulus of the Republic of Sakha (Yakutia). The bridge is located at 731 km of the A360 Lena federal highway. From June to September 2018, about 80 m³ SFRC were poured over the precast concrete slabs of the bridge. The SFRC mixture was made on a small-sized self-loading concrete mixer FIORI DB 110.
Currently, the bridge is in normal operation, observations show the absence of chips, cracks and deformations of the SFRC. The results of assessing the strength of SFRC by non-destructive methods of monitoring structures have confirmed the required design compressive strength.

Thus, the research results show the feasibility of using steel fiber concrete for strengthening, restoration and reconstruction of bridge structures operated in the harsh climatic conditions of Yakutia.

4. Conclusions
1. The expediency of replacing conventional heavy concrete with SFRC for repairing the bridge structure has been substantiated.
2. Using the methods of experiment planning, an adequate regression mathematical model of the dependence of the SFRC strength in compression on the mass fractions of the content of steel fiber and additives in the form of a second order regression equation was obtained.
3. A causal relationship has been established between the content (by weight) of the additive and fiber for the compressive strength of the SFRC.
4. The composition of the SFRC modified by the additive with the specified physical, mechanical and operational parameters has been developed.

5. References
[1] Baranov I M 2013 Innovative materials for the construction and repair of bridges J. Con. Mat. 3 82-87
[2] Filatova A V, Ignat’ev P V, Rodionov M V 2018 Repair of span structures of a bridge using alkylalcoxysilane mixture and polymer fiber in the construction of automobile roads J. Eng. Bulletin of Don. 48 119
[3] Karapetov E S, Myachin V N, Frolov Yu S 2013 Maintenance and reconstruction of urban transport facilities J. UMC. 163 51-59
[4] Gorbunov I A, Kapustin D E 2019 Design resistance of concrete and steel fiber reinforced concrete in a probabilistic interpretation J. BSTU Bulletin 1 58-64
[5] Talantova K V 2016 Structure and properties of steel fiber concrete, determining the given performance characteristics of structures based on it J. Inf. P. U. of Comm. 4 546-552
[6] Muhamediev T A, Sokolov B S 2017 New in steel fiber concrete rating and calculations of steel fiber concrete structures J. Con. Mat. 4 59-64
[7] Saranchuk I A, Chuev K V, Panischcheva I A 2017 Purpose of steel fiber concrete J. A. Sci. 12 81-86
[8] Tatarinova R E 2017 Steel fiber concrete: features of application J. Sci. Ed. 9 15-17
[9] Dorf V A, Krasnovskij R O, Kapustin D E, Sultygova P S 2017 Influence of steel fiber characteristics and its content in steel fiber concrete on its fire resistance J. C. Eng. Herald. 5 38-46
[10] Hegaj A O, Kirillin N M, Hegaj E O 2019 Experimental studies of the strength properties of steel fiber reinforced concrete of increased classes J. C. Eng. Herald. 7256-60
[11] Tang V L, Nguyen Ch Ch, Bulgakov B I, Aleksandrova O V, Larsen O A 2018 Calculation of the composition of heavy concrete and assessment of the possibility of cracking in the bridge support being erected J. C. Eng. Herald. 6 45-54
[12] Kalashnikov V I 2008 Calculation of the composition of high-strength self-compacting concrete J. C. Eng. Herald. 10 4-6
[13] Belov V V, Smirnov M A, Obrazcov I V 2012 Method for determining the optimal grain composition of heavy concrete aggregate J. Bulletin TSTU 20 72-76
[14] Semenyuk S D, Kuzmenko I M, Medvedev V N 2009 Prerequisites for planning a multifactorial experiment to study the bearing capacity of a composite bearing element of building structures J. R-S Tech. 1 252-253
[15] Mestnikov A E, Fedorov V I 2019 Mathematical planning in the design of the composition of lightweight concrete J. M. Sci. Tech. 11 82-87
[16] Vartanyan M A 2020 Analysis of the technology of producing ceramics from silicon carbide by methods of experimental planning J. Mat. Sci. 1 36-41

[17] Krupin A E, Zujkov D V 2014 Filtering out factors when planning an experiment J. Bulletin of NGIEI 4 62-70

[18] J van der Geer, Hanraads J A J, Lupton R A 2000 The art of writing a scientific article J. Sci. Commun. 163 51-59

[19] Sidnyaev N I, Govor S A 2016 Testing the hypothesis of the adequacy of the statistical model for rotatable experimental design J. MSTU Bulletin 1 3-16