The Need to Improve the Physico-Engineering Properties and Durability of Building Materials

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Abstract. The paper is devoted to the need to improve the physical and engineering properties and durability of building materials used in construction, reconstruction, and repair.

1. Introduction

Strengthening requirements for the safety of buildings and structures has led to the need to improve the physical and engineering properties and durability of building materials used in construction, reconstruction, and repair.

New designs of architectural forms, shells, thin-shell panels with complex relief, tanks; coatings of flight strips of airfields, roads, flooring of industrial buildings; pipes in road culverts, collectors, tunnels, and bridges require increased tensile and bending strength, crack resistance, impact strength, durability, frost, water, and wear resistance, and low contraction.

2. Main part

To improve the above listed concrete properties, various techniques are used, one of which is dispersed concrete reinforcement with steel, glass, basalt, cellulose, synthetic, carbon, and other fibers. When introducing fibers into concrete, its strength increases, therefore, according to GOST 24211-2008, dispersed concrete reinforcement with fiber can be classified as an additive increasing the concrete strength. Concrete reinforced with dispersed fibers is called fiber-reinforced concrete.

Obvious advantages of fiber-reinforced concrete are the multifold increase in strength, crack and wear resistance, etc.

Dispersed reinforcement of fine-grained concrete allows improving a number of its properties, i.e. crack, wear, and frost resistance, as well as the strength characteristics and durability.

The study objective is to determine the dispersed reinforcement contents and types optimal for fine-grained fiber-reinforced concrete.

The below tasks have been set:
- studying literature sources to get acquainted with the techniques for the research of the dispersed micro-reinforcement fiber size effect on the compressive and bending strength,
- determining the specifications of raw materials and their compliance with the requirements of regulatory documents,
- determining the recommended optimal contents (ensuring the maximum effect) of dispersed reinforcement fiber in fine-grained concrete,
- performing experiments to study the effect of the dispersed micro-reinforcement fiber geometry on the strength properties of fine-grained concrete, i.e. the compressive and bending strength.
- comparing the effect of basalt, steel, and polypropylene fibers on the strength properties of fine-grained concrete.

The specifications of raw materials obtained empirically in the laboratory fully meet the requirements of regulatory documents and are suitable for testing to evaluate the efficiency of additives according to GOST 30459. These raw materials can be used as components of fine-grained fiber-reinforced concrete.

List of designations and abbreviations
B – basalt,
P – polypropylene,
S – steel,
\( R_{\text{comp}} \) – compressive strength,
\( R_{\text{bend}} \) – bending strength,
\( \Delta R_{28} \) – increase in the strength of the basic compositions relative to the reference ones.

With an increase in the fiber content, the bending strength increases by an average of 10%.

3. Studying the issue of effect of various fibers on the fiber-reinforced concrete properties

3.1. Dispersed reinforcement of concrete with fiber
Meanwhile, certain disagreements have emerged on a number of issues concerning dispersed concrete reinforcement. Thus, some researchers of steel fiber-reinforced concrete consider fiber the diameter of which does not exceed 0.7 mm to be the most effective one, while others prefer to use larger steel fibers. There is no consensus in evaluating the dispersed reinforcement effect on the concrete compressive and axial tensile strength. Experts also disagree on the prospects for the use of low-modulus fibers, including the polymer ones, in heavy concrete. At the same time, the complex structure of concrete reinforced with dispersed fiber makes it difficult to generalize and develop analytical techniques for their calculation. Despite the importance of certain theoretical approaches for studying the cement composite properties, most researchers report the absence of a fiber-reinforced concrete strength theory suitable for practical use and still apply the mixture rule in the qualitative evaluation of this indicator, according to which:

\[
R = \phi \tau \frac{1}{d} \mu + (1 - \mu) R_c \tag{1}
\]

where \( R \) is the fiber-reinforced concrete strength,
\( \tau \) is the adhesion of the reinforcing fibers to the cement stone,
\( d \) and \( l \) are the diameter and length of the fibers, respectively,
\( \mu \) is the 3D reinforcement factor,
\( R_c \) is the initial concrete strength,
\( \phi \) is the complex coefficient considering the effect of ‘fiber-fiber’ interaction, fiber orientation, and the probability of their crossing the assumed plane, as well as the homogeneity and the fiber defectiveness degree.

4. Raw material specifications
In this section, research methods and the specifications of the source raw material are given. For research, we used washed quartz sand, cement CEM I 42.5 N, and polypropylene, basalt, and steel fibers.

4.1. Research techniques
When studying raw materials, the below test techniques were used:
- measuring the content of dusty, clay, and silt particles by elutriation according to GOST 8735-88,
- determining the grain composition and fineness modulus according to GOST 8735-88,
- measuring the average sand grain density using the beaker technique,
- determining the bulk density according to GOST 8735-88,
- determining the cement grinding fineness according to GOST 310.2-76,
- determining the cement mortar standard concentration, setting time, and consistency according to GOST 310.3-76.

The fiber concrete reference specimens were tested for strength according to GOST 310.4-81. GOST 310.4-81 was used since we decided to study the effect of the dispersed micro-reinforcement fiber size and type not on fiber-reinforced concrete but fine-grained one.

Since fibers are additives increasing strength, their efficiency is evaluated according to GOST 30459-2008 by the formula:

$$\Delta R_{28} = \frac{R_{\text{base}} - R_{\text{ref}}}{R_{\text{base}}}$$

The bending strength was calculated as the arithmetic mean of the two largest test results for three specimens by the formula:

$$R_{\text{bend}} = \frac{3P_l}{2bh^2}$$

Compressive strength was calculated as the arithmetic mean of the four largest test results for six specimens by the formula:

$$R_{\text{comp}} = \frac{P}{S}$$

When molding specimens with fiber, the technique described in GOST 310.4-81 was applied, but while mixing sand with cement, fiber was gradually added to the dry building mix. Also, when adding water, the mortar stirring time was increased by 20-30 % to ensure uniform distribution of the fiber throughout the mortar volume.

The fiber-based mixture was prepared as follows: first, the dry components - sand, cement, and fiber were mixed, then mixing water was added, and finally, the mixture was stirred until ready. The recommended stirring duration is regulated according to GOST 7473-2010.

### 4.2. Cement CEM I 42.5 N specifications

The specifications of the cement produced by Sukholozshcement JSC are given in Table 1.

| Indicator | Specimen | GOST Requirements |
|-----------|----------|-------------------|
| Natural bulk density, kg/m$^3$ | 1.455 | NA |
| Average density, kg/m$^3$ | 2.570 | NA |
| Grain size: | | |
| – content of grains ≥ 10 mm, % | 0.29 | 0.5 - 5 |
| – content of grains ≥ 5 mm, % | 1.55 | 5 - 10 |

### 4.3. Natural sand specifications

In the study, the Garde I sand was used. By the fineness modulus, it is medium sand. In all respects, it complies with GOST 8736-2014. The specifications of natural sand produced by ISM-Invest OJSC are given in Table 2.

| Indicator | Specimen | GOST Requirements |
|-----------|----------|-------------------|
| Natural bulk density, kg/m$^3$ | 1.455 | NA |
| Average density, kg/m$^3$ | 2.570 | NA |
| Grain size: | | |
| – content of grains ≥ 10 mm, % | 0.29 | 0.5 - 5 |
| – content of grains ≥ 5 mm, % | 1.55 | 5 - 10 |
content of grains ≤ 0.16 mm, %

| Grain Size | Content (%) |
|------------|-------------|
| 2.5        | 5.89        |
| 1.25       | 13.95       |
| 0.63       | 39.46       |
| 0.315      | 66.74       |
| 0.16       | 90.50       |

Finesness modulus (Mf) 2.18

Content of dust and clay particles, % (elutriation)

| Group | Content (%) |
|-------|-------------|
| I     | 1.4         |
| II    | 2.0 - 2.5   |

group I no more than 3

4.4. Fiber specifications

The polypropylene, basalt, and steel fiber specifications are given in Table 3.

Table 3. Fiber Specifications.

| Property                         | Fiber type     | Material       | Average density, kg/m³ | Fiber length, mm | Fiber diameter, μm |
|----------------------------------|----------------|----------------|------------------------|------------------|-------------------|
|                                  | Polypropylene  | Basalt         |                        |                  |                   |
| material                         | High thermoplastic polymer | modified Basalt | 910                    | 6 & 12           | 20                |
| modulus                          |                 |                |                        |                  |                   |
| mobility                         |                 | Carbon steel   | 2,800                  | 6 & 12           | 17                |
| content                          |                 |                | 7,800                  |                  | 500               |
| F/C ratio                        |                 |                |                        |                  |                   |
| mobility                         |                 |                |                        |                  |                   |

4.5. Conclusions

The specifications of raw materials obtained empirically in the laboratory fully meet the requirements of regulatory documents and are suitable for testing to evaluate the efficiency of additives according to GOST 30459. These raw materials can be used as components of fine-grained fiber-reinforced concrete.

5. Studying the effect of the dispersed reinforcement parameters on the fine-grained concrete properties

The experimental studying the effect of the dispersed reinforcement fiber size, content, and type on the fine-grained concrete properties involved molding specimens with different fiber percentages but the same water-to-cement ratio; the concrete mobility was also recorded. As a reference, we took a composite of fine-grained concrete without fiber added (500 g cement, 1,500 g sand, 350 ml water) and compared the strength properties Rcomp and Rbend of fine-grained concrete with the basalt, polypropylene, and steel fibers added, as well as the fiber introduction efficiency with this reference specimen.

5.1. The effect of the amount of fiber added on the fine-grained fiber-reinforced concrete mobility

The effect of the amount of fiber added on the fine-grained fiber-reinforced concrete mobility is shown in Table 4.

Table 4. Fine-Grained Fiber-Reinforced Concrete Mobility.

| Composition No. | Fiber content | F/C ratio | Mobility, cm |
|-----------------|---------------|-----------|--------------|
|                 | % vol.        | kg/m³     |              |
|                 |               |           |              |
1   2   3   4   5
0-0  0   0   9.0
   0.2  1.82  8.4
   0.4  3.64  7.7
P 6  0.6  5.46  7.3
   0.8  7.28  6.8
   1.0  9.10  0.7  6.4
   0.2  1.82  8.6
   0.4  3.64  7.4
P 12 0.6  5.46  6.0
   0.8  7.28  5.7
   1.0  9.10  5.3
   0.2  5.6   8.0
   0.4  11.2  7.7
B 6  0.6  16.8  7.4
   0.8  22.4  7.0
   1.0  28.0  6.7
   0.2  5.6   8.4
   0.4  11.2  7.6
B 12 0.6  16.8  0.7  7.1
   0.8  22.4  6.5
   1.0  28.0  6.0
   0.2  15.6  8.5
   0.4  31.2  8.7
S 14 0.6  46.8  8.4
   0.8  62.4  8.6
   1.0  78.0  8.8

Note - P 6, P 12, B 6, B 12, S 14, are compositions of fine-grained concrete with fiber: the letter and the figure specify the fiber type and length, respectively.

5.2. Dependence of the slump on the fiber content and type
According to the concrete mix mobility study results, it can be concluded that the mobility of concrete mix based on basalt and polypropylene fibers decreases by 2-3 cm with an increase in the fiber content.

The tests were performed on a modern Instron 5900 press. The dependence of the slump on the amount and type of fiber added is shown in Figs. 3.1 & 3.2.

After the preparation, the specimens have been kept for 24 hours in a bath with a water seal or in a cabinet. Thereupon, the specimens have carefully been demolded, placed in baths with water, and left to gain strength.

After the expiration of the hardening period, in our case it was 28 days, we first tested the specimens for bending, and then the specimen halves for compression using the press. The bending and compressive strengths were determined by the formulas (2.2) & (2.3), respectively.
Figure 1. Dependence of the Slump on the Fiber Content and Type.

The results of testing 28-day age specimens with polypropylene, basalt, and steel fibers for bending are given in Table 5.

Figure 2. Dependence of the Slump on the Fiber Content and Type.
### 5.3 Experimental bending strength data obtained at the age of 28 days

**Table 5.** Experimental Bending Strength Data Obtained at the Age of 28 Days.

| Fiber length and type, mm | Fiber content, % | R<sub>bend</sub>, MPa | ΔR<sub>28</sub>, % |
|--------------------------|-----------------|---------------------|------------------|
| 0-0                      | 2               | 7.24                | 4                |
|                          | 0               | 7.16                | -1.10            |
|                          | 0.2             | 7.26                | 0.27             |
| P – 6                    | 0.6             | 7.49                | 4.45             |
|                          | 0.8             | 7.67                | 5.94             |
|                          | 1.0             | 7.85                | 8.43             |
|                          | 0.2             | 7.25                | 0.14             |
|                          | 0.4             | 7.37                | 1.79             |
| P – 12                   | 0.6             | 7.58                | 4.70             |
|                          | 0.8             | 7.79                | 7.60             |
|                          | 1.0             | 7.99                | 10.36            |
|                          | 0.2             | 7.4                 | 2.21             |
|                          | 0.4             | 7.62                | 5.25             |
| B – 6                    | 0.6             | 7.77                | 7.32             |
|                          | 0.8             | 7.92                | 9.39             |
|                          | 1.0             | 8.06                | 11.33            |
|                          | 0.2             | 7.51                | 3.73             |
|                          | 0.4             | 7.68                | 6.08             |
| B – 12                   | 0.6             | 7.80                | 7.73             |
|                          | 0.8             | 7.98                | 10.22            |
|                          | 1.0             | 8.23                | 13.67            |
|                          | 0.2             | 7.15                | -1.24            |
|                          | 0.4             | 7.57                | 4.56             |
| S – 14                   | 0.6             | 7.90                | 9.12             |
|                          | 0.8             | 8.55                | 18.09            |
|                          | 1.0             | 9.01                | 24.45            |

According to the study results, the introduction of fibers into fine-grained concrete allows obtaining higher bending strength values; on average, the strength increases by 5-15% relative to the reference composition.

The dependencies of R<sub>bend</sub> on the fiber content and type are shown in Figs. 4.3 & 4.4, and the fiber effect efficiency is given in Fig. 3.5.
Figure 3. Dependence of $R_{\text{bend}}$ on the Fiber Content and Type.

Figure 4. Dependence of $R_{\text{bend}}$ on the Fiber Content and Type.
5.4 Evaluating the fiber introduction efficiency depending on the fiber content and type

![Graph demonstrating fiber introduction efficiency](image)

**Figure 5.** Evaluating the Fiber Introduction Efficiency Depending on the Fiber Content and Type.

The results of testing specimens with polypropylene, basalt, and steel fibers for compression at the age of 28 days are given in Table 6.

**Table 6.** Experimental Compressive Strength Data Obtained at the Age of 28 Days.

| Fiber length and type, mm | Fiber content, % vol. | R_{comp}, MPa | ΔR_{28}, % |
|--------------------------|-----------------------|---------------|------------|
| 1                        | 2                     | 35.31         | 0          |
| Without fiber            | 0.2                   | 33.45         | -5.27      |
|                          | 0.4                   | 33.92         | -3.94      |
| P – 6                    | 0.6                   | 34.79         | -1.47      |
|                          | 0.8                   | 35.35         | 0.11       |
|                          | 1.0                   | 35.16         | -0.42      |
|                          | 0.2                   | 34.16         | -3.26      |
|                          | 0.4                   | 34.65         | -1.87      |
| P – 12                   | 0.6                   | 35.29         | -0.06      |
|                          | 0.8                   | 35.53         | 0.62       |
|                          | 1.0                   | 35.23         | -0.23      |
|                          | 0.2                   | 34.68         | -1.78      |
|                          | 0.4                   | 35.55         | 0.68       |
| B – 6                    | 0.6                   | 35.52         | 0.59       |
|                          | 0.8                   | 34.90         | -1.16      |
|                          | 1.0                   | 34.51         | -2.27      |
|                          | 0.2                   | 35.19         | -0.34      |
| B – 12                   | 0.4                   | 35.95         | 1.81       |
According to the results obtained, the introduction of polypropylene and basalt fiber is advisable to a limited extent, and an increase in the steel fiber content allows achieving an increase in compressive strength by more than 3 MPa.

The dependencies of $R_{\text{comp}}$ on the fiber content and type are shown in Figs. 3.6 & 3.7, and the fiber effect efficiency is given in Figure 3.8.

![Figure 6](image-url)

**Figure 6.** Dependence of $R_{\text{comp}}$ on the Fiber Content and Type.
Figure 7. Dependence of $R_{\text{comp}}$ on the Fiber Content and Type.

Figure 8. Evaluating the Fiber Introduction Efficiency Depending on the Fiber Content and Type.
Deformation of a fine-grained concrete specimen with and without fiber added is shown in Figs. 4.9 & 4.10.

**Figure 9.** Deformation of the Specimen with the Basalt Fiber Added.

**Figure 10.** Deformation of the Specimen without Fiber Added.

According to these plots, the following can be reported: first, elastic deformations arise in the specimen, which contributes to the microcracks in concrete, then with increasing load, plastic deformations arise and the main crack begins to form, after which the specimen is destroyed. It is worth noting that these plots are typical.

Finally, in the experimental part, the histogram is given, which shows the optimal contents ensuring the maximum effect for all fibers at which the fine-grained concrete has the highest strength properties (Fig. 3.11).

According to the histogram, steel fiber is the most effective reinforcing component, while basalt and polypropylene fibers have lower efficiency.
5.5. Conclusions

With an increase in fiber content, the bending strength increases by an average of 10%.

When adding polypropylene and basalt fibers, the fine-grained fiber-reinforced concrete mobility decreases by 2-3 cm with an increase in the fiber content.

Each fiber (polypropylene, basalt, steel) fiber gives the maximum effect at certain content limits.

For polypropylene fiber with a length of 6 mm, the optimal content is 0.8%.

For polypropylene fiber with a length of 12 mm, the optimal content is 0.8%.

For basalt fiber with a length of 6 mm, the optimal content is 0.6%.

For basalt fiber with a length of 12 mm, the optimal content is 0.6%.

For steel fiber with a length of 14 mm, the optimal content is 1%.

At a large content of polypropylene and basalt fibers, the compressive strength virtually does not increase and even decreases as compared with the reference specimen.

An increase in the fiber length leads to an increase in the fine-grained fiber-reinforced concrete strength.

6. Conclusion

As a result of the analysis of scientific and technical sources, the below conclusions have been drawn:

- when introducing fiber into the concrete mixture, along with increasing strength, the wear resistance and the concrete surface quality are significantly improved,
- dispersed reinforcement of concrete with fiber gives a positive effect only if optimal contents are observed,
- the fiber significantly increases the concrete plasticity and allows avoiding the formation of microcracks.

The study objective is to determine the dispersed reinforcement contents and types optimal for fine-grained fiber-reinforced concrete.

The below tasks have been set:

- studying literature sources to get acquainted with the techniques for the research of the dispersed micro-reinforcement fiber size effect on the compressive and bending strength,
- determining the specifications of raw materials and their compliance with the requirements of regulatory documents,
- determining the recommended optimal contents (ensuring the maximum effect) of dispersed reinforcement fiber in fine-grained concrete,
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- comparing the effect of basalt, steel, and polypropylene fibers on the strength properties of fine-grained concrete.

Dispersed reinforcement of fine-grained concrete allows improving a number of its properties, i.e. crack, wear, and frost resistance, as well as the strength characteristics and durability.

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At a large content of polypropylene and basalt fibers, the compressive strength virtually does not increase and even decreases as compared with the reference specimen.

An increase in the fiber length leads to an increase in the fine-grained fiber-reinforced concrete strength.

Coming from the study, you can confidently conclude that fine-grained concrete with the addition of fiber for the manufacture of decorative products, architectural facades, and landscapes, can also be used as a floor screed for industrial premises.

7. References
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