



Design of steel fiber-reinforced concrete for slip forming

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Abstract. Introduction. Slip forming is one of the effective and promising methods of concrete mix casting. Development of slip forming technologies largely depends on accumulated experience and tools, one of which is the composition design methodology. The use of special types of concrete, such as fiber-reinforced concrete, requires additional knowledge and the creation of special technological tools. The purpose of the study: to develop a methodology for designing steel fiber-reinforced concrete composition for slip forming. **Methods and materials.** Known methods for designing concrete and steel fiber-reinforced concrete compositions are used. A methodology for designing steel fiber-reinforced concrete composition for slip forming has been developed, consisting of two stages: designing the matrix composition to ensure a given ultimate extensibility of the mixture; designing steel fiber-reinforced concrete based on a pre-obtained matrix composition. Cement CEM I 42.5N, medium-sized sand, crushed stone with particles size 5-10 mm and 36 mm length steel milling fiber are used. **Results and discussion.** According to the proposed methodology, the composition of steel fiber-reinforced concrete with specified properties was designed (ultimate extensibility not less than 100 mm/m; cone slump 1...4 cm; compressive strength not less than 40 MPa; flexural strength not less than 6.5 MPa). The results of laboratory tests of the obtained composition are presented. In terms of strength, workability and ultimate extensibility, the composition meets the technical specifications. **Conclusions.** The proposed methodology of designing the composition of steel fiber-reinforced concrete for slip forming has been successfully tested in laboratory and can be recommended for use in production.

Keywords: steel fiber-reinforced concrete, slip forming, rheology, ultimate extensibility, mixture composition

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1. INTRODUCTION

Slip forming is one of the effective and promising methods of concrete mix casting, that has been actively developing since the 70s of the 20th century and has taken a strong positions in concrete technology, because it is characterized by a high degree of automatization and robotization of technological processes. A feature of such molding is a number of specific requirements for the rheological and technological properties of concrete mixtures, the effective regulation of which is a key issue in obtaining high-quality concrete products [1].

In recent years, Russian and foreign scientists have shown great interest in concrete mixtures for slip forming, including for additive technologies [2-6]. One of the most important results of the research is the experimentally proven provision that the determining property of such mixtures is their plasticity, that is responsible to obtain continuity during deformation, which inevitably occurs when using such technologies [1]. The quantitative assessment of plasticity is the numerical value of the ultimate extensibility of the concrete mix, i.e. its relative elongation in mm/m, at which cracks are recorded in the molded product [7].

Recent studies have let to accumulate the necessary knowledge and solve one of the key problems in the technology of slip forming, namely, to develop a methodology for designing the composition of concrete mixes that ensures not only the strength characteristics of concrete and the workability of the concrete mix, but also its plasticity [1]. However, this direction is only at the beginning of its development today, and the developed methodology has proven its effectiveness only for heavy and fine-grained concrete mixes on widespread raw materials. Many questions remain about the influence of various specific types of aggregates, binders, additives, the features of various types of mixes, etc., what requires further study [8-12].

The issue considered in this paper is devoted to the design of steel fiber-reinforced concrete composition for slip forming. The scientific base created over several decades in the field of fiber reinforcement of concrete allows us to accurately predict the behavior of fiber-reinforced concrete under load, determine the optimal amount of fiber in their composition depending on specific tasks, and solve many other issues. However, today there is no methodology for designing the composition of fiber-reinforced concrete that would ensure the required properties of the composite, including the characteristics of the concrete mixture, taking into account the features of slip forming technology.

Taking this into account, the purpose of the work is to develop a methodology for designing the composition of steel fiber-reinforced concrete for slip forming technology.

2. METHODS AND MATERIALS

The following materials were used to make the experimental part of the study:

- Portland cement CEM I 42.5N produced by JSC Slantsy cement plant "CESLA": normal consistency of cement paste 27%, strength $R_C = 48$ MPa;
- fine aggregate – quartz sand: fineness modulus $FM = 2.3$, grain density $\rho_{FA} = 2650$ kg/m³, water demand 7%;
- coarse aggregate – granite crushed stone of fraction 5–10 mm: grain density $\rho_{CA} = 2700$ kg/m³, water demand 4%;
- steel milling fiber: length $l = 36$ mm, equivalent diameter $d_{eq} = 0.6$ mm (Fig. 1).



Fig. 1. Steel milling fiber.

The proposed methodology for designing the composition of steel fiber-reinforced concrete consists of two stages: designing the concrete matrix and designing fiber-reinforced concrete based on the known composition of the matrix.

The design of the concrete matrix is carried out according to the methodology developed at SPbGASU, that takes into account the features of the slip forming technology and ensures the required ultimate extensibility of the concrete mix [7, 13]. The methodology consists of a theoretical calculation of the composition and experimental adjustment.

Design of the composition of the concrete matrix includes:

1. Determining the water-cement ratio according to the Bolomey-Skramtayevev law

$$R = A \cdot R_c \cdot \left(\frac{C}{W} \pm 0,5 \right) \quad (1)$$

where – A is the coefficient taking into account the quality of the aggregates, we take it equal to 0.6, as for ordinary aggregates

2. Determining the consumption of components per 1 m³ of concrete mix by the enumeration method using a specially developed computer program

$$\begin{aligned} \varepsilon^{\text{ult}} = & 11,7 \cdot \left(\left(\frac{W}{C} - \frac{FA \cdot W_{FA} + CA \cdot W_{CA}}{C} \right) \cdot 100 - NC \right) + \\ & + 0,032 \cdot \left(\left(1 - \frac{FA}{\rho_{FA}} - \frac{CA}{\rho_{CA}} \right) \cdot 100 - 41,5 \right)^3 + 137 \end{aligned} \quad (2)$$

where: ε^{ult} – ultimate extensibility of the concrete mix, mm/m; C, FA, CA, W – consumption of cement, fine aggregate (sand), coarse aggregate (crushed stone), water respectively per 1 m³ of concrete mix in kg; W_{FA} and W_{CA} – water requirement of fine and coarse aggregates respectively, in shares; ρ_{FA} and ρ_{CA} – density of fine and coarse aggregates grains respectively, kg/m³; NC – normal consistency of cement paste, %

3. Checking the workability of concrete mix according to the generalized dependence presented in Fig. 2.

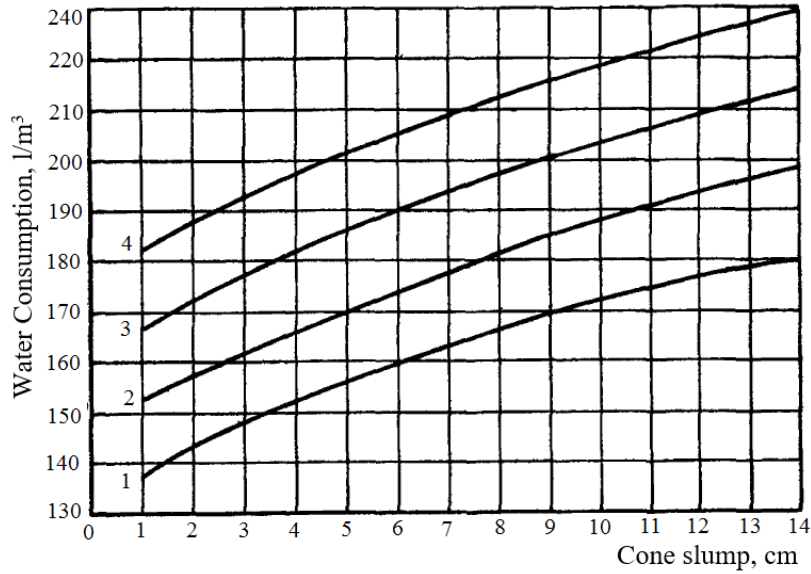


Fig. 2. Generalized dependence of water consumption on the required workability of concrete mixture with the largest aggregate size: 1 – 70 mm, 2 – 40 mm, 3 – 20 mm, 4 – 10 mm. [14].

To adjust the composition of the concrete matrix, the recommendations presented in Table 1 are used.

Table 1. Recommendations for adjusting the composition of concrete, provided that the specified strength is ensured.

		Workability of the concrete mix		
		lower (higher) than required	meets the required	higher (lower) than required
Ultimate extensibility of the concrete mix	higher than required	Increase the share of the cement paste, $W/C = const$	Adjusting not required	Decrease the share of the cement paste, $W/C = const$
	meets the required	Increase the share of the cement paste, $W/C = const$	Adjusting not required	Decrease the share of the cement paste, $W/C = const$
	lower than required	Increase the share of the cement paste, $W/C = const$	Add plasticizing additive and decrease the share of the cement paste	Decrease the share of the cement paste, $W/C = const$

These recommendations require repeated application after each adjustment of the composition.

Design of fiber-reinforced concrete based on the known composition of the matrix consists of determining the optimal consumption of fiber that allow to obtain the specified strength. To do this, the dependence of the fiber-reinforced concrete strength on the volume percentage of fiber reinforcement is constructed by calculation at two points using formulas (3) and (4) [15, 16].

$$\mu_{\min} = \frac{V_{CZ} \cdot R_{CS}}{(\varphi\tau) \cdot 2 \cdot \frac{l}{d} - (2 \cdot \frac{E_F}{E_{CZ}} + 3,5) \cdot R_{CZ} + 4,5 \cdot R_{CS}} \quad (3)$$

$$\mu_F = V_{CZ} \cdot \alpha \cdot \frac{R_{CZ} - R_{CS}}{R_{CS} \cdot (2 \cdot \frac{E_F}{E_{CS}} - 1) - R_{CZ} \cdot (2 \cdot \frac{E_F}{E_{CZ}} - 1)} \quad (4)$$

where: μ_{\min} – the minimum volume share of fibers after they begin to show reinforcing properties; μ_F – the fiber consumption corresponding to the formation of a fiber-cement framework; V_{CZ} – the volume share of cement paste in which fibers can be distributed to form contact zones; R_{CS} – the bending strength of cement stone according to samples made of cement paste of normal consistency; R_{CZ} – the strength of the contact zone, equal to $1.4R_{CS}$; $(\varphi\tau)$ – the characteristic of adhesion of fibers to the matrix; E_F , E_{CS} and E_{CZ} – the elastic modulus of the fiber, cement stone and contact zones, respectively; l – the fiber length; d – the fiber diameter; α – a coefficient taken to be equal to 0.785.

For each of the critical reinforcement limits, the bending strength of fiber-reinforced concrete R_{FRC} is calculated [17, 18].

$$R_{FRC} = \frac{2 \cdot (\varphi\tau) \cdot l \cdot \mu}{d} + 3,5 \cdot R_{CZ} \cdot \mu + R_{btb} \cdot (1 - 4,5 \cdot \mu) \quad (5)$$

where: R_{btb} is the ultimate bending strength of concrete of the same composition as the fiber-reinforced concrete matrix, determined experimentally.

Based on the obtained values, the dependence of the strength of fiber-reinforced concrete on the percentage of reinforcement is constructed, according to which the amount of fiber required to achieve a specified strength [19, 20, 21, 22].

3. RESULTS AND DISCUSSION

To test the proposed methodology, a task for designing the composition of fiber-reinforced concrete for the manufacture of a steel fiber-reinforced concrete structure using a slip forming method was formulated:

- compressive strength of at least 40 MPa;
- bending strength of at least 6.5 MPa;
- workability grade P1 (cone slump = 1...4 cm);
- ultimate extensibility of concrete mix of at least 100 mm/m

To design the matrix composition according to formula (1), $W/C = 0.53$ is determined. Using formula (2), the consumption of coarse aggregate corresponding to the specified ultimate extensibility is selected by the enumeration method. The results of the enumeration are presented in Table 2.

Table 2. Results of calculations of ultimate extensibility at a specified consumption of coarse aggregate.

Coarse aggregate, kg	Fine aggregate, kg	Cement paste volume share	Cement, kg	Water, kg	Ultimate extensibility of concrete mixture, mm/m
	$FA = r \cdot CA$	$\varphi_{CP} = 1 - \frac{FA}{\rho_{FA}} - \frac{CA}{\rho_{CA}}$	By formula (6)	$W = C \cdot \frac{W}{C}$	By formula (2).
950	760	0,361	427	226	186
960	768	0,355	419	222	176
970	776	0,348	411	218	166
980	784	0,341	403	214	155
990	792	0,334	395	209	143
1000	800	0,328	387	205	129
1010	808	0,321	379	201	115
1020	816	0,314	371	197	100
1030	824	0,308	363	193	83

$$C = \frac{1000 \cdot \rho_c \cdot \varphi_{cp}}{1000 + \frac{W}{C} \cdot \rho_c} \quad (6)$$

The presented data shows that the maximum permissible consumption of coarse aggregate with a fine to coarse aggregate consumption ratio of 0.8 is 1020 kg. Thus, the calculated composition of the concrete mix per 1 m³ is: Cement (C) = 371 kg; Fine aggregate (FA) = 816 kg; Coarse aggregate (CA) = 1020 kg; Water (W) = 197 kg.

The workability check according to Fig. 2 showed that the cone slump of the calculated composition is 4 cm, what is consistent with the design assignment for the composition.

The results of the experimental check of the calculated composition, indicated in Table 3, showed the need to adjust the composition for ultimate extensibility and strength.

Table 3. Results of the experimental check of the calculated composition.

Indicator	Indicator value
Density of concrete mixture, kg/m ³	2412
Workability (cone slump), cm	2
Ultimate extensibility of mixture, mm/m	96
Strength at 28 days at normal conditions, MPa	39

For this purpose, a nanomodified superplasticizer was used, what allowed to increase the ultimate extensibility of the concrete mixture while reducing the consumption of cement and water and increasing the strength of concrete without changing the W/C ratio. The consumption of the additive recommended by the manufacturer is 0.6% of the cement mass. The results of the adjustment and optimization are given in Table 4.

Table 4. Results of adjusting the calculated composition

Indicator	Indicator value	
The actual composition of the concrete mixture (per 1 m ³)	Cement, kg	333
	Fine aggregate, kg	844
	Coarse aggregate, kg	1055
	Water, kg	176
	Plasticizer, kg	2
Density of concrete mixture, kg/m ³	2410	
Workability (cone slump), cm	3	
Ultimate extensibility of mixture, mm/m	113	
Compression strength at 28 days at normal conditions, MPa	44	
Bending strength at 28 days at normal conditions, MPa	4,31	

Thus, the component consumption presented in Table 6 corresponds to the technical specifications and can be used as a matrix for steel fiber-reinforced concrete.

According to formulas (3)-(5), the coordinates of the dependence of the percentage of reinforcement with steel milled fiber on the fiber-reinforced concrete bending strength were calculated. According to the obtained dependence (Fig. 3), the percentage of reinforcement required to achieve the specified bending strength was determined as 0.84%.

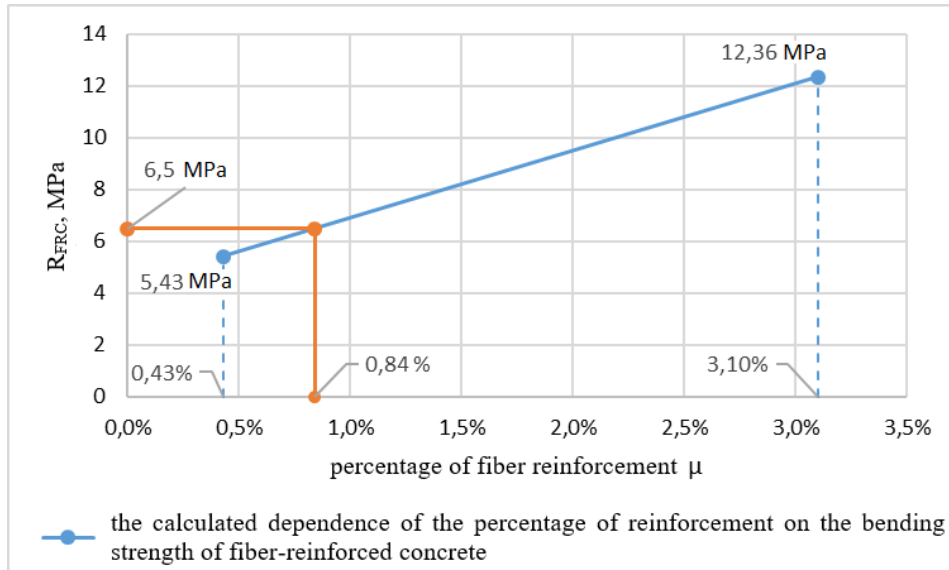


Fig. 3. Dependence of the percentage of reinforcement with steel milled fiber on the bending strength of fiber-reinforced concrete.

The results of the experimental verification of the calculated composition of steel fiber-reinforced concrete are presented in Table 5.

Table 5. Results of the experimental verification of the calculated composition of steel fiber-reinforced concrete.

Indicator		Indicator value
The actual composition of the concrete mixture (per 1 m ³)	Cement, kg	327
	Fine aggregate, kg	828
	Coarse aggregate, kg	1035
	Water, kg	173
	Plasticizer, kg	1,96
	Fiber reinforcement, kg	64
Density of concrete mixture, kg/m ³		2429
Workability (cone slump), cm		2
Ultimate extensibility of mixture, mm/m		107
Compression strength at 28 days at normal conditions, MPa		49,5
Bending strength at 28 days at normal conditions, MPa		6,51

The results show that the obtained steel fiber concrete composition meets the requirements of the technical specifications.

4. CONCLUSIONS

Technologies of slip forming of concrete and reinforced concrete products and structures have been successfully developing in recent decades, due to the high degree of automation and robotization of technological processes. At the same time, the key to obtaining high-quality products is the fulfillment of a number of specific requirements for the rheological and technological properties of concrete mixtures, the effective regulation of which depends not only on the equipment and tools used, but largely depends on the correct choice of the initial raw materials and the accumulated experience in designing the composition of cement composites.

One of the effective and therefore very popular cement composites in modern construction is fiber-reinforced concrete, which has not only outstanding structural characteristics, but also high manufacturability acquired due to fiber reinforcement, which is of particular interest in relation to

methods of slip forming. However, at present there is no methodology for designing the composition of fiber-reinforced concrete that allows for the required properties of the composite and the characteristics of the concrete mixture that meet the conditions for implementing this technology.

As a result of the research, a method for designing the composition of steel fiber-reinforced concrete for continuous formwork-free molding was proposed, based on a combination of previously developed methods by the authors and supplemented by new knowledge about the effect of steel fiber on the plasticity of the concrete mix and the strength characteristics of the obtained composite.

The proposed methodology for designing the composition of steel fiber concrete consists of two stages: designing a concrete matrix according to the method developed at SPbGASU and allowing to ensure the necessary ultimate extensibility of the concrete mix taking into account the features of continuous formwork-free molding, and designing the fiber-reinforced concrete itself with the final determination of the optimal consumption of fiber reinforcement allowing to obtain the specified strength of the composite.

This method has been tested in laboratory conditions and can be recommended for use in designing production compositions of steel fiber-reinforced concrete mixtures.

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