Mechanical properties of concrete with small fibre for numerical modelling

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Abstract. The study specializes in the area of mechanical properties of select fibre reinforcement concrete. For the research fibre concrete reinforced with short steel fibres was used without bending. Fibre concrete is produced in the dosing 40 and 75 kg/m³. Laboratory program includes a complete group of tests, i.e. concrete compressive strength in cubes, three-point bending test, and split tension strength perpendicular and parallel to filling direction. Results are processed in summary, and they also include fracture-mechanical parameters needed for structural modelling. The research carried out found the positive influence of fibre on tensile strength and fracture energy. However, with more fibre, only fracture energy increases. It has also been found that the effect on compressive strength is small. For numerical modelling, the suitability of using a 3D computational model in combination with the fracture-plastic material model for fibre reinforcement concrete was verified.

1. Introduction
Fibre reinforcement concrete ranks among the category of fibre-concrete composites [1]. Fibre reinforcement concretes may vary by concrete and especially by fibres used, i.e. by shape, length, diameter, and finishing [2, 3, 4, 5]. For building structures such as floors, foundation structures, tunnel linings or underground structures [6, 7, 8], the use of fibre concrete is often more beneficial that of the ordinary reinforced concrete or plain concrete. Concrete reinforcement by fibres increases the tensile strength [9, 10] and ductility of concrete, which is very small as compared with plain concrete. Other benefits of fibre concrete may include limitation of shrinkage cracks [11] and deformations of concrete, increased ductility and fatigue strength, improved consistency (no falling-off at marginal parts of concrete). For the design of structures from fibre concrete, it is important to know in details its properties, which are most frequently defined in laboratories on testing samples [12, 13, 14]. Fibre concrete itself and its testing are dealt with in the Czech Republic and globally on a long time basis. Research results can be found in many suggestions and national standards, norms, and technical conditions [15], [16]. There are also many associations dealing with fibre concrete, e.g. RILEM [17], DafStB [18], BS [19] and Model Code 2010 [20]. The topics in the area of fibre concrete being currently deal with in the CR include for example durability or definition and verification of mechanical properties.
2. Fibre concrete
For the experimental program, fibres Dramix OL13/20 [16] have been selected. General characteristics of these fibres are shown in Table 1 and the fibres shape is shown in Figure 1. The initial concrete matrix has a formula stated in Table 2. Samples were prepared in the laboratory.

| General characteristic | Dramix® OL 13/20 (figure 4) |
|------------------------|------------------------------|
| Length [mm]            | 13                           |
| Diameter [mm]          | 0.21                         |
| Tensile strength [N/mm²] | 2750                        |
| Impact on concrete strength [kg/m³] | 60                      |
| Modulus of elasticity [GPa] | 200                        |

The concrete mixture used for tested samples may be classified in the category of ordinary concrete of class C25/30.

![Figure 1](image_url)  
**Figure 1.** Dramix® OL13/20 [20].

| Specification          | Formula [kg/m³] |
|------------------------|-----------------|
| Cement                | CEM II/A-S 42.5 |
| Min. cement content   | 320 kg          |
| Water-cement ration: w/c | 0.625         |
| Aggregate 0/2 DTK Mankovice | 525 kg        |
| Aggregate 0/4 DTK Mankovice | 420 kg        |
| Aggregate 4/8 Tovačov | 150 kg          |
| Aggregate 8/16 HDK    | 820 kg          |
| Water                 | 200 l           |
| Plasticizer STACHEPLAST | 3.2 L         |
3. Experimental program – methodology

Initial testing of fibre concrete includes compressive strength in cubes. These are tests of cubes with the typical size of 150 x 150 x 150 mm. The testing diagram is shown in figure 2. The demonstration sample from the splitting tension test is in figure 3 and sample from the bending tensile strength test is in figure 4.

![Figure 2. Compression and split tension tests.](image)

Compressive strength testing in cubes is performed always perpendicularly to the filling direction. Compressive strength in cubes \( f_{c,cube} \) is defined as:

\[
f_{c,cube} = \frac{P_{\max}}{a^2}
\]  

(1)

where \( P_{\max} \) is the maximum strength and \( a \) is the size of the cube side.

Next tests in the experimental program include split tension testing. Specifically, two variants have been chosen: perpendicular to the filling direction and parallel to the filling direction. The testing diagram is shown in figure 5. Split tension strength is defined as follows:

\[
f_{st,sp} = \frac{2 \cdot P_{\max}}{\pi \cdot l \cdot d}
\]  

(2)
where \( P_{\text{max}} \) is the maximum load, \( l \) is the length of contact line of the body, and \( d \) is the lateral dimension of the body. To verify cogency of the split tension test and define fractural-mechanical parameters, bending tension test is performed in its three-point version. The testing diagram is shown in figure 5.

\[
f_{\text{cr.bl.3B}} = \frac{3 \cdot P_{\text{max}} \cdot L}{2 \cdot b \cdot (h - a_0)^2}
\]

\[
f_{\text{cr.sp}} = \frac{3 \cdot P_{\text{max}} \cdot L}{1.65}
\]

Tensile strength of concrete in case of three-point configuration may be defined as:

\[
G_f = \frac{W}{h \cdot (b - a_0)}
\]
4. Experimental program – Results

Compressive strength testing included three samples. Total of 6 tests were carried out. In case of the variant with fibre dosing of 75 kg/m$^3$, the compressive strength was higher. The difference was however relatively small. The spread of measured strengths is also well apparent from the diagram. The compressive strength for dosing of fibres 40 kg/m$^3$ was 36.4 MPa. In the variant with dosing 75 kg/m$^3$, strengths were very similar, i.e. 40.1 MPa. Summarized compressive strengths and volume densities are shown in figure 6.

![Figure 6. Linear dependence of compressive strength and density.](image)

Split tension strength testing included 10 samples, i.e. 6 samples, the direction perpendicular to filling direction and 4 parallel to filing direction. The weight of these samples ranged about 8 kg. Based on the testing, split tension strengths were calculated. Tensile strength difference for dosing of 40 and 75 kg/m$^3$ was almost minimal and moved in hundredths. Tensile strengths were 3.07 and 3.08 MPa. In the case of a tensile test parallel to the filling direction, the strength was less, i.e. 2.7 MPa and 2.5 MPa.

Other selected testing options included the three-point bending test. Specifically, total of 6 joists of the size 150 x 150 x 600 mm and the notch in the middle were concreted. The notch depth was 50 mm and the span in the load test was 500 mm. The weight of samples ranged about 31 kg. Three joists were reinforced with the fibre content 40 kg/m$^3$, and the remaining 3 with 75 kg/m$^3$. After 28-day maturing period, a three-point bending test was carried out on joists, determining subsequently values of the bending tension strength of all test samples. The load test was applied up to the deflection of 8 mm. The bending tension strength was 4.73 and 4.98 MPa. Results are also shown in a diagram in figure 7 and table 3. The influence of the direction of filling is evident with the comparison of the results in table 4.

| Value | Fibre content [kg/m$^3$] | Volume density [kg/m$^3$] | Compressive strength (cube) [MPa] | Split tension strength (⊥) [MPa] | Split tension strength (∥) [MPa] | Bending tension strength [MPa] |
|-------|--------------------------|---------------------------|-----------------------------------|---------------------------------|---------------------------------|-------------------------------|
| Average | 40 | 2310 | 38.5 | 3.1 | 2.7 | 4.7 |
|        | 75 | 2323 | 40.2 | 3.1 | 2.5 | 5.0 |
Figure 7. Split and Bending tension strength.

Table 4. Splitting strength ratio.

| Fibre content [kg/m$^3$] | Fibre type | Filling direction | Splitting tension test [MPa] | Ratio $\perp / \parallel$ [-] |
|--------------------------|------------|------------------|-----------------------------|-----------------------------|
| 40                       | Dramix     | $\perp$          | 3.1                         | 1.1                         |
| 40                       | OL13/20    | $\parallel$      | 2.7                         |                             |
| 75                       |            | $\perp$          | 3.1                         | 1.2                         |
| 75                       |            | $\parallel$      | 2.5                         |                             |

Also the assessment of all load diagrams shown in figure 8 was made, and the work $W_f$, or the energy to fracture $G_f$ for deformations 5 mm and 8 mm were determined. By adding fibres to concrete, the load displacement diagram changes dramatically as compared with plain concrete.

Table 5. Comparing ratios of fracture energy adequate to deformations 5 and 8 mm.

| Fibre content [kg/m$^3$] | Fibre type | Deformation [mm] | Energy to fracture [N/m] | Fracture energy ratio $(8 \text{ mm} / 5 \text{ mm})$ [-] |
|--------------------------|------------|------------------|--------------------------|-----------------------------------------------|
| 40                       | Dramix     | 5                | 1121                     | 1.206                                         |
| 40                       | OL13/20    | 8                | 1352                     |                                               |
| 75                       |            | 5                | 1377                     | 1.209                                         |
| 75                       |            | 8                | 1665                     |                                               |

In the load displacement diagram is seen increase tensile strengths are in case of higher dosing. For detail description, it is however necessary to define energies to fracture. Average values of energies to fracture are shown in table 5. With respect to the fact that residual tensile strengths still remained at the end of testing, ratios of energies to fracture were therefore defined as a supplementary descriptive.
behaviour. Summarized results are stated in table 5. The ratio of the energy to fracture for deformations 8 mm and 5 mm in samples was 1.21.

![Graph](image)

**Figure 8.** LD diagram for fibres Dramix OL13/20 with fibre dosing 40 kg/m$^3$ and 75 kg/m$^3$.

### 5. Numerical model of fibre reinforcement concrete

For analysis of concrete structures is currently typical used the finite element method. However, a non-linear solution is needed to take account of actual behaviour. The calculation must account the typical concrete failure. In pressure, the concrete is crushed and cracks are formed in the tension. These assumptions are met by the use of fracture theory and the Newton-Rapston nonlinear solver. For the numerical models and analysis using was used system Atena [21] with fracture plastic material model [22]. The specific problems of using nonlinear analysis of concrete structures are important to determine the input parameters of fibre reinforcement concrete [23]. The tensile softening is specific to each of fibre concretes recipe [24], [25].

![Numerical model](image)

**Figure 9.** Numerical model in the Atena system for fibre dosing 75 kg/m$^3$ - displacements [m].

The determination of the specific fracture energy defined in the material model cannot be determined from bending tensile tests. For these reasons, it is necessary to use a parametric study [25] or inverse analysis to select the appropriate tensile softening approximation. It is also important to take into account numerical model uncertainties and respect recommendations [26] and [27]. A three-point bending tensile test was used to numerical modelling and determine the specific fracture energy. The typical 3D computational model is shown in figure 9. The modulus of elasticity was determined on the basis of class concrete and the used value for numerical analysis was 31 GPa. Compressive strength was used in the tests.
Figure 10. Numerical model in the Atena system for fibre dosing 75 kg/m$^3$ – stress $\sigma$ [MPa].

Figure 11. Load – displacement diagrams – fibre dosing 40 kg/m$^3$.

Figure 12. Load – displacement diagrams – fibre dosing 75 kg/m$^3$.

Exponential crack law was used to approximate tensile softening in the interval specific fracture energy 300 - 1000 N/m. The initial tensile strength was also used from split tension testing and gradually decreased to a level of effective tensile strength. Figures 9 and 10 are used to illustrate numerical
calculations. Figure 9 shows the deformations and figure 10 shows the normal stress $\sigma$ at a load of 4.5 kN and a deformation of 1.5 mm.

The resulting set of specific fracture energy values are 400 N/m with effective tensile tension of 0.87 MPa for a fibre of 40 kg/m$^3$ and 900 N/m with effective tensile tension of 0.95 MPa for 75 kg/m$^3$. The resulting comparison of load displacement diagrams from experiments and numerical modelling is shown in figure 11 for the 40 kg/m$^3$ case, and for case 75 kg/m$^3$ in figure 12.

6. Conclusion
The research dealt with mechanical parameters of fibre reinforcement concrete, which differ by dosing 40 and 75 kg/m$^3$. Specifically, straight fibres Dramix OL13/20. Results showed positive impact on both, the compressive strength, fracture energy and tensile strength of concrete. The impact of fibres on the compressive strength is however small. It has also been demonstrated that the split tension strength parallel to filling direction is lower than in the direction perpendicular to filing direction. The difference in tensile strength both dosing types was small, about 15%. In the load displacement diagram is see increase fracture energy are in case of higher dosing. By summary to note that the increase of the fibre content from 40 to 75 kg/m$^3$ does not significantly increase the compressive strength nor tensile, but the residual tensile strength and fracture energy increases, about 19%. In the case of 3D numerical modelling and fracture-plastic material model, it is advisable to use information of laboratory tests.

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