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Different types of basalt fibers for disperse reinforcing of fine-grained concrete

***A.S. Rassokhin*[a], *A.N. Ponomarev*[b], *S.L. Shambina*[*b], *A.I. Karlina*[c]**

[a] *Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia*

[b] *Peoples' Friendship University of Russia, Moscow, Russia*

[c] *Moscow State University of Civil Engineering, Moscow, Russia*

**E-mail: shambina_sl@mail.ru*

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Abstract. The paper concentrates on the experimental research of basalt fibers presented at Russian market with eight samples of fibers selected for this research. Five of them are chopped basalt roving (manufactured by LUKE, Rusbazalt Inc, Kamenny Vek Ltd, Armastek), one of them is chopped polymer-basalt wire (manufactured by SK Ltd), two of them are basalt microfibers (manufactured by NTC of Applied Nanotechnologies Inc.). Each of the fibers was added to fine-grained concrete at concentrations of 0.25 vol.-%, 0.5 vol.-%, and 1 vol.-%. Changes in density, compressive strength, and flexural strength were investigated. The density of fine-grained concrete increased proportionally to the quantity of chopped basalt roving. Concrete's density decreased proportionally with the fiber percentage when using chopped polymer-basalt wire and basalt microfiber. The highest compression strength enhancement (9.8 %) of fine-grained concrete was achieved when using fibers manufactured by SK Ltd and Kamenny Vek Ltd. The highest flexural strength enhancement was achieved when using polymer-basalt fiber manufactured by SK LLC (68.6 %) and modified basalt microfiber manufactured by NTC of Applied Nanotechnologies Inc (52.9 %).

1. Introduction

It is widely known that concrete perceives the compression load better than bending, and concrete reinforcement is used to improve the load-bearing capacity of concrete for bending. Traditionally, the reinforcement is steel bars and wire, depending on the type of structure. However, alternative methods of reinforced concrete structures, as various types of fibers, are now used [1–4]. This is mainly used as additional reinforcement. Also, fiber reinforcement is used as the main one in concrete 3D printing [5, 6].

Fibers in concrete have been widely used over the past decades [7, 8]. Even in antiquity, horsehair was sometimes used in Roman concrete [9]. However, in modern construction, fibers returned in the form of cut metal wire, as well as anchor fiber [10–12].

Initially, fibers were used in special concrete in unique buildings and structures, as well as in special regions with extreme natural conditions, for example, in areas with increased seismic activity [13].

However, the development of fiber reinforced concrete industry has led to higher use of fibers in various construction industries. Alternatives to steel fibers have also appeared, as steel fibers and steel reinforcing bars do not have a long service life, as they can corrode fairly quickly [14, 15]. As a result, the ability to increase the durability of reinforced concrete structures is not fully used. Therefore, various types of non-metallic fibers have appeared on the construction market, specifically: mineral (basalt, glass, carbon,

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etc.) [16], polymer (polypropylene, polyvinyl alcohol, polyaramid, etc.), as well as organic (viscose, hemp, bamboo, etc.) [17, 18].

Fibers are used to improve the characteristics of the liquid concrete mixture, for example, to prevent separation, as well as to increase the mobility of the concrete mixture [19]. Also, it is possible to reduce the amount of cement with the current mechanical and operational characteristics. Moreover, fibers more significantly affect the properties of hardened concrete, specifically the flexural and compression strength enhancement [20], freeze-thaw resistance [21], durability [22], abrasion resistance [23], crack resistance [24], etc.

The comparative analyses of the different kinds of fibers are shown in Table 1 where the main characteristics of some known kinds of fibers used for the disperse reinforcement of concrete structures are provided [25–30].

Table 1. Comparative properties of different materials for fiber production.

Characteristic	Basalt	Polypropylene	Glass	Steel	Carbon	Polyaramid
Material	Basalt	Polypropylene	E-Glass/ S-Glass	Steel	Carbon	Polyaramid
Tensile strength, MPa	3100–3500	150–600	1500–3500	600–1500	2000–7000	4500–5500
Modulus of elasticity, GPa	Not less than 75	16–35	51–88	190–210	200–800	140–180
Coefficient of elongation, %	3.1	20–150	4.5	3–4	2–3	2–3
Temperature resistance, ^{O}C	–260 + 700	–10 + 160	–60 + 350	–40 + 450	–260 + 2000	–260 + 400
Resistance to alkalis and to acid corrosion	High	High	Only S-Glass	Low	High	High
Density, g/cm^3	2.60	0.91	2.60	7.80	1.7–1.9	1.4–1.5

Table 1 shows that basalt fibers are in the top three in terms of basic technical characteristics. At the same time, from the economic point of view, they are several times cheaper. So low cost and high technical characteristics of basalt fibers provide increased interest in this material for manufacturers of high-performance concrete [31].

The distinctive properties of basalt fiber are high mechanical strength, chemical resistance [32], relative cheapness, as well as high-temperature resistance [33]. Basalt fibers are used in modern construction in reinforced concrete structures, hollow concrete [34], cement floor screed [35], industrial floors, small architectural forms [36], etc. Also, one of the upcoming sectors for the use of basalt fiber is 3D printing [37–39]. With mechanical characteristics comparable to carbon fiber, the cost of basalt fiber is lower several times, and sometimes tens of times.

Therefore, basalt fibers have been widely used in construction in Russia and there are a significant number of companies manufacturing basalt fibers. Moreover, there is an almost unlimited amount of raw materials for the production of basalt fibers, because they are produced from the melt of natural basalt stone. The final fibers are produced by chopping of basalt roving for segments of the necessary length.

This makes basalt fiber one of the most promising fibers on the market. In turn, the study of the use of basalt fiber in concrete is becoming a relevant research task.

Based on the above, the following research tasks have been set:

- selection of the most available mass-produced basalt fibers on the Russian market;
- manufacture and testing of concrete samples with different dosage of basalt fiber;
- analysis of experimental data and conclusions.

2. Methods

For this research, eight fibers presented on the Russian market were selected. Five of them are chopped basalt roving (LUKE, Rusbazalt Inc, Kamenny Vek Ltd, Armastek), one of them is chopped polymer-basalt wire (SK Ltd), two of them are basalt microfibers (NTC of Applied Nanotechnologies Inc. NTC of AN Inc).

Two types of basalt microfibers produced by NTC of Applied Nanotechnologies Inc have indicated in the following way: the actual row basalt microfibers have a MB index. And the modified basalt fibers which contain carbon toroidal nanoparticles “Astralene” deposited on the surface of each filament have a MBM index. In this case, short basalt fibers serve as carriers of carbon nanoparticles in concrete and are added to the concrete using the known method of "successive dilution". This method allows to distribute of the micro-quantity of any additives (in this case it is carbon nanoparticles) in a large volume (mass) of the substance uniformly.

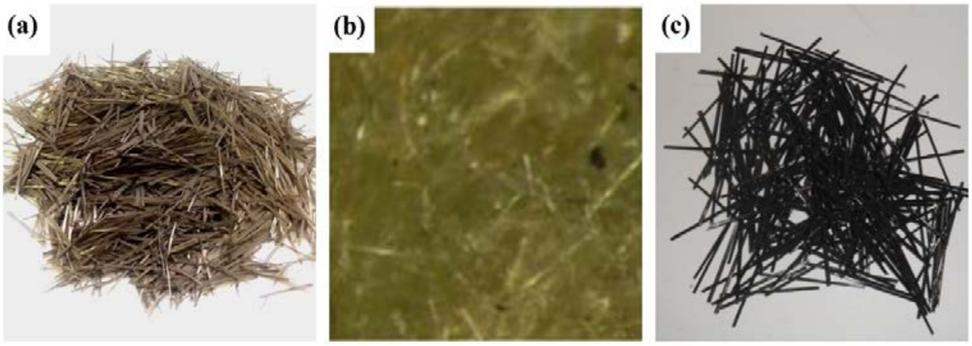

Figure 1. Basalt fibers produced by “Armplast” group (www.arm-plast.ru) – a; modified basalt microfiber produced by “NTC of Applied Nanotechnologies Inc.” (www. ntc-pn.ru) – b; basalt-polymer fiber produced by “SK Ltd.” – c.

Table 2 shows the properties of basalt fibers that have been declared by manufacturers in their certificates.

Table 2. Basalt fiber properties claimed by manufacturers.

Properties	LUKE	Rusbazalt Inc	Kamenny Vek Ltd	Armastek	SK Ltd	MB and MBM, NTC “AN Inc”
City and country of manufacture	Shandong, China	Chelyabinsk, Russia	Dubna, Russia	Perm, Russia	St. Petersburg, Russia	St. Petersburg, Russia
Density, (linear density)	2.8 kg/m^3	2.6 – 2.8 kg/m^3	2.8 kg/m^3	2.8 kg/m^3	1.9 kg/m^3	2.8 kg/m^3
Young's modulus of elasticity	93 – 110 GPa	~80 GPa	85 – 95 GPa	N/A	N/A	N/A
Tensile stress (force) at break	2800 – 3800 MPa	~3100 GPa	2700 – 3200 Mpa	N/A	N/A	N/A
Elongation at break	≤ 3.1%	2.0 – 4.5%	3.1%	3.1%	3.1%	3.1%
Operating temperature	–260+ 400 °C	–260+700 °C	–260+460 °C	–260+600°C	–70+600°C	–250+530 °C
Alkali resistance	≥ 75%	N/A	≥ 93	High	High	High
Diameter of a filament	5 – 26 µm	13 – 17 µm	23 – 25 µm	17 – 19 µm	80 150 µm	10 – 14 µm
Fiber length	6 mm	6 mm	6 mm	6 mm	6 mm	1 – 6 mm

Fine-grained concrete cubes with dimensions of 100×100×100 mm in a quantity of 3 pieces, and prisms of dimensions of 40×40×160 mm in a quantity of 3 pieces, were made from each batch according to Russian State Standard GOST 10180-2012.

The control samples were prepared according to the following fine-grained concrete recipe with the same water-cement ratio which was equal to 0.35:

1. Portland cement PP 500-D0-H produced by Oskolcement Inc…..29 %
2. Gabrodiabasic sand of fraction 0-5 mm ……………………………………….………………..…23.5 %
3. River washed sand according to Russian State Standard GOST 8736-2014……………….37.3 %

4. Water according to Russian State Standard GOST 23732-2011…………………………….…10.2 %

The concrete samples were prepared in moulds and removed from the moulds after 1-day curing at room temperature. All the samples (and also the control samples) have been hardened in thermo-humidity conditions for 28 days according to Russian State Standard GOST 10180-2012.

Fiber-reinforced fine-grained concrete cubes were made with a fiber dosage of 0.25 vol.-%, 0.5 vol.-%, and 1 vol.-%.

The density of fine-grained concrete was determined according to Russian State Standard GOST 10180-2012.

The compressive strength test of concrete cubes with dimensions of 100x100x100 mm and the flexural strength tests (by the method of 3-point bending) of concrete prisms with dimensions of 40×40×160 mm was carried out on the hydraulic laboratory testing machine WK-18 ZARZAD SPRZETU (Poland) according to Russian State Standard GOST 10180-2012.

3. Results and Discussion

During this research, experimental data have been obtained on the changes in density and strength of concrete depending on the fiber's dosage. Experimental data are presented in Tables 3, 4 and Fig. 2–5.

Table 3. Density of concrete with basalt fiber of various manufacturers with different fiber dosage.

Manufacturer of fibers	Density of fiber-reinforced concrete, kg/dm³			
	without fiber	0.25 %	0.5 %	1 %
LUKE Inc.	2.312	2.319	2.338	2.354
Rusbazalt Inc.		2.329	2.342	2.362
Kamenny Vek Ltd.		2.315	2.327	2.351
NTC of Applied Nanotechnologies Inc. (MB)		2.294	2.271	2.254
Armastek Inc.		2.322	2.341	2.349
NTC of Applied Nanotechnologies Inc. (MBM)		2.303	2.291	2.272
SK Ltd.		2.309	2.302	2.293
Armplast group		2.314	2.317	2.321

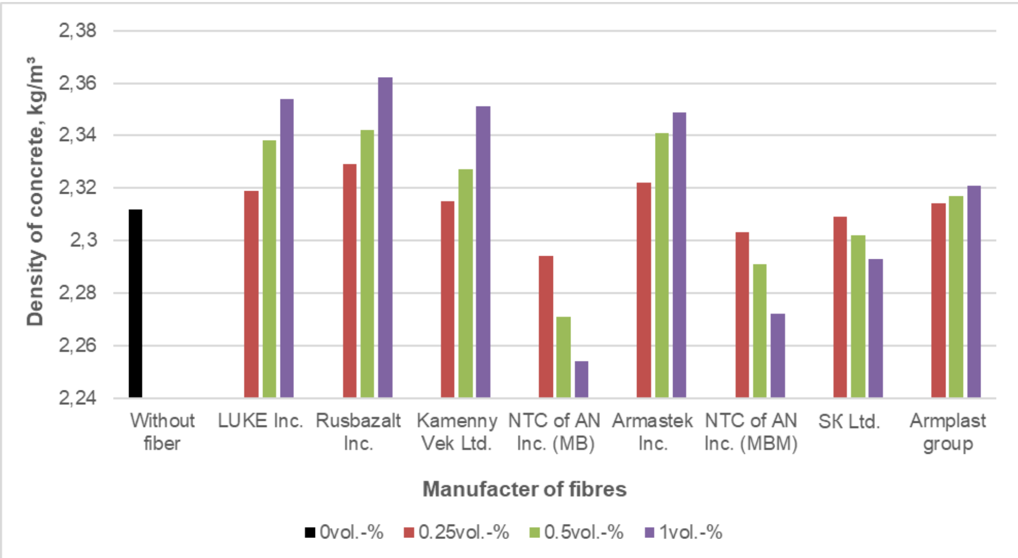

Figure 2. Density of fiber-reinforced concrete, Kg/dm³.

Table 3 and Fig. 2 show concrete density depending on fibers dosage. Fibers that are made from chopped basalt roving (manufactured by LUKE, Rusbazalt Inc, Kamenny Vek Ltd, Armastek) result in a proportional increase in density as the fiber content increases. On one hand, this is since the fibers improve the structure of concrete and reduce air entrainment. On the other hand, this because the density of the fibers (2.6 – 2.8 kg/dm³) is higher than the density of fine-grained concrete (2.3 kg/dm³), as confirmed by the results of other researchers [40].

The density of concrete with chopped polymer-basalt wire fiber (manufactured by SK Ltd) decreases proportionally as the amount of fiber increases. This is primarily due to the lower density of this fiber (1.9 kg/dm³) relative to the density of fine-grained concrete (2.3 kg/dm³).

The density of microfibers (manufactured by NTC of AN Inc.) reinforced concrete decreases proportionally with increasing fibers dosage. This is since microfibers involve additional air in the concrete. However, in the case of the modified basalt microfiber (MBM), the density reduction is slower, which is most likely because nanoparticles lead to the structuring of cement rock, which confirms the previously obtained results [41].

Table 4. Strength of basalt fiber-reinforced fine-grained concrete.

Manufacturer of fibers	Compressive strength of fiber-reinforced concrete after 28 days, MPa			Flexural strength of fiber-reinforced concrete after 28 days, MPa		
	0.25 vol.-%	0.5 vol.-%	1 vol.-%	0.25 vol.-%	0.5 vol.-%	1 vol.-%
Without fibers	51.7	51.7	51.7	5.1	5.1	5.1
LUKE Inc.	52.7	53.9	54.8	5.9	6.8	7.3
Rusbazalt Inc.	53.3	54.6	55.7	6.0	7.1	7.6
Kamenny Vek Ltd.	52.9	55.4	56.7	6.2	7.0	7.7
NTC of Applied Nanotechnologies Inc. (MB)	52.5	53.1	54.3	5.4	6.3	7.1
Armastek Inc.	52.9	53.8	54.9	5.9	6.7	7.5
NTC of Applied Nanotechnologies Inc. (MBM)	53.5	55.2	56.3	6.1	7.3	7.8
SK Ltd.	53.7	54.9	56.8	5.7	7.4	8.6
Armplast group	53.4	54.5	56.5	5.9	6.6	7.4

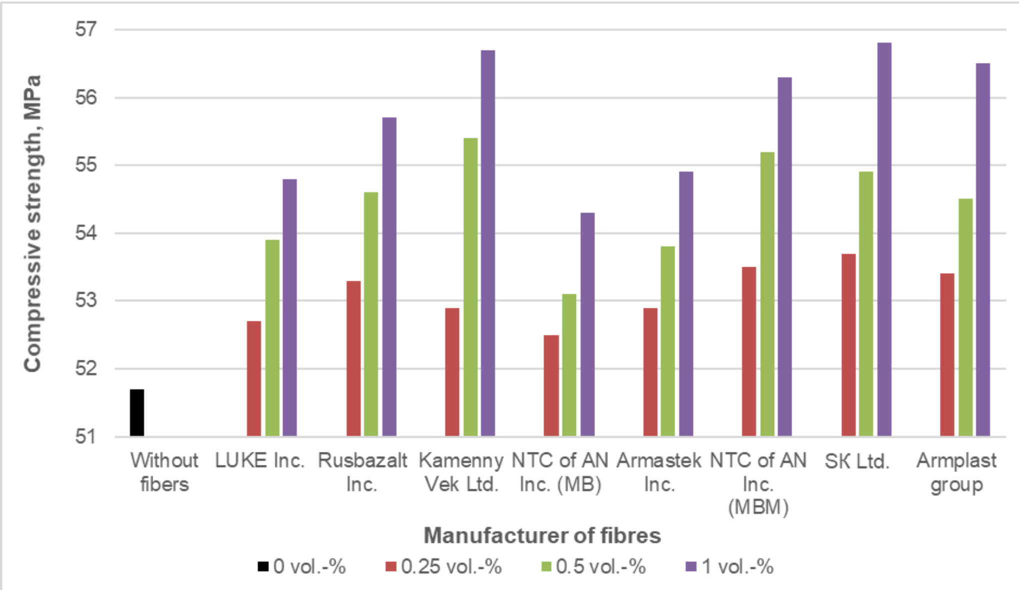

Figure 3. Compressive strength of concrete reinforced with basalt fibers of various manufacturers.

Table 4 and Fig. 3 show the effect of basalt fibers on fine-grained concrete properties. The compressive strength enhancement when using each of the fibers occurs proportionally to the increase in fibers dosage in concrete. Maximum strength enhancement was obtained for each type of fibers at the fiber dosage of 1 vol.-%.

The maximum compressive strength enhancement (9.8%) was achieved using fibers manufactured by SK Ltd (from 51.7 MPa to 56.8 MPa) and by Kamenny Vek Ltd (from 51.7 MPa to 56.7 MPa). It is worth to remark that the fibers manufactured by Kamenny Vek Ltd are chopped basalt roving, and the fibers manufactured by SK Ltd are cut polymer-basalt wire.

The minimum compressive strength enhancement (6%) from fibers from chopped basalt roving was achieved using fibers manufactured by Luke Ink (China). This is most likely due to a lower quality raw material for the production of this fibers compared to other fibers or due to the difference in production technology. Other fibers also made of chopped basalt roving gave the following compressive strength enhancement values: maximum strength enhancement using basalt fibers of Rusbasalt Inc was 7.7% (from 51.7 MPa to 55.7 MPa), maximum strength enhancement using basalt fibers of Armastek Inc was 6.2% (from 51.7 MPa to 54.9 MPa), maximum strength enhancement using basalt fibers of Armplast group was 9.3% (from 51.7 MPa to 56.5 MPa).

The compressive strength enhancement using basalt microfibers produced by NTC of AN Inc was 4.1% (from 51.7 MPa to 54.3 MPa), and using modified basalt fibers was 6.7% (from 51.7 MPa to 56.3 MPa) since carbon toroidal nanoparticles "Astralene" were used for medication of the basalt microfibers. It led to the structuring of the concrete matrix, as well as to an increase in adhesion between concrete and basalt microfibers. This can be seen in Fig. 5.

The obtained results are consistent with the results of other researchers. For example, these papers also note an increase in the compression strength of concrete using basalt fiber [33], [37]. In this paper [37], a 10% increase in the compressive strength of concrete was obtained using basalt fiber. In the paper [42], it was also obtained a compression strength increase of 8–11%. However, this was achieved using a dosage of 2-3 vol.-% of the fiber.

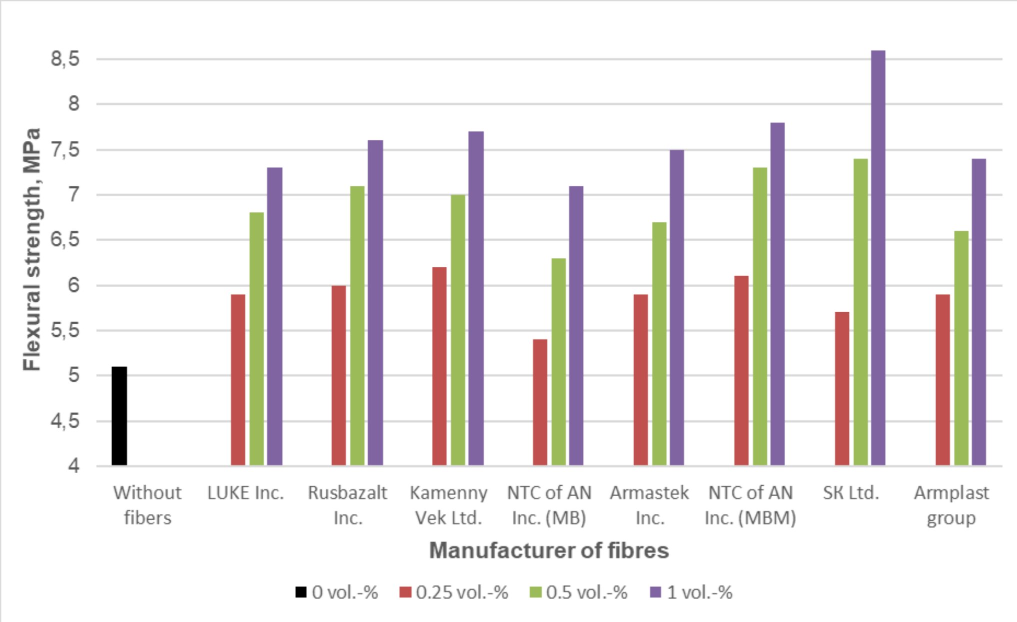

Figure 4. Flexural strength of concrete reinforced with basalt fiber of various manufacturers.

Table 3 and Fig. 4 show that all the used fibers result in a significant flexural strength enhancement. The highest flexural strength enhancement was achieved using fiber manufactured by SK Ltd (68.6%, from 5.1 MPa to 8.6 MPa), NTC of AN Inc (52.9%, from 5.1 MPa to 7.8 MPa) and Kamenny Vek Ltd (50.9%, from 5.1 MPa to 7.7 MPa).

The highest flexural strength enhancement of basalt fibers reinforced fine-grained concrete is due to the fact that the fibers produced by SK Ltd are a chopped polymer-basalt wire, which allows large agglomerates of basalt fibers to work together.

The other type of fiber also made of chopped basalt roving gave the following flexural strength enhancement values: maximum strength enhancement using basalt fibers from Rusbasalt Inc was 49% (from 5.1 MPa to 7.6 MPa), maximum strength enhancement using basalt fibers from Armastek Inc was 47.1% (from 5.1 MPa to 7.5 MPa), maximum strength enhancement using basalt fibers from Armplast group was 45.1% (from 5.1 MPa to 7.4 MPa).

The difference between the increase in strength of concrete reinforced with basalt microfibers (39.2%, from 5.1 MPa to 7.1 MPa) and modified basalt fibers is explained by the fact that carbon toroidal nanoparticles "Astralene" were used to modify the basalt microfibers (52.9%, from 5.1 MPa to 7.8 MPa). It led to the structuring of the concrete matrix and an increase in adhesion between concrete and basalt microfiber. This can be seen in Fig. 5.

The results obtained differ for the better from the results obtained in the paper [42] where an increase in strength of 2–26% was obtained depending on the dosage of the fiber. However, the results obtained are quite well consistent with the results obtained in this paper [43]. Here, the increase in flexural strength was also about 30–40 %. It has also been found that the use of 6 mm long fiber results in a superior increase in concrete strength than 12 mm long fiber.

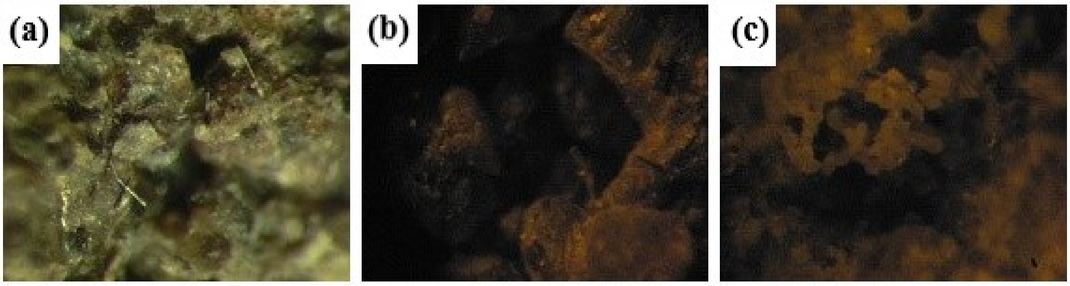

Figure 5. Structure of the fiber-reinforced concrete with MFM at the maturity period of: (a) – 1 day; (b) – 28 days; (c) – 6 months.

In Fig. 5 one can see the elongated outgrowths on the surface of basalt fibers, which were formed during the maturation of concrete. During the maturing process, the elongated outgrowths formed on the surface of basalt fibers are transformed into "druses" from the dicalcium silicate, and they increase thereby the effect of dispersed reinforcement. This is an unexpected and important effect of using nanoparticles “Astralene” for obtaining a new type of nano-modified high-strength concrete.

4. Conclusions

1. Each of the used fibers showed a significant compression and flexural strength enhancement of fine-grained concrete.

2. The maximum compressive strength enhancement (9.8%) was achieved using fibers manufactured by SK Ltd and Kamenny Vek Ltd. It is worth remarking that fibers manufactured by Kamenny Vek Ltd are chopped basalt roving, and fibers manufactured by SK Ltd are a cut polymer-basalt wire. When dispersing basalt fiber is used, the maximum strength values are slightly lower. This increase in strength was about 7%.

3. The highest flexural strength enhancement was achieved using fibers manufactured by SK Ltd (68.6%), NTC of AN Inc (52.9%) and Kamenny Vek Ltd (50.9%). The highest flexural strength enhancement fine-grained concrete reinforced with basalt fibers was due to the fact that fibers produced by SK Ltd are a cut polymer-basalt wire, which allows large agglomerates of basalt fibers to work together.

4. Basalt fiber improves the structure of concrete and reduces its porosity, which is one of the reasons for the strength and operational properties enhancement of concrete.

5. Basalt microfiber manufactured by NTC of Applied Nanotechnologies Inc modified with carbon toroidal nanoparticles "Astralene" leads to an additional strength enhancement compared to basalt microfiber without modification due to the additional reinforcement with elongated outgrows that appeared in the concrete during its maturation.

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Contacts:

Aleksandr Rassokhin, rassokhinaleksandr@gmail.com
Andrey Ponomarev, 9293522@gmail.com
Svetlana Shambina, shambina_sl@mail.ru
Antonina Karlina, karlinat@mail.ru