Mechanical properties and durability of basalt fiber-reinforced fine-grained concrete

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Abstract. The creation of modern high-efficiency building materials and products, to which the demands are constantly increasing, can be successfully implemented using technologies using composite materials. Particularly promising are dispersed reinforced concrete, in which a strong matrix and reinforcing fibers are successfully combined. The matrix provides high compressive strength, bending strength, and durability, while dispersed fibers are characterized by significant tensile strength, high elastic modulus, and the ability to distribute loads throughout the entire volume. Such a combination increases crack resistance, improves the operational properties and durability of structures, and opens up new possibilities for use in modern engineering structures and industrial construction.

Keywords: concrete, basalt fiber, strength, stability, corrosion, elasticity modulus, fine-grained concrete, alkali resistance and acid resistance.

1. Introduction

Studying the initial characteristics of different types of fibers will allow for the selection of the most effective component for dispersion reinforcement of fine-grained cement concretes from the point of view of the ratio of the achieved strength characteristics and the low cost of the designed structural material.

An analysis of the technical and performance characteristics of the primary types of fibers currently employed in the construction industry was conducted for the purpose of dispersed reinforcement of cement concrete (see Table 1) [1-3]. This assessment allowed for the ranking of available reinforcing fibers according to their efficiency in producing fine-grained, dispersed-reinforced concretes with specific, predetermined properties. By evaluating their mechanical behavior and compatibility with the cement matrix, it became possible to identify which fibers are most suitable for achieving enhanced strength, durability, and overall performance in reinforced concrete applications.

Based on the information presented in the table, basalt fiber outperforms many other types of fibers in a variety of key properties. In particular, it exhibits higher tensile strength than steel, which makes it an excellent option for reinforcing concrete structures. At the same time, basalt fiber has a lower relative elongation at break compared to steel, indicating that it stretches less before failure. Beyond its mechanical characteristics, basalt fiber shows strong chemical affinity with cement, ensuring better adhesion to the concrete matrix. This combination of high strength, chemical compatibility, and moderate flexibility enables basalt fiber to effectively minimize the formation and propagation of microcracks in concrete under stress, thereby improving the overall durability and longevity of reinforced concrete elements.

Analysis of the fiber characteristics given in Table 1 allows us to conclude about the prospects of using basalt fiber as an armoring component in the design of building composites.

Table 1. Properties of various types of fibers

Fiber type	Density, kg/m^3	Strength at stretching, MPa	Elasticity modulus, MPa
Polypropylene	900	400-800	3500-8000
Polyethylene	950	700	1400-4200
Nylon	1100	770-900	4000
Acrylic	1200	210-420	2100
Polyester	1400	730-780	8400
Whole-headed	1200	300-500	10000
Asbestos	2600	1200-3100	160000
Glass	2600	1050-3850	7000-8000
Steel	7800	600-3150	200000
Carbonaceous	2000	2000	245000
Carbonic	1630	7800	380000
Polyamide	900	720	1900
Viscose	1200	660	5600
Basalt	2700	1600-3600	7000-11000

Thus, according to the set of variable criteria, basalt fiber was chosen as a disperse-army component.

To justify the choice of the most effective basalt fiber for reinforcing the cement matrix, taking into account the wide geographical scope of its application in the construction industry, as well as the constantly increasing construction volumes in the territory of the Republic of Uzbekistan, an analysis of the basalt fiber of leading world manufacturers, whose annual production volume exceeds 1000 tons, was carried out.

Taking into account the set of initial characteristics, a comprehensive analysis of the raw material composition, the ratio of the geometric parameters of the fiber (length and diameter), as well as the applied technologies for its production, was carried out in order to more reasonably select basalt fiber.

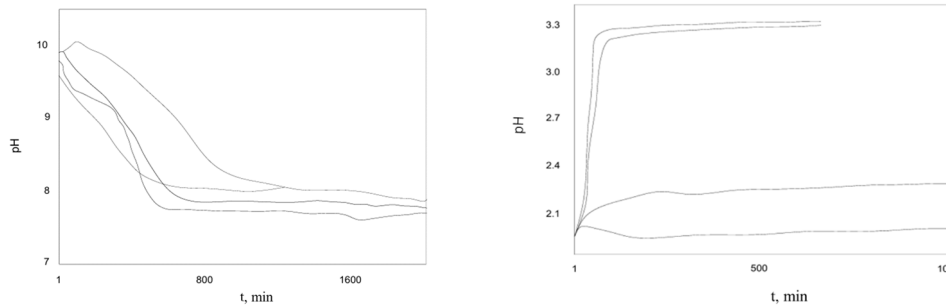
Table 2. Overview of basalt fiber properties from multiple manufacturers

Company	Technology	Raw materials	Diameter, μm
"Qoraqalpoq Basaltwool LLC" LLC	centrifugal dispersion	silica-containing basalt (Si02 – 49 %)	3-5
"DXO BAZALT" LLC Navoi	blowing the melt with a swirling stream of air	pyroxene porphyrite	1-3
"Basalt Uzbekistan" LLC Karakalpak	duplex process	Basalt (Si02 – 52 %)	1-3
"Basalt Uzbekistan" LLC Jizzakh	blowing the melt with a swirling stream of air	basalt (Si02 – 53 %)	3-12

The chemical nature of a fiber is a key initial factor. Fibers that are largely silicate achieve stronger adhesion to cement, thanks to the alkaline conditions in the concrete matrix [4], [5].

The elemental composition of basalt fiber (Table 3) of various producers is characterized by insignificant variations in the concentrations of petrogenic elements. An exception is the increased content of magnesium and iron in the products of "Basalt Uzbekistan" LLC in Jizzakh and "Basalt Uzbekistan" LLC in Karakalpakstan. This may be a consequence of the increased content of olivine in the initial basalt raw material.

Despite the abundance of literature data [6], the question of the stability of basalt fiber in an aggressive environment still remains open. We studied the fibers of four manufacturers for acid and alkali resistance (Fig. 1).



a) b)

Fig. 1. Change in the pH of the solution depending on the type of fiber during testing for a) alkali resistance and b) acid resistance: Fiber No. 1 – LLC "Qoraqalpoq Basaltwool", No. 2 – LLC "DXO BAZALT" Navoi, No. 3 – LLC "Basalt Uzbekistan" Karakalpak, No. 4 – LLC "Basalt Uzbekistan" Jizzakh

Table 3. Elemental composition of basalt fiber

Component	LLC "Qoraqalpoq Basaltwool LLC"	LLC "DXO BAZALT" Navoi	"Basalt Uzbekistan" LLC Karakalpak	LLC "Basalt Uzbekistan" Jizzakh
	Fiber No. 1	Fiber No. 2	Fiber No. 3	Fiber No. 4
Sodium (Na)	1.81	3.3	2.3	1.62
Magnesium (Mg)	3.07	1.8	1.8	2.62
Aluminum (Al)	5.21	6.4	6.9	5.39
Silicon (Si)	19.43	18.4	19.2	18.03
Phosphorus (P)	0	0.2	0.2	0.23
Potassium (K)	0.33	0.5	0.5	0.59
Calcium (Ca)	3.1	3.2	2.9	3.21
Titanium (Ti)	0.69	0.5	0.5	0.39
Marganese (Mn)	0	0.1	0.1	0
Iron (Fe)	3.64	4.2	3.5	7.05
Oxygen (O)	62.19	18.4	19.2	17.03
Sulfur (S)	0.46	0	0	0.02

2. Research methods and results

The most probable explanation for the obtained data may be the following. The chemical phenomena underlying the action of silica on the fiber consist in the transformation of silica into stable anions that do not polymerize in an alkaline medium: Si04 4~, Si205 2~, Si032~, and cations located in the vitreous phase form compounds of the zincate and aluminate type. If the solution is not renewed and the accumulation of decomposition products occurs, then the decomposition process slows down [7].

It is known that the process of basalt fiber destruction is influenced not only by the interaction of hydroxyl ions with silicon-oxygen groups, but also by the ability of the cation of the alkaline solution to exchange ions with the cations of metals that are part of the basalt fiber. When the alkali solution is in contact with basalt fiber, viscosity of the vitreous phase occurs first and only then destruction occurs. The rate of fiber breakdown is determined by the rate of transition of Na ions (modifier ion) into the solution [8].

The action of alkaline solutions begins with the adsorption of Na and OFT ions by the surface of the basalt fiber. As a result, an unstable compound is formed, which is broken down by the bonds ↓Si-O-SiO with the formation of the groups ↓Si-ONa and ↓Si-OH. After the destruction of a sufficiently large amount of Si-O-Si bond, the transition of the destroyed silicates to the solution begins. In the process of interaction of basalt fiber with alkaline solution, several stages are conventionally distinguished [9], [10]. First, adsorption occurs on the sheeloid surface of the basalt fiber. Then a so-called alkali attack takes place, which begins at surface defects and then spreads

throughout the entire surface [11]: ≡Si-O-Si≡ + OH-> ≡Si-OH + ≡Si-C$^-$.

In the final stage, the reaction products are removed from the surface of the fiber without forming a protective film. The chemical composition of the raw material used to produce basalt fibers plays a key role in determining their resistance to harsh environments. Specifically, incorporating structure-stabilizing oxides-such as zirconium, aluminum, iron, and tin-enhances the fiber's strength by increasing its compactness. The technology and method of production also have a significant impact on fiber durability. All this in combination can determine possible submicronous heterogeneities associated with different Fe2+/Fe3+ content in the fiber. Figure 2 shows the Fe3+ content in the fibers obtained by the Mössbauer spectroscopy method.

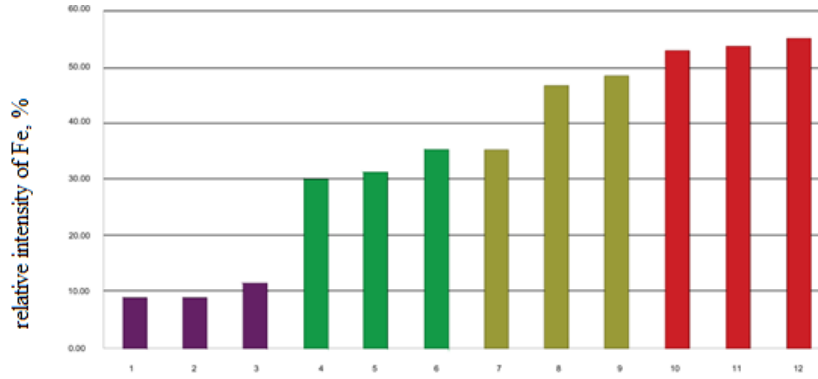


Fig. 2. Fe content in basalt fibers: 1-3 – LLC "Qoraqalpoq Basaltwool", LLC "DXO BAZALT"; 4-6 – LLC "Basalt Uzbekistan" Karakalpak; 7-9, 10-12 – LLC "Basalt Uzbekistan" Jizzakh

In Fig. 2, the horizontal axis represents the sample numbers (1-12) corresponding to different production batches of the four manufacturers, while the vertical axis shows the relative content of iron ions in different oxidation states.

According to a number of researchers [12-15], differences in the Fe^{2+} and Fe^{3+} concentrations in fibers promote the development of submicron heterogeneities, which are linked to iron atoms not incorporated into the silicon-oxygen framework. This structural feature decreases the oxidation resistance of the fibers and increases the likelihood of crystallization at elevated temperatures.

As previously mentioned, the geometric properties of fibers play a significant role in the design of dispersed reinforced materials. Literature sources indicate that achieving an optimal plastic-aggregate condition of the dispersed mixing component requires selecting initial materials with a length-to-diameter ratio exceeding 10 [13]. The analysis of the geometric characteristics of basalt fibers manufactured by LLC "Basalt Uzbekistan Jizzakh" confirms that these fibers possess the required proportions. Cement slurry with a high alkalinity (pH = 12.9) was employed as an aggressive environment. Pre-expanded basalt fibers were introduced into this solution (Fig. 3). The fiber content was determined considering the maximum permissible amount of basalt fiber in cement mixes, reported in the literature to range from 3 % to 12 % of the binder mass. In this study, a fiber content of 7 % was used.

The samples were stored at room temperature for 7, 14, 28, and 72 days. After the designated exposure periods, fibers were washed with a 0.1 % dilute hydrochloric acid solution using filter paper to remove cement matrix residues. To eliminate any remaining impurities, the samples were further rinsed with 1 liter of distilled water. The basalt fibers retained on the filter paper were then dried at room temperature until a constant weight was achieved.

Fiber solubility was evaluated by comparing the mass of the initial sample with the dry residue after exposure to the alkaline medium. Weight loss was expressed as a percentage (Table 4). Potential fiber losses during washing (termed technological losses) were assumed to be uniform across all experiments.

During observations on the 7th day, a slight formation of white precipitate was recorded on the surface of the basalt fiber, which is presumed to be related to the crystallization of calcium oxide (CaO) on the compacted surface of the fiber. In the interval from 14 to 28 and 62 days, due to the thinning of the smallest villi, the gradual destruction of the aggregated fiber clot occurred, accompanied by the slow deposition of finely dispersed fragments, the proportion of which reached about 20 % of the total mass.

Table 4. Results of the study on the alkali resistance of basalt fiber

No.	Test time, days	Initial mass, g	pH starting	Weight after holding, g	Weight loss, %	pH after holding	Color
1	7	4.67	11.9	4.17	12.4	11.9	Norm
2	14	4.95	11.9	3.45	24.2	11.5	Norm
3	28	5.01	11.9	3.31	29.9	11.5	Slightly lit
4	72	4.85	11.9	2.01	56.8	11.3	Slightly lit

By the 28th day, the amount of white precipitate increased significantly and spread mainly to larger fibers. During visual examination of the samples on the 72nd day, a change in the color of the fiber surface was observed: from a weakly lightened color in fine villi to a grayish tint in more massive elements.

In addition, to assess the long-term durability of basalt fiber under real environmental impacts, tests were also conducted under cyclic loading and freeze-thaw conditions. The frost resistance tests were carried out in accordance with GOST 10060-2012 (Basic method). These experiments showed that basalt fibers retain more than 80 % of their initial strength after 100 freeze-thaw cycles, indicating high resistance to microcrack propagation and structural degradation. The results confirm that basalt fiber maintains its reinforcing ability even after repeated temperature fluctuations and mechanical stresses [14], which is critical for its application in regions with continental and sharply variable climates.

3. Conclusions

Microstructure and mechanical properties: Basalt fiber is characterized by high tensile strength (1600-3600 MPa) and high elastic modulus (7000-11000 MPa). Although the relative elongation of the fibers is low, due to their chemical compatibility, they adhere well to the cement matrix and effectively prevent microcracks.

Chemical stability: fibers from various manufacturers were tested in a hydroxide and acidic environment. The results of storage from 7 to 72 days showed that the mass of the fibers decreases to a maximum of 50 %, but this process is slow and the fibers retain their mechanical properties. The silicate composition of the fibers and the $Fe^{2}+/Fe^{3}+$ ratio were noted as the main factors determining their stability.

Climate and mechanical resistance: Test results in cyclic loading and freezing-melting cycles showed that basalt fibers retain more than 80 % of their initial strength. This confirms their high resistance to the development of microcracks and structural degradation.

Optimal concentration and geometry: In the study, the maximum fiber content in the concrete composite was 3-12 %, and the best results were observed at a concentration of 7 %. A fiber length-diameter ratio of more than 10 ensures optimal mixing with the plastic and aggregate.

Practical conclusions: Basalt fiber can be used as a component of highly effective dispersed reinforcement due to its high mechanical strength, chemical stability, and good integration with cement. This ensures the long-term durability of concrete structures, especially in regions with a continental climate and frequent temperature fluctuations.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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