High-strength steel fiber reinforced concrete for road construction

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Abstract. To obtain high-performance road surfaces, it is necessary to use concretes with high performance. The use of steel fiber reinforcement significantly increases the physical and mechanical characteristics of the composite material, but leads to an increase in the stiffness of the mixtures, which complicates the process of laying and compaction. The article proposes a composition of high-performance construction concrete with an increased bending tension and compression strength as compared to the known compositions. The authors make a comparison with the known compositions of high-performance concrete. They present the results of studying the experimental samples of the material. A characteristic feature of the considered steel fiber concrete is the use of microsilica, which is production waste. The use of this composition in road construction increases the performance characteristics of road slabs.

1. Introduction
The scientific development refers to the construction materials industry, namely - to high-performance mortars and concretes.

We know high-performance concrete [1] containing Portland cement, road metal, sand, 30-03 superplasticizer and water. High performance is preconditioned by the reduced porosity due to a low water content in the concrete mix, which is possible due to the introduction of a 30-02 superplasticizer, which is rather expensive. It is generally recognized that high-performance concretes have an increased failure fragility, which does not allow to fully realize their strength properties.

We know a composition of concrete [2] with a reinforcing additive of microsilica - introduced for the purpose of cement economy. This composition does not have a high performance due to the low binder content and a non-optimal amount of the reinforcing additive.

We know a composition of concrete having a high bending tension strength [3], comprising (wt.%) cement - 20, sand - 69.8, fiber reinforcement - 5.0 and water - 5.2. Such a composition has a very high rigidity and can be compacted only by roller molding, hence, the use of this material is limited in reinforced concrete structures, for example, containing prestressed reinforcement, and is impossible in monolithic construction.

The composition of steel fiber concrete [4], containing in wt.% cement - 17; sand of Mcr = 2.71 - 26.6, road metal of 3 - 10 mm fractions - 46.1; MTS-1 plasticizer (0.22%) – 0.72; water – 7.15; steel fiber reinforcement - 2.77, is the closest to the proposed one by the technical essence and the achieved result. Steel fiber concrete of such a composition aged 28 days has the compression strength of up to 40 MPa, and the bending tension strength of 6.9 MPa.
Concretes with a high bending tension strength and crack resistance are necessary to improve the performance characteristics of road slabs [5-8]. This composition of steel fiber concrete [4] does not meet the modern requirements to building structures due to its low strength.

The composition of steel fiber concrete [4] contains fiber reinforcement in the amount of 71 kg/m, which is insufficient for obtaining a high strength, the non-optimal amount of fiber does not allow us to restrain the growth of most cracks under load.

The use of a MTC-I plasticizer is not effective at a particularly low water content in the steel fiber concrete mix. In addition, due to some toxicity of the additive, handling requires special technological methods.

The content of cement is overestimated as compared to the generally used compositions, but it is not enough to produce high-performance concrete. An important factor for increasing the strength is the choice of the optimal grain composition of the fillers for different types of concrete, which is not taken into account in the composition. To ensure a high performance of the reinforced road bed, steel fiber concrete should have an increased fine filler content.

2. The proposed composition of steel fiber concrete

The purpose of this invention is to eliminate the above disadvantages, namely, to increase the bending tension and compression strength.

This purpose is achieved by the fact that high-performance concrete, including Portland cement, coarse and fine filler, fiber reinforcement, plasticizer and water, additionally contains microsilica, ferrosilicon production waste and a hardening agent with the following component ratio:

Portland cement – 18.9…23.0 wt.%; microsilica, ferrosilicon production waste – 2.7…… 4.7 wt.%; Fine filler – sand of Mer=2.11 – 26.2…..30.2 wt.%; Coarse filler – road metal of 5….10 mm fractions –33.7…. 36.9 wt.%; Fiber reinforcement – 3.9…….5.7 wt.%; Hardening agent (caustic soda) – 0.049…0.074 wt.%; Plasticizer - a polycondensation product of naphthalenesulfonic acid and formaldehyde – 0.25…..0.29 wt.%; water  – remaining.

The proposed composition contains microsilica in the range of 2.7 ... 4.7 wt.%, which is 80 - 95% amorphous silica capable to bind lime released during the hydration of Portland cement into poorly soluble calcium silicates. The formation of an additional amount of hydrated newgrowths leads to an additional compaction of concrete and an increase in its strength. Microsilica - the ferrosilicon production waste - also includes iron and aluminum oxides (up to 1.5%) and some other compounds that do not affect the physical and mechanical characteristics of concrete. Microsilica is a fine powder with the specific surface area of 25 m²/g.

It is generally accepted [5] that the introduction of microsilica almost proportionally increases the strength of concrete, however, the rigidity of the mix increases substantially and the workability is worsened. Hence, workable concrete mixes can be obtained only within the limits specified in the proposed composition. In case of a high content of fiber reinforcement and microsilica, there is no increase in the strength of steel fiber concrete [13-20], and in case of lower contents due to an insufficient modification of the cement stone and concrete structure, no high strength is achieved.

The proposed composition contains 0.049 ... 0.074 wt.% of the hardening agent (caustic soda). The introduction of the hardening agent leads to a more complete flow of the process of the interaction between microsilica and hydrated newgrowths of Portland cement, which contributes to a denser, crystallized structure of the material capable to bear an increased load without destruction.

The proposed composition includes fiber reinforcement within 3.9. - 5.7 wt.%. A smaller content of fiber reinforcement does not provide an effective reinforcement of growing microcracks when the material is loaded. A low percentage of reinforcement of high-performance concretes leads to an avalanche-like microcrack formation, which leads to an almost instantaneous destruction of steel fiber concrete. The use of such concrete in structures requires a significant margin of safety, which results in a non-rational use of the material and increased costs. The introduction of fiber reinforcement in an amount of over 5.7 wt.% leads to an increase in the rigidity of the mix containing microsilica, as a result of which the strength is reduced due to the insufficient compaction.
It is possible to produce high-performance steel fiber reinforced concrete without the use of microsilica [10]. However, such concrete contains fiber reinforcement in an amount of 19.2 wt.%. An increase in the content of fiber reinforcement complicates the concrete mix production technology (requires a phased introduction of the fiber), and it is necessary to use special equipment to prepare and compact the mix because of its rigidity. The proposed composition contains a C-3 plasticizer in an amount of 0.25-0.29 wt.%. In standard concretes, it is recommended to introduce such plasticizer (C-3 - the polycondensation product of naphthalenesulfonic acid and formaldehyde) in the amount of 0.13-0.2 wt.% (0.5-0.8% by the binder weight) [9,11]. A large amount of the plasticizer in standard concrete mixes does not give an additional increase in mobility. In steel fiber concrete mixes with a low water-binder ratio containing fiber reinforcement and microsilica additives, the use of the plasticizer in the amount of less than 0.25 wt.% is not sufficient for obtaining mixtures workable by the mass production equipment. The addition of the plasticizer of above 0.29 wt.% does not significantly influence the mobility of the steel fiber concrete mix.

In the proposed composition, one of the components contributing to a sharp increase in the strength of steel fiber concrete is microsilica - the production waste (dust), precipitates on electric filters during the flue gas cleaning of electric smelting furnaces producing ferrosilicon. Microsilica is a fine powder with the specific surface area of 25 m²/g. Microsilica is poorly caked, when exposed to wind, it is sprayed and substantially pollutes the air.

3. Examples
In all the examples, the bending tension strength of steel fiber concrete was determined on 10x10x40 cm beam samples, and the compressive strength - on 10x10x10 cm cube samples (according to GOST 10180).

The steel fiber concrete mix was prepared on a power-activated SB-80 mixer, the samples were compacted on a vibrating pad (with the vibration frequency of 3000 cells/min and the amplitude of 0.5 mm), then, the samples were steamed according to the 6 + 4 + 12 + 2 hour mode, at the isothermal holding temperature of 90 C. Then, the samples were placed in normal humidity conditions for 7 days and tested. M600 Portland cement, washed coarse filler – diabasic road metal of 5-10 mm fractions and fine filler – sand, coarseness model M=2.11, fiber reinforcement – sheet [8], section 0.5x0.5 mm, length 25 mm, were used to prepare the mix.

The choice of the ratio of the coarse, fine filler and fiber reinforcement is important for obtaining the maximum strength in steel fiber concrete. We made an experiment using the method of mathematical planning to solve this problem. The following factors were chosen as independent factors: the ratio of the content of the fine filler to the coarse filler (Sand/Road metal) in the concrete mix and the content of fiber reinforcement (F). We realized the matrix of the full two-factor experiment (Table 1).

Unchangeable components of the mix (kg per 1 m³): plasticizer - 6.5; hardening agent -1.5; water - 162; the total amount of the fine and coarse filler - 1544. The change in the content of fiber reinforcement was compensated by the binder consumption, provided that the sum total of the volumes of all the components of the steel fiber concrete mix is always equal to 1 m³. The sum total of the volumes of fiber reinforcement and the binder was always 0.193 m³ (19.3% by volume). Since the specific weight became much higher than the weight of the binder, the amount of the binder changed insignificantly (the ration of microsilica to Portland cement was always constant 0.12).

The computer processing of the experiment results allowed us to obtain a regression equation (1) (adequate by the Fisher criterion) describing the dependence of the bending tension strength of steel fiber concrete on the fine to coarse filler ratio and the quality of fiber reinforcement (kg).

\[ R_{\text{bend}} = 127.46 - 2.15X_1 + 2.88X_2 - 5.05X_1^2 + 6.75X_1X_2 - 14.25X_2^2 \]

where \( \text{Sand} = X_1 \), \( \text{Road metal} = X_2 \), \( f = f, f = 1.17 < f = 4.3 \).
Proceeding from the received equation, using the computer, we built isolines of the bending tension strength of steel fiber concrete depending on the fine to coarse filler ratio and the content of fiber reinforcement, volume%.

**Table 1.** Results of the matrix of the full two-factor experiment.

| Composition # | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     |
|---------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Content of binder, volume/kg | 18.9/586 | 18.1/561 | 17.3/536 | 18.9/586 | 18.1/561 | 17.3/536 | 18.9/586 | 18.1/561 | 17.3/536 |
| F code | -1 | 0 | +1 | -1 | 0 | +1 | 0 | 0 | 0 |
| F physical volume | 0.4/1.2 | 0.4/1.2 | 0.4/1.2 | 0.4/1.2 | 0.4/1.2 | 0.4/1.2 | 0.4/1.2 | 0.4/1.2 | 0.4/1.2 |
| %/kg | 31.2/93.6 | 31.6/93.6 | 31.6/93.6 | 31.6/93.6 | 31.6/93.6 | 31.6/93.6 | 31.6/93.6 | 31.6/93.6 | 31.6/93.6 |
| Sand/Road metal code | -1 | -1 | -1 | 0 | 0 | 0 | +1 | +1 | +1 |
| Sand/Road metal phys. | 0.6 | 0.6 | 0.6 | 0.8 | 0.8 | 0.8 | 1 | 1 | 1 |
| Sand, kg | 579 | 579 | 579 | 686 | 686 | 686 | 772 | 772 | 772 |
| Road metal, kg | 965 | 965 | 965 | 858 | 858 | 858 | 772 | 772 | 772 |
| R bend, MPa | 11.52 | 11.23 | 10.77 | 10.83 | 13.2 | 11.36 | 9.74 | 11.8 | 11.9 |

An analysis of the regression equation and the strength isolines shows that there is an optimal area of the content of fine and coarse filler and fiber reinforcement in the mix (Sand/Road metal = 0.7-0.9, F = 1.2-1.6 volume%). Outside this area, there is a decrease in the strength due to a lack of the coarse filler and fiber reinforcement or an undercompaction (in case of a large content of fiber and road metal, the mix becomes very rigid and it is impossible to compact it using standard vibration equipment).

We prepared concrete mixes to determine an optimum content of the plasticizer, the vibration time of which during molding is indicated in Table 2, to obtain a compaction factor of at least 0.95. The 10x10x10 cm cube samples were studied. The change in the amount of the plasticizer in the concrete mix was compensated by the coarse filler consumption. Unchangeable components in the composition of steel fiber concrete; wt. %: Portland cement - 21.9; microsilica - 3.9; fine filler - 27.6; fiber reinforcement – 5.056; hardening agent - 0.064; water - 6.7.

**Table 2.** Results of the matrix of the full two-factor experiment.

| Composition | 10 | 11 | 12 | 13 | 14 |
|-------------|----|----|----|----|----|
| Content of road metal, wt.% | 34.55 | 34.53 | 34.5 | 34.49 | 34.47 |
| Content of plasticizer, wt.% | 0.23 | 0.25 | 0.28 | 0.29 | 0.31 |
| Compaction time, s. | 300 | 210 | 190 | 180 | 180 |

An analysis of the results indicates the existence of the plasticizer content area, in which its diluting functions (0.26-0.31 wt.%) are manifested most effectively for steel fiber concrete mixes. An increase in the amount of the polycondensation product of naphthalenesulfonic acid and formaldehyde in excess of this lower limit does not lead to additional plasticization of the concrete mix.

Caustic soda is added to the mix in the amount of 0.049-0.074 wt. % [12] to accelerate hardening of steel fiber concrete and to ensure an increased strength of the material at the brand age.

One of the main ways to reduce the porosity of concrete, and therefore, to increase its density and strength is to reduce the water content in the concrete mix [10]. It is recommended to reduce the water-binding ratio when choosing a concrete composition before obtaining rigid mixes, but with a sufficient workability to exclude the appearance of undercompaction pores in the material. For this purpose, we made the following experiment, wt. %: coarse filler - 34.5; fine filler – 27.6; fiber reinforcement – 5.8; hardening agent - 0.06. The influence of the water-binding ratio on the compression strength of the material is presented in Table 3. In all the compositions, the ratio of microsilica to Portland cement was constant (0.13).
The results of the experiment show that there is an increase in the compression strength of steel fiber concrete at a decrease in the water-binding ratio to 0.26, a further decrease in the water content leads to an undercompaction, hence, the strength decreases.

The introduction of microsilica in increased amounts significantly worsens the workability of the concrete mix, especially when fiber reinforcement is added to the mix. The final experiment to determine the composition of high-performance steel fiber concrete was the optimization of the microsilica additive to obtain a homogeneous, non-stratified steel fiber concrete mix, with a rigidity, which allows us to compact it using standard commercial vibration equipment. The obtained results are shown in Table 4. The change in the amount of microsilica in the mix was compensated by the consumption of Portland cement, so that the binder consumption in the studied compositions always remained constant (the grain separation coefficient did not change). Consumption of the unchangeable components, wt. %: binders – 25.2; coarse filler - 35.1; fine filler - 27.6; plasticizer - 0.28; fiber reinforcement – 5.056; hardening agent - 0.064; water - 6.7.

Table 4 shows that the highest strength of the composite material is observed with the addition of microsilica in an amount of 3.3 - 4.6 wt.%, an increase in the content results in a decrease in the strength due to the undercompression of the steel fiber concrete mix.

A comprehensive analysis of the conducted experiments confirms that high-performance steel fiber concrete, which can be prepared using commercial vibration equipment, can be produced only if the above components are used within the specified limits.

High-performance steel fiber concrete can be produced from traditional compositions [3] using the roller molding technology. An increased strength is obtained due to the use of particularly rigid mixes and a directed orientation of the fibers in the matrix. To implement such a technological limit, an installation is needed that includes: a stabilizing beam, a bin feeder for the concrete mix, guides, a crank mechanism, a roller conveyor to move the mold, and a drive to move the mold. The cost of the lime composition [3] is close to the cost of the proposed composition, however, the proposed composition is molded and compacted using standard equipment, i.e. there is no need for roller molding equipment. In addition, process roller molding involves the production of flat products, it is impossible to use prestressed reinforcement, without which it is not allowed to manufacture critical structures. It is also impossible to obtain irregular-shaped products and to use it in monolithic construction.

The use of high-performance fiber concrete in road construction makes it possible to obtain a similar load-bearing capacity of the roadbed at a 1.5 - 2 times less thickness than the thickness of the roadbed made of a prototype composition, which is 200 mm instead of 300 mm, thus, 1.5 - 2 times less concrete mix is used per 1 m³ of the roadbed. The base concrete mix in the proposed composition has close rheological properties, so it can be prepared using the same equipment, however, due to the fact that the consumption per 1 m² of the roadbed using the proposed mix is 1.5 - 2 times less, the
equipment performance will be 1.5 - 2 times higher, all other things being equal. The increase in the performance leads to a decrease in the product cost due to a 20-30% decrease of the site employees’ labor costs.

4. Conclusions
We proposed high-performance steel fiber concrete, including Portland cement, coarse and fine filler, fiber reinforcement, plasticizer and water. It is characterized by the fact that in order to increase the bending tension strength and compression strength, it additionally contains microsilica - ferrosilicon production waste and a hardening agent. The use of high-performance fiber concrete in road construction allows us to reduce the concrete mix consumption and to increase the equipment performance, all other things being equal.

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