Magazine of Civil Engineering. 2020. 97(5). Article No. 9702

Magazine of Civil Engineering

ISSN 2071-0305

journal homepage: http://engstroy.spbstu.ru/

DOI: 10.18720/MCE.97.2

Fine-grained concrete with various types of fibers

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Keywords: fiber, fine-grained concrete, amorphous fiber, strength properties, fiber reinforced materials, fiber-reinforced concrete cements, binders concretes, cementitious concrete, mechanical activation

Abstract. This paper investigates the strength properties of the fine-grained concrete reinforced with the amorphous fiber based on the Fe-B-C system and obtained by the "spinning" method, and concretes reinforced with commercially available types of fibers: fiber based on mineral wool, basalt fiber, fiberglass, steel and polypropylene fibers. The flexural and compressive strength tests with the fiber-reinforced concrete specimens were carried out in accordance with the standard method corresponding to the Russian State Standard. The analysis of results was made by comparison with the characteristics of the control specimens without reinforcement. The best flexural strength characteristics were shown by specimens with the amorphous fiber, while the highest compressive strength was demonstrated with the steel fiber. The addition of the amorphous fibers leads to an increase of 56 % in the flexural strength, but decreases the compressive strength by 30 % compared to the control specimens, which proves the efficiency of this fiber working in bending. The addition of the steel fiber shows an increase of 20 % in flexural strength and an increase of 14 % in compressive strength, which confirms the positive effect of adding a commercially available fiber to the fine-grained concrete. The compounds of the fiber concrete with the compression strength limit up to 38 MPa and tensile strength in bending up to 12 MPa were developed, which allows to use amorphous fiber as a compound of fine-grained concrete in the construction industry.

1. *Introduction*

Nowadays, the actual direction of the development of high-quality cement concretes, characterized by a wider range of functional capabilities, is the use of complex additives that combine components with various functional purposes. Such additives allow to effectively manage the processes of structure formation at all stages of the technology of concrete preparation and, as a result, allow to obtain the concrete with various high-performance properties [1−3].

To increase the strength characteristics of modern concrete, various technical and technological solutions are used, including dispersed reinforcement with fibers. This type of building material is called fiber-reinforced concrete. The industry of modern building materials demonstrates various types of fibers used in the manufacture of the fiber-reinforced concrete. Fibers of both artificial and natural origin are used.

Every year the application field of the fiber-reinforced concrete is becoming wider. The use of various types of fibers is determined by their purpose: the amorphous and the steel fibers are used in new construction to increase the bearing capacity of the structure. It is generally recommended to use these fibers in floor slabs or walls experiencing strong bending loads. In the reconstruction of buildings and structures, the amorphous and the steel fibers are used to strengthen the load-bearing structures. It is proposed to use a layer of the fiber-reinforced concrete as a reinforcement for damaged vertical structures due to its increased bending strength compared to the ordinary concrete [4, 5]. The other types of fibers are mainly used to unweight construction and increase crack resistance. These fibers are added to various blocks (autoclaved aerated concrete, foam concrete and others) to reduce their weight and to the floor screed construction.

Begich, Y.E., Klyuev, S.V., Jos, V.A., Cherkashin, A.V. Fine-grained concrete with various types of fibers. Magazine of Civil Engineering. 2020. 97(5). Article No. 9702. DOI: 10.18720/MCE.97.2

Besides the new properties of the fiber-reinforced concrete, this material suggests a new technology for the manufacturing of reinforced concrete products. This technology allows preparing a reinforced concrete mixture in concrete mixers due to the possibility of adding fibers with other aggregates directly into the mixers. In this case the time of the manufacturing is reduced and the labor costs for reinforcing works are becoming unnecessary.

Moreover, the fiber-reinforced concrete opens up great opportunities for the use of recycled materials, and, as a result, for the improvement the environmental situation in the world through the efficient disposal of material debris. The use of fibers from the plastic PET (polyethylene terephthalate) waste in the fiber-reinforced concrete showed the comparable efficiency with using the commercial synthetic fiber specimens [6]. The authors of [7] investigate the efficiency of using recycled steel fibers obtained from machining process discards.

The widely used and most studied artificial types of fibers are steel ones, as well as fibers based on polymers, for example, polypropylene fiber.

The articles [8, 9] present the results of the study of the steel fiber for dispersed concrete reinforcement. The experimental studies of the deformation characteristics of the steel fiber concrete specimens are described. It was obtained that reinforcement with the steel fiber increases the compressive strength of concrete by 15 % and the flexural strength by 50 % compared to concrete without reinforcement. In contrast to the previous studies, where the cement was a binder in the fiber-reinforced concrete mix, the papers [10–12] deals with the steel-fiber-reinforced concrete specimens based on the fine ground cement and the low water demand binder. It was established that the use of composite binders and the high-density packing of aggregate grains significantly increases strength characteristics. The compressive strength of the specimens ranged from 84.8 MPa to 160.2 MPa, when the flexural strength was in the range from 19.8 MPa to 31.2 MPa.

The issues of using the polymer fiber for the concrete reinforcement are considered in [13, 14]. The results of determining the strength characteristics are presented. The studies show that the adding of the polymer fibers increases the flexural strength of the concrete specimens by 18–32 %. The simultaneous use of the steel and the polypropylene fibers for the reinforcement in shows a positive synergistic effect [15]. These specimens show the higher flexural strength compared with the studied specimens, where the steel and the polypropylene fibers were used separately from each other. The steel-fiber-reinforced concrete mixtures and the concrete mixtures reinforced with the polymer fibers were studied in detail in [16], where the features and recommendations for the preparation of these mixtures are described.

In the article [17] the authors use waste in the production of mineral wool as an additive to concrete. The compressive strength of the obtained materials reaches 80 MPa. Moreover, these specimens are characterized by high water resistance.

Also, some fibers of organic origin are used for the dispersed reinforcement. The jute fibers have a positive effect on the flexural and compressive strengths [18]. The authors of articles [13, 19] consider sisal fiber as dispersed reinforcement. The results demonstrate that the sisal fiber reinforcement could provide the same level of residual strength for concrete as the polypropylene fiber reinforcement.

The main issue of optimizing the geometric parameters and the physical properties of the fiber is the need to ensure reliable adhesion of the fiber to the cement matrix under loads, as well as resistance to withstand tensile forces [20–22]. The interfacial connection of the fiber and the matrix is very important – it helps to counteract the shear stress transmitted from the cement matrix to the fibers at the interface. As the adhesion increases, the resulting cement composites become more durable and elastic due to the transmission of the arising tangential stresses from the concrete to the fibers. The results of experimental studies of the influence of the type, length, and amount of reinforcing fibers on the structure and strength of the fiber-reinforced concrete are presented in [12, 23].

The paper [24] investigates the numerical model for predicting the diffusion of chloride ions in fiber-reinforced concrete. Moreover, the results demonstrate that four factors, including the fiber diameter, the volume fraction of fibers, the aggregate diameter and the volume fraction of aggregates, significantly affect the diffusion of chloride in fiber concrete.

In addition, one of the most important characteristics of fiber-reinforced concrete is the increased crack resistance. This characteristic was investigated during the bending tensile tests by constructing and analyzing stress-strain curves of the specimens [25], as well as crack growth resistance curves [26].

The goal of the present work is to study the effect of the dispersed reinforcement of the fine-grained concrete with the amorphous fiber based on the Fe-B-C system, and to compare the strength characteristics of the fine-grained concrete specimens reinforced with the amorphous fiber with reinforcement with the following types of fibers: polypropylene fiber (Fig. 1), basalt fiber (Fig. 2), fiberglass (Fig. 3), mineral wool fiber (Fig. 4), steel fiber (Fig. 5).

Figure 1. Polypropylene fiber.

Figure 2. Basalt fiber.

Figure 3. Fiberglass.

Figure 4. Mineral wool fiber.

Figure 5. Steel fiber.

Figure 6. Amorphous fiber (Fe-B-C system).

The field of application of the fine-grained concrete and its characteristics depend on the properties of the fiber material. Currently three main types of dispersed micro-reinforcement are used abroad: fibers as short cuts of steel thin wire, glass and polypropylene fibers. Authors of this paper suggest using six different types of dispersed reinforcement: polypropylene, basalt, glass-fiber, mineral wool, steel and amorphous (Table 1).

Table 1. Technical characteristics of different fibers.

Indicator	Polypropylene fiber	Basalt fiber	Fiber-glass fiber	Mineral wool fiber	Steel fiber	Amorphous fiber
Material	Polypropylene	Basalt fiber	Glass fiber	Mineral wool	Carbon steel wire	Fe-B-C alloy
Fiber diameter	10−25 μm	13−17 μm	13−15 μm	15−30 μm	0,5−1,2 mm	30 μm
Fiber length	6−18 mm	3.2−15.7 mm	4.5−18 mm	0.5−1 mm	30−50 mm	35 mm
Melting temperature, °C	160	1450	860	1110	1550	1700
Corrosion and alkali resistance	Low	High	Medium	High	Medium	Medium

2. Methods

To obtain the amorphous fiber the multicomponent amorphous metal alloy (metallic glass) was used. This alloy of the Fe-B-C system consisting of Mo (up to 20 %), Cr (up to 17 %), and V (6 %) was obtained at the “Material Science and Technology” department of «Institute of Metallurgy, Mechanical Engineering and Transport» of Peter the Great St. Petersburg Polytechnic University.

The initial ingots (40–50 g) of multicomponent alloys were made in quartz crucibles using high frequency currents (HFC). Melting was carried out in stages. At the first stage, the components of the Fe-B-C alloy in a certain weight ratio were melted in vacuum. Secondly the crucible was filled with an inert gas, after which sparingly soluble alloying additives were introduced into the melt in the order of their reaction activity (Cr, Mo, V). Overheating at 200–500 °C above the melting temperature ensured complete dissolution of the components and a fairly uniform alloy structure.

In the following stage after melting, the necessary gas pressure in the crucible (Δp) is created and the melt is squeezed out in the form of a thin (fraction of a millimeter) jet onto a drum rotating at a speed of V_d. The drum is made of copper and rotates at a speed that provides a linear surface speed, and, consequently, provides a linear speed of the tape up to 50 m/s. The jet of melt drops at a speed V_m at an angle α to the surface, as a result, a stationary pool of melt is formed on the surface of the refrigerator drum [27].

This method of producing amorphous metal alloys in the form of thin tapes by means of ultrafast cooling of the melt on the surface of a rotating cold drum is called «spinning».

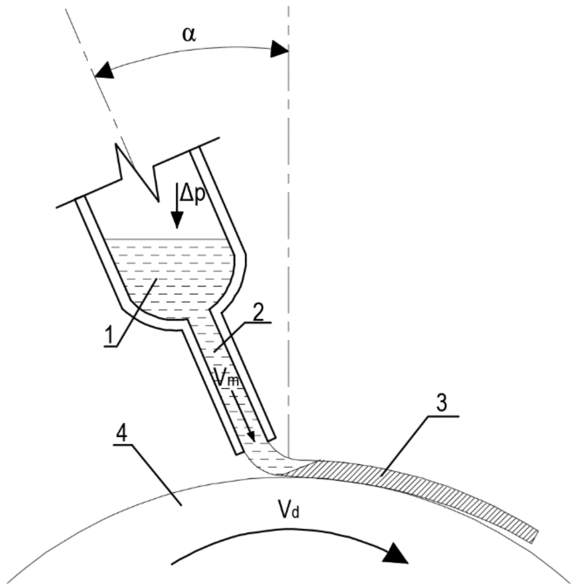

Figure 7. Scheme of the spinning process.
1 – molten metal, 2 – jet of melt, 3 – amorphous metal fiber, 4 – cold drum

The melt spinning method has been particularly investigated by many authors. Various modifications of this method can be used both for research purposes and for an industrial production of amorphous tapes of various alloys.

Cement PJSC “Evrocement group” (Joint stock company) Cement I 42,5N D0 and aggregate were used in the work in order to get high quality fiber concrete compounds. Their main physical-mechanical properties were studied for the estimation of the quality of the applied aggregate (Table 2).

Table 2. Physical-mechanical properties of the aggregate.

Indicator	Sand of Sestrinskii origin
Fraction module	1.38
Bulk density, kg/m^3	1448
True density, kg/m^3	2630
Voidness, %	44.9
Water demand, %	7

The compounds of the disperse-reinforced fine-grained concretes are presented in Table 3.

Table 3. Compounds of the disperse-reinforced fine-grained concretes.

№	Compound	Unit of measurement	Control
1	Cement	kg	650
2	Sand	kg	1500
3	Water	liters	210
4	Water/Cement Ratio		0.32

To obtain the beam specimens with the dimensions of 40×40×160 mm, the mortar mixture prepared according to the method, which was described above, was placed in a three-section mold. To consolidate the concrete by vibration the mold was fixed on a standard vibrating. Finally, this molds with the concrete specimens were stored for the first 24 hours in the high humidity space, then the beams freed from the molds were stored in water at a temperature of (20 ± 2) °C.

To obtain the comparable results, the described method of preparing a mortar mixture was also used in the process of manufacture of the test specimens with fibers. The fibers were added to the dry mixture of sand and cement in the amount of 1 % (21.8 kg), 2 % (43.7 kg) and 3 % (65.5 kg) of the mass of the concrete grout (2240 g). Then, after achieving a uniform distribution of the fibers in the mixture, water was added. The polypropylene fiber was added in the amount of 0.1, 0.5 and 1 % because of the low density.

Thereby the volume of this fiber is very significant, which violates the rheological properties of the concrete grout due to an increase of the overall specific surface. It is significant to note that during the process of adding water and the further process of preparing the mixture, the so-called “hedgehogs” (fiber clumping) were not observed, which proves the correctness of the fiber percentage in the concrete grout.

The flexural and compressive strength tests were carried out in accordance with the standard method corresponding to the Russian State Standard 310.4-81 at the age of 3, 7, 28 days.

3. *Results and Discussion*

The flexural and compressive strengths test results of the prismatic specimens from fiber-reinforced concrete are presented in the diagram form in Fig. 8 and Fig. 9 respectively.

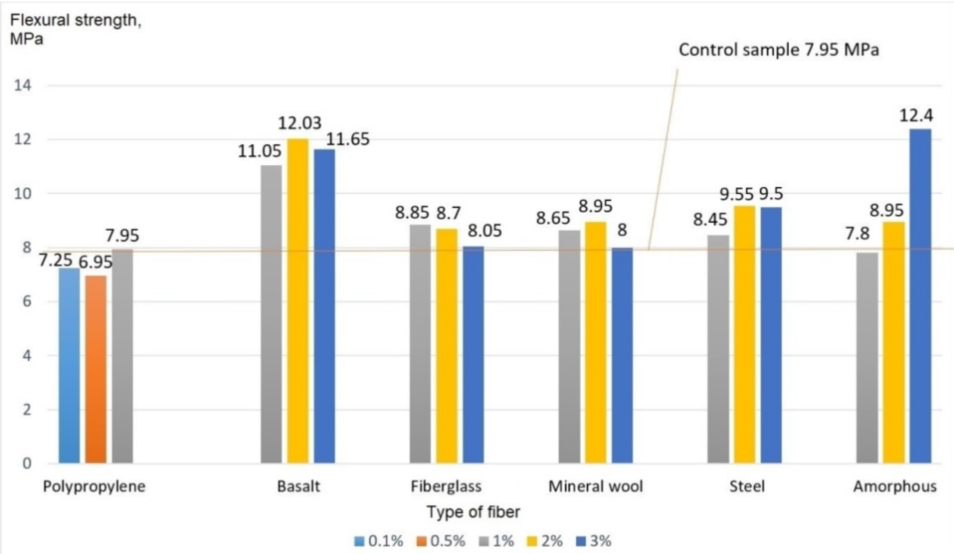

Figure 8. Flexural strength test results of fiber-reinforced concrete specimens.

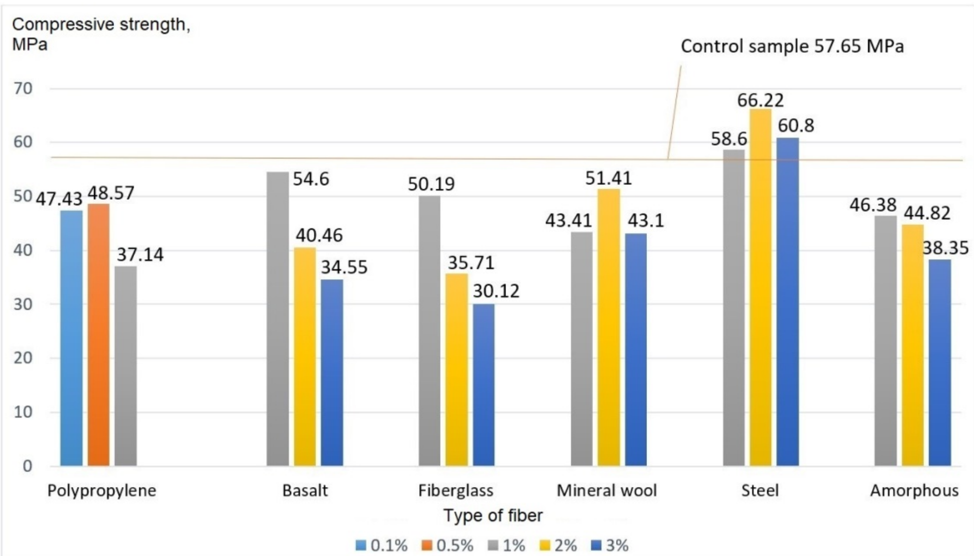

Figure 9. Compressive strength test results of fiber-reinforced concrete specimens.

The bar chart on Fig. 8 illustrates that the best flexural strength characteristics were shown by specimens with a content of 3 % amorphous fiber. This fact proves that the amorphous fiber works well together with the concrete matrix in bending. The specimens with basalt fiber demonstrate comparable results with the specimens reinforced with amorphous fiber. While the amorphous fiber shows an increase in flexural strength with increasing percentage concentration, the basalt fiber values remains nearly constant. All the others specimens show worse results, but an increase in flexural strength is still observed. The exception is only the specimens with polypropylene fiber demonstrating lower values compared to the control specimens.

The Fig. 9 represents that the sample with the steel fiber in 2 % concentration has the best compressive strength characteristic. It can be seen that the addition all the others fibers to the specimens led to a fall in compressive strength values. The main cause for such result is that the geometrical parameters of the steel fiber are smaller compared to the others (the length is about 10–12 mm). Such dimensions make the beam wall works in bending, which increases the compressive strength. It is important to note that the rise of percentage concentration of the fiberglass, basalt and amorphous fibers decreases the compressive strength.

The flexural and compressive tests of concrete specimens reinforced with different fibers were also carried out by the other authors. M.G. Gabidullin et al. found that the single-level dispersed concrete reinforcement with the steel fiber allows to increase the compressive strength of concrete by 15 % and the flexural strength by 50 % compared to concrete without reinforcement [8]. The authors of the paper [9] conducted experiments with concrete specimens reinforced by steel fiber to determine the compressive strength. The results show a growth in the range of 18.6–21 % compared with the specimens without reinforcement. The percentage value of the compressive strength increase in the present work is approximately 15 % (Fig. 9) which is very similar to the results obtained by the authors mentioned above.

The flexural strength of the steel fiber-reinforced fine-grained concrete is equal to 9.55 MPa and the compressive strength is equal to 66.22 MPa accordingly to the Fig. 8 and Fig. 9 respectively.

However, there are studies which demonstrates very high values (approximately 2 times higher) for the flexural and compressive strengths for the same type of fiber-concrete. The compressive strength of the specimens ranges from 84.8 MPa to 160.2 MPa, when the flexural strength is equal to 19.8–31.2 MPa [10–12]. Such high values of these strength characteristics were obtained because of special types of cement and aggregates used in the concrete mixture. These studies investigate the fine-grained concrete based on the fine ground cement and the low water demand binder. Moreover, the special type of technogenic sand was used. The sand was mined in Kursk Magnetic Anomaly. Technogenic sands comparing with natural ones have fundamental differences concerning the shape of grains, main properties and composition. The most obvious distinction is the rough, irregular and nonspherical shape of technogenic sand grains in contrast to the round and smooth shape of the natural sand structure. It is significant for comparative analysis to take into account the characteristics and of all the components in concrete mixture. In addition to this, the shape of fiber itself is quite important. For instance, the highest test results in [11] were demonstrated by the specimens with the wave-shaped fibers compared with other shapes. Authors of this research claim that the wave-shaped fibers as a reinforcing compound in steel fiber-reinforced fine-grained concrete have the best strength characteristics. The same wave-shaped fibers were used in [10, 12].

Polypropylene fiber is another commercially available type of fiber that demonstrates the decrease of strength values in experiments (Fig. 8, Fig. 9). Nevertheless, the papers [13–15] provide the positive conclusions about using the polymer fibers. D.N. Petrov observed the growth of the flexural strength in the range of 18–32 % with the addition of the polymer fiber to the concrete. This controversial fact may be explained by the use of fibers with different technical parameters and characteristics of material.

4. Conclusion

At this stage of the studies of the amorphous fiber of the Fe-B-C system and the comparison of its effect on the mechanical-and-physical properties of the fine-grained concrete with other types of fibers, the following conclusions may be highlighted:

1. The addition of the amorphous fibers in various concentrations to the cement composite leads to an increase of 56 % in the flexural strength, but decreases the compressive strength by 30 % compared to the control specimens.

2. The steel fiber showed an increase of 20 % in flexural strength and an increase of 14 % in compressive strength, which confirms the positive effect of adding a commercially available fiber to the fine-grained concrete.

3. The selected percentages (1, 2, 3 % of the weight of the control concrete grout) for all the above-mentioned fibers, except the polypropylene fiber, are optimal because of absence of the "hedgehogs" (fiber clumping).

4. The compressive strength decreases for all the observed fiber-reinforced concrete specimens (except the specimens with the steel fiber) compared to the control specimens. This fact proves that fibers, like dispersed inclusions in a concrete, adversely affect the compressive strength.

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