Abradability of steel fiber concrete

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Abstract. It presents an analysis of the main provisions of the theory of concrete wear. It considers the mechanism of destruction of a material as a result of the impact of abrasive loads thereon. It justifies the importance of using steel fiber concrete in the structures experiencing dynamic, impact, abrasive loads. The article presents the methods of carrying out the research, the obtained results and the diagrams of the dependence of the steel fiber concrete strength on the consumption of steel fiber, abradability of steel fiber concrete on the consumption of steel fiber, abradability on the strength, as well as the analytical dependencies of the above-mentioned values. The obtained conclusions are based on the foregoing. The introduction of steel fiber allows us to significantly reduce the abradability of concrete (steel fiber concrete) and increase its strength. If the strength of steel fiber concrete is increased by introducing an additional amount of steel fiber, and (or) when using a higher class of concrete, the abradability is reduced. In the course of the research, the authors obtained a dependence of the change in the abradability on the strength of steel fiber concrete.

1. Introduction
Steel fiber concrete has long been known to builders as a structural material that differs from ordinary concrete and reinforced concrete by its improved physical and mechanical characteristics [1,2]. Many researchers have noted its increased tensile and compression strength, fracture toughness, impact toughness, frost resistance and cavitation resistance [3-6]. The use of monolithic steel fiber concrete in construction and manufacture of prefabricated building structures allows us to eliminate or significantly reduce reinforcing [7]. This significantly reduces the complexity and duration of works [8,9]. The dispersed distribution of steel fiber in the matrix of concrete allows the material to successfully resist both compression and stretching throughout the volume of the material. Thus, the strength characteristics of steel fiber concrete are dependent on the spatial arrangement of the reinforcement, in contrast to conventional reinforced concrete [10]. Therefore, it is recommended to use steel fiber concrete in structural elements experiencing mainly dynamic and shock loads, crushing and cavitation impact [11-13].

Several structures, where steel fiber concrete is widely used, experience such type of load as abradability or wear [14].

Abradability is one of the most important properties for a number of structures, which surface are subject to processes, such as: movement of heavy equipment on caterpillar or wheeled track, flowing fluid, impact from shoes. This is an indicator of the service life for industrial floors, staircases, sewage pipes, hydraulic structures, etc.
The higher the structural material’s resistance to abradability, the slower the wear is, and the more reliable and durable the life cycle of the surface will be (the more durable and safer the operation will be) [15].

Considering concrete surfaces, wear phenomena can be divided by the type of elementary effects: adherence friction, abrasive action, dynamic blows, pressing of solid objects, local chipping and crushing of protruding parts of coatings [16].

One of the most significant (destructive) types of wear is abrasive wear, it is thoroughly studied, and the existing test methods allow it to be numerically evaluated.

In the graphical presentation (Figure 1) for abrasive wear, there are two typical sections: initial curvilinear section (1) and subsequent, rectilinear section (2)

$$A_{cnt} = k \cdot T \cdot n$$  \hspace{1cm} (1)

$$A_{cnt} = A_{cnt} + k_1 (T - T_{cel})$$  \hspace{1cm} (2)

where $A_{cnt}$ – abradability of concrete in cm. (abradability depth); $A_{cel}$ – abradability (abradability depth) of the surface layer in cm.; $T$ – duration of abrasion, rpm of the abrasive disc; $T_{cel}$ – duration of abrasion of the surface layer of concrete, rpm of the abrasive disc; $k$, $n$ – constants characterizing the initial curvilinear section of the diagram; $k_1$ – coefficient characterizing the specific abradability of concrete (below the surface layer).

![Figure 1. Dependence of the abradability of concrete on the duration of abrasion.](image)

The initial section has a curvilinear section, since the top layer of concrete that receives primary abrasive loads consists of cement milk, which, after laying and compacting the concrete mixture, floats to the surface. The subsequent section is rectilinear, because in the underlying layers of concrete, a coarse filler comes into operation, which takes abrasive effects well. We will dwell on it in detail.

Concretes consist of cement stone (hardened cement with sand) and fillers of strong and dense rocks. The nature of concrete wear depends on the wear resistance of its components.

The total abradability of concrete ($A_{cnt}$) is formed by the abradability of cement stone ($A_{cem}$), the abradability of the filler ($A_f$) and concrete dying ($S_{cnt}$):

$$A_{cnt} = A_{cem} + A_f + S_{cnt}$$  \hspace{1cm} (3)
In the course of abrasion, i.e. as the wear surface shifts towards the deeper layers of concrete, the area of the cement stone decreases, and the area of the filler increases.

To reduce the wear, it is necessary to reduce the relative area of the cement stone on the surface of the coating. The size of this area depends on the flow of water and cement in concrete. The water flow is determined by the composition of concrete. If the water flow is constant, an increase in the consumption of cement leads to an increase in the area of the cement stone in the coating, but at the same time, the density increases and the abradability of the cement stone decreases, as well as the adhesion increases and the dying of fillers decreases [17].

In this case, one should strive to increase the relative area of the filler in the surface of the coating, which is achieved by selecting an optimal grain size of the fillers. An optimal grain size of the fillers allows us to reduce the wear of cement concretes.

Theoretically, if we add fiber, the total abradability should decrease due to the minimization of the dying process, by reinforcing the wear layer. The relief surface of the steel fibers will increase the adhesion of the cement stone with the filler, so that the surface will wear more evenly.

We carried out these studies to qualitatively and quantitatively assess the effect of the amount of steel fiber in the composition of steel fiber concrete on its abradability.

2. Methodology
We evaluated the abradability of concretes and other stone materials by the abradability coefficient, which is determined by the abrasion of samples on the laboratory abrasive disc (LKI-3) according to GOST 13087-81 “Concretes. Methods for determining abradability” [18].

The abradability coefficient is determined at 560 revolutions of the disc and is expressed by the sample weight loss of the samples in g/cm² of the abrasion surface.

For the experiments, heavy concrete B22.5 was chosen as the most commonly used. The consumption of steel fiber was chosen: 25, 50, 75, 100 kg per 1 m³ of the concrete mixture. The results are shown in Figures 2 and 3.

3. Results and Discussions
The general nature of the dependences of the strength on the consumption of steel fiber and the abradability on the strength correlates with the works of other researchers and the fundamentals of the materials science: when adding steel fiber to the concrete matrix, the material strength increases, and with an increase in the material strength, its abradability decreases [19, 20]. By varying (changing) the percentage of reinforcement, it is possible to adjust the strength, and, consequently, the abradability of steel fiber concrete [21].

A significant decrease in the abradability can be observed with the introduction of up to 25 kg of steel fiber per 1 m³ of concrete: the abradability is reduced by 20% from 0.601 g/cm² to 0.478 g/cm². A further increase in the fiber content in steel fiber concrete from 25 kg/m² to 100 kg/m² allows us to reduce the abradability by only 18% from 0.478 g/cm² to 0.392 g/cm².

The strength of steel fiber concrete with an increase in the amount of the introduced steel fiber to 100 kg/m³ is increased by 18% from 33.04 MPa to 39.97 MPa, which coincides with a relative decrease in the abradability (increase in the wear resistance).

We are most interested in the dependence of the abradability on the compressive strength. The general nature of the diagram in Fig. 4 predictably indicates a decrease of the abradability with an increase in the strength of steel fiber concrete in the studied range of values.
Figure 2. Abradability of steel fiber concrete depending on the consumption of steel fiber (percentage of reinforcement).

Figure 3. Compressive strength of steel fiber concrete depending on the consumption of steel fiber (percentage of reinforcement).

Figure 4. Dependence of the abradability on the compressive strength of steel fiber concrete

In order to determine how the abradability of steel fiber concrete will change if another class of concrete is chosen as a matrix, and whether this dependence is valid, we chose steel fiber concrete
with significantly different characteristics. The class of concrete was B40 and the fiber consumption was 150 kg/m³. If we combine the obtained results with the previous ones in one diagram, we can conclude that the nature of the change in the abradability remains the same: the higher the strength, the lower the abradability. Taking into account the previous experience on this problem, it can be asserted that regardless of the concrete class and the consumption of fiber, the regularity of the change in the abradability on the strength of steel fiber concrete will be maintained. For heavy concrete with a coarse filler made of strong rocks, at the consumption of steel fiber up to 150 kg/m³, the dependence of the abradability on the strength of steel fiber concrete can be described by the following formula:

\[ A_{\text{cuf}} = 9.4871R_b^{-0.824} \]  

where \( A_{\text{cuf}} \) – abradability of steel fiber concrete, g/cm²; \( R_b \) – compressive strength of steel fiber concrete, MPa.

\[ y = 0.0041x^2 - 0.3255x + 6.8295 \]  
\[ R^2 = 0.9992 \]

\[ y = 9.4871x^{-0.824} \]  
\[ R^2 = 0.8568 \]

Figure 5. Dependence of the abradability on the compressive strength of steel fiber concrete.

4. Conclusions

Based on the aforesaid, we can make several conclusions:

The introduction of steel fiber up to 100 kg/m³ can significantly reduce the abradability of concrete (steel fiber concrete) to 18%. At the same values of the fiber consumption, the compressive strength increases by 18%.

If the strength of steel fiber concrete is increased by introducing an additional amount of steel fiber, and (or) when using a higher class of concrete, the abradability is reduced. In the course of the research, we obtained the dependence of the change in the abradability on the strength of steel fiber concrete.

The obtained results allow us to refer steel fiber concrete to abradability grade G1 and to recommend it for structures operating under the conditions of an increased traffic intensity and abrasive effect [22,23].

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