Proportioning of steel fiber concrete tailored composition using the method of mathematical experiment planning

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Abstract. Suggested proportioning of steel fiber concrete tailored composition can be made by using the method of mathematical experiment planning. A wide variety of types of fiber, the size and aggregate grain-size distribution, the number and characteristics of cement, and the need to obtain concrete mixes of different fluidity are used in the production of fiber reinforced materials. That is why it is impossible to develop a proportioning standard method. Thereby it is suggested to conduct an experiment of proportioning of steel fiber concrete tailored composition using the method of mathematical experiment planning in each specific case. The article provides an example of proportioning of steel fiber concrete on specific components. When planning the experiment, we selected water-cement ratio, cement consumption, fiber reinforcement content and the ratio of the content of coarse and fine aggregates as the independent factors. The compressive and tensile strengths of steel fiber concrete and the fluidity (stiffness) of the mixture were selected as responses. This article presents the possibility to make a choice of the ratio of the number of primary components for obtaining steel fiber concretes with the necessary characteristics by analyzing the obtained regression equations.

1 Introduction

High performance characteristics of fiber reinforced concrete explain the effectiveness of their use in building structures used under conditions of static and dynamic loads, cyclic freezing-thawing [1-4]. To obtain high-quality fiber-reinforced concrete, steel fiber concrete, in particular, it is necessary to ensure the structure of the composite material in which all components will interact effectively [5-7]. When selecting composition material aggregate, the question of determining the influence of the ratio of components on the resulting physical and mechanical characteristics inevitably comes up [8-11]. Existing methods do not take into account the variety of used concrete aggregate types, and, first of all, the significant differences in the used fibers [9, 12-16].

Previously, we carried out preliminary studies to optimize the composition of steel fiber reinforced concrete through mathematical planning, in which we studied the effect of the

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ratio of coarse and fine aggregate and fiber reinforcement [10]. The following were chosen as the independent factors: the ratio of the content of fine to coarse aggregate in the concrete mixture and the content of fiber reinforcement. A matrix of a full two-factor experiment was implemented.

Unchangeable components of the mixture (kg per 1 m^3): plasticizer—6.5; hardening accelerator—1.5; water—162; the sum of fine and coarse aggregate—1544. The change in the content of fiber reinforcement was compensated by the consumption of the binder, with the condition that the sum of the volumes of all components of the steel fiber concrete mixture was always equal to 1 m^3. The sum of the volumes of the fiber reinforcement and the binder was kept constant at 0.193 m^3 (19.3 vol%). Since the bulk density of steel is much higher than that of the binder, the amount of binder changed slightly (the ratio of silica fume : Portland cement always remained constant at 0.12).

Processing the results of the experiment made it possible to obtain a regression equation (adequate according to Fisher's criterion), which writes off the dependence of the tensile strength in bending of steel fiber reinforced concrete on the ratio of small to large aggregate (Sand/Road metal) and the amount of fiber reinforcement (F) (kg).

$$R_{bend} = 127.46 - 2.15X_1 + 2.88X_2 - 5.05X_1^2 + 6.75X_1X_2 - 14.25X_2^2, \quad (1)$$

where X_1= Sand/Road metal, X_2=F, f=1.17 < ft=4.3.

Based on the obtained equation (1), the isolines of the tensile strength in bending of steel fiber reinforced concrete were constructed depending on the ratio of the content of fine to coarse aggregate and the content of fiber reinforcement, volume%.

Analysis of the regression equation and the strength isolines shows that there is an optimal area of the content of fine and coarse aggregate and fiber reinforcement in the mixture (Sand/Road metal = 0.7–0.9; F=1.2–1.6 volume %). Outside this area, a drop in strength is observed due to the lack of coarse aggregate and fiber reinforcement or under-compaction (with a higher content of fiber and crushed stone, the mixture becomes very rigid and its compaction is impossible with conventional vibration equipment). However, these studies cover a narrow area of composition selection and take into account the influence of a small number of factors.

Currently, no clear recommendations are prescribing the proportioning of steel fiber concrete depending on the characteristics of the components of the material. The task in this work was to optimize the composition of steel fiber concrete using specific types of binder, aggregates, and fiber reinforcement.

2 The proposed components of composition of steel fiber concrete

We used Portland cement of grade 500 manufactured without active mineral additives for our research.

2.1 Cement characteristics

- Portland cement brand 500
- Bending strength after 28 days, MPa—6.9.
- Compressive strength after 28 days, MPa—58.7.
- Normal density of cement paste, %—26.
- Setting time: start—1 hour 40 minutes; end—3 hours 20 minutes
- Sieve residue 008—12%

- Specific surface area—3200 cm^2/g

2.2 Slag characteristics

For our study, we used ground acidic granulated blast furnace slag manufactured. The chemical composition of the slag is given in table. 1. One weak reflection of 2.86 A was observed on the x-ray of the slag, which is the main reflection in melilite. Quantitative x-ray phase analysis using synthetic melilite as a reference showed 9.4% crystallization [17].

Table 1. Slag chemical composition.

Oxide content, %							
SiO_2	Al_2O_3	CaO	MgO	FeO	S^{2-}	Na_2O	K_2O
41.2	0.6	37.4	10.0	0.6	0.6	0.4	1.2

The specific surface area of ground slag is 3300cm^3/g.

2.3 Aggregate characteristics

Quartz sand was used as the fine aggregate. The properties of the fine aggregate as determined in accordance with [18]: density—2.63 g/cm^3; bulk density—1.49 g/cm^3; voidness—43.4%; clay, dusty impurities content no greater than 3%; particle size modulus 2.15–2.25; specific surface area 205 cm^2/g; particle size distribution is in accordance with the requirements of [19].

Granodiorite churning stone was used as the large aggregate.

The properties of the crushed stone as determined in accordance with [20]: density—2.66 g/cm^3; bulk density—1.56 g/cm^3; water absorption by weight 1.21%; number of lamellar and needle-like grains—11.6%; content elutriated impurities—not greater than 1%.

We used crushed stone fractions of 5-10 mm in the research.

2.4 Steel fiber reinforcement

The fiber reinforcing element [21–23] consists of steel chips with longitudinal ribs on the surface, inclined to the longitudinal axis of the chips, while the chips are curved in the longitudinal direction along the helix, and the longitudinal ribs are oriented, in turn, along the helix described around the axis of the chip. Such reinforcing elements have high rigidity and good adhesion to concrete due to developed surface irregularities.

Fibers are made from a 0.5 mm thick rolled sheet from 0.8KP steel. The resulting fibers with dimensions of 0.5x0.5x32 mm are relatively easily inserted into the concrete mix and have far less of a balling up tendency compared to other fibers from wire. The volumetric weight of the used fiber reinforcement is 640 kg/m^3.

3 The theoretical part

To study the effect of aggregates and fiber reinforcement we use on the easy-to-pace mix and the strength characteristics of steel fiber concrete, a four-factor experiment was carried out using the method of mathematical planning. The experiment was carried out according to an asymmetric quasi-D-optimal design [24, 25]. The following factors were selected as independent:

- water cement ratio (WCR);
- cement consumption, kg (C);

- fiber reinforcement content,% of volume reinforcement (μ);
- the ratio of the mass of sand to the mass of crushed stone in 1 m^3 of concrete mix (S/G).

Cement was obtained by mixing 80% Portland 500 and 20% ground blast furnace slag. Samples of steel fiber concrete 10x10x10 cm and 10x10x40 cm (after molding) were steamed according to the 2+4+8+2 hours mode at an isothermal holding temperature of 80 °C. The samples were tested after the cooling.

After the experimental implementation of the plan, the results were processed using standard programs, which included:

- the uniformity of the hypothesis experiments testing according to the Cochran's Q Test;
- calculation of regression coefficients; regression dependencies of the form are obtained,

$$y = b_0 + \sum_{i=1}^{n} b_i\, x_i + \sum_{i+j=1}^{n} b_{ij}\, x_i x_j + \sum_{i=1}^{n} b_{ii}\, x_i^2; \quad (2)$$

- verification of the hypothesis of the adequacy of the obtained regression equations according to the Fisher's criterion. The condition for adequacy is the fulfillment of the inequality,

$$F_s \leq F_t(P, f_1, f_2); \quad (3)$$

where Fs is the experimentally determined value of the Fisher's criterion;

F_t is a tabular value depending on the confidence probability P, the number of rows of the matrix of the experimental design $N=f_1$ and the number of repetitions of the experiment $\gamma=f_2+1$.

- construction of isolines of the geometric image of 11 response surfaces.

4 Examples

The experimental design matrix and the responses obtained are presented in Table 2. The coefficients of the regression equations are given in Table 3.

Table 2. Experiment Planning Matrix.

Composition No.	Factors								Feedback		
	X_1 (WCR)		X_2(C)		X_3(μ)		X_4(S/G)		Rcom. MPa	Rbend. MPa	St. sec
	code	physical	code	physical	code	physical	code	physical			
1	2	3	4	5	6	7	8	9	10	11	12
1	-1	0.4	1	480	1	2.4	1	1	36.0	7.1	55
2	1	0.6	-1	380	1	2.4	1	1	25.1	5.4	2
3	1	0.6	1	480	-1	0	1	1	14.1	3.2	0
4	1	0.6	1	480	-1	0	-1	0.6	14.9	3.5	0
5	1	0.6	-1	380	1	2.4	-1	0.6	20.1	4.3	6
6	-1	0.4	-1	380	-1	0	1	1	21.5	4.5	45
7	-1	0.4	-1	380	-1	0	-1	0.6	24.6	5.7	60
8	0	0.5	1	480	1	2.4	-1	0.6	27.9	5.5	43
9	-1	0.4	0	430	1	2.4	-1	0.6	31.9	6.9	87
10	-1	0.4	1	480	0	1.2	-1	0.6	31.0	6.2	70
11	1	0.6	-1	380	-1	0	0	0.8	19.9	4.0	0

Continuation of Table 2.

Composition No.	Factors								Feedback		
	X_1 (WCR)		X_2(C)		X_3(μ)		X_4(S/G)		Rcom. MPa	Rbend. MPa	St. sec
	code	physical	code	physical	code	physical	code	physical			
12	-1	0.4	1	480	-1	0	0	0.8	29.0	6.0	35
13	-1	0.4	-1	380	1	2.4	0	0.8	37.0	7.7	83
14	1	0.6	1	480	1	2.4	0	0.8	29.2	5.8	0
15	0	0.5	0	430	0	1.2	0	0.8	28.9	5.6	16
16	0	0.5	1	480	-1	0	1	1	18.7	4.1	2

Table 3. Regression equation coefficients.

Coefficient	b_0	b_1	b_2	b_3	b_4	b_{11}	b_{12}	b_{13}
$R_{com.}$ MPa	29.07	-4.77	0.62	4.61	0.39	-0.14	-0.40	-0.36
$R_{bend.}$ MPa	5.66	-0.99	0.07	0.84	-0.04	0.03	0.00	-0.03
St. sec	16.73	-29.4	-4.03	9.35	-6.97	8.97	3.80	-7.41
Coefficient	b_{14}	b_{22}	b_{23}	b_{24}	b_{33}	b_{34}	b_{44}	
$R_{com.}$ MPa	0.69	0.72	0.47	-0.07	-0.92	1.33	-4.90	
$R_{bend.}$ MPa	0.24	0.00	-0.03	0.02	0.18	0.35	-0.78	
St. sec	4.93	6.46	0.07	-1.41	-2.85	-2.18	2.2	

It is possible to conduct an experiment of proportioning of steel fiber concrete tailored composition to achieve specified strength characteristics using the regression equations and isolines of strength of steel fiber concrete (Fig. 1). The specified cement consumption of 430 kg/m^3 of the mix, WCR = 0.45.

Analysis of the regression equations and isolines shows that the consumption of fiber reinforcement and the water-cement ratio have the greatest impact on the strength of steel fiber concrete. From Fig. 2, Fig. 3 obtained for steel fiber concrete compositions with a cement content of 430 kg/m^3, it follows that for these components of steel fiber concrete, there is an optimal ratio of the content of coarse and fine aggregates in the mix, which supports the most efficient use of the effect of fibers on the strength of the material. The optimal ratio varies slightly depending on the WCR and cement consumption. However, in general, the optimum is always in the range of Portland = 0.7-0.9.

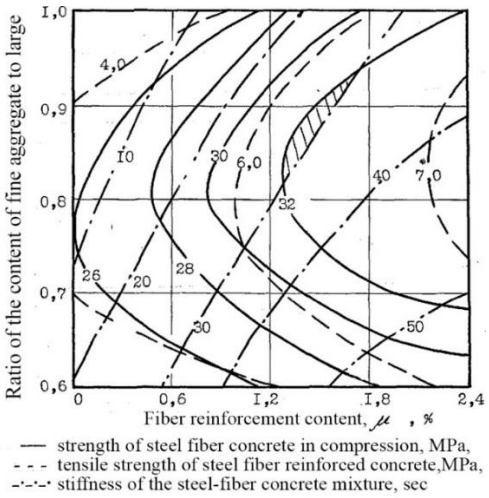

Fig. 1. Steel fiber reinforced concrete contours.

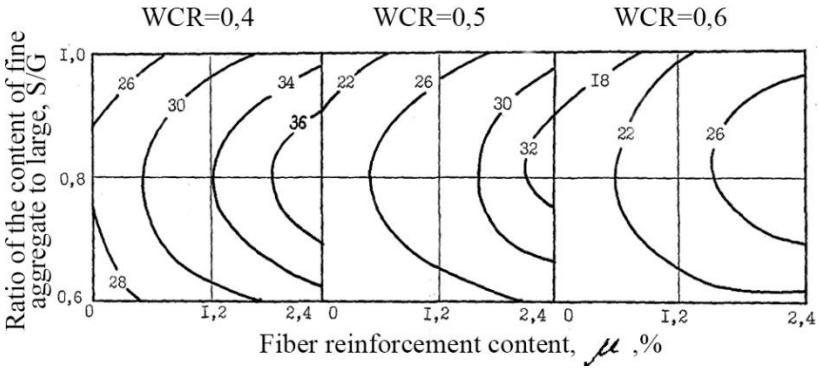

Fig. 2. Isolines of compressive strength of steel fiber reinforced concrete, MPa.

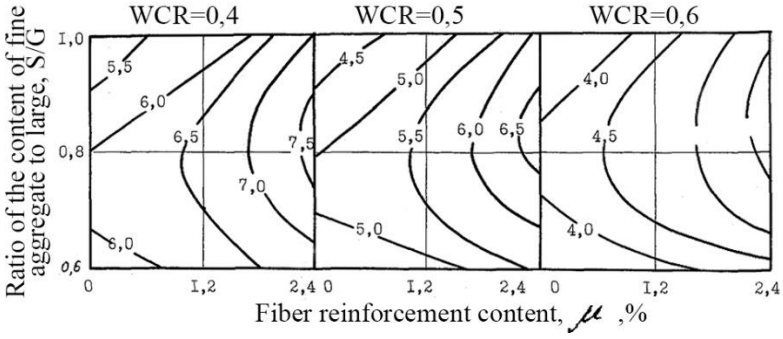

Fig. 3. Isolines of tensile strength of steel fiber reinforced concrete, MPa.

5 Conclusions

In this article, we suggest the proportioning of steel fiber concrete tailored composition technique using the method of mathematical experimental planning. When planning an experiment, it is necessary to determine independent factors based on the expected specific components of the composition of steel fiber concrete and their characteristics. The choice

of the planning matrix depends, among other things, on the estimated number of experiments and the necessary responses. After the experiments implementation, it is necessary to analyze the obtained regression equations, for example, in graphical form, and determine the number of initial components to obtain steel fiber concrete with the desired properties.

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