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Abstract
Ultra High Performance Fiber Reinforced Concrete (UHPFRC) is a relatively new material with enhanced mechanical properties. The tensile performance characteristics are predominant of the high energy absorption and toughness. The actual stress-strain model in tension can be determined by direct tensile tests. However, it is not always feasible to conduct direct tensile tests and a common practice is to perform indirect tests such as the flexural testing of standard prisms. The tensile characteristics of Steel Fibre Reinforced Concrete (SFRC) can be calculated using the flexural testing results in conjunction with models from the literature. However, until now there are not any relevant published models on UHPFRC. In this study the results of an extensive experimental program have been used to investigate the ‘size effect’ of UHPFRC. Prisms with different cross-sectional depths have been tested together with dog-bone shaped UHPFRC specimens in direct tension. These results have been analyzed and a model is proposed for the correlation of the tensile strength with the respective flexural strength of UHPFRC prisms with various depths.

1. INTRODUCTION
UHPFRC is a novel material with superior mechanical properties. These properties are highly affected by the type, quantity, and distribution of the steel fibres in the mix. The tensile stress-strain characteristics are of main importance and these should be determined through direct tensile tests. However, it is not always easy to perform direct tensile tests, so alternative indirect testing methods are extensively used in practice to determine the flexural and tensile characteristics.

Kang et al. [1] and Yoo et al. [2] examined the effect of steel fibers amount on the flexural strength of UHPFRC and it was found that the flexural strength increased with the fiber volume ratio while the ductility was decreased. Kang et al. [1] presented an inverse analysis to determine the tensile fracture model of UHPFRC and a tri-linear tensile fracture model of UHPFRC tensile softening model proposed. The orientation and distribution of the fibers in the mix is an important parameter for the mechanical properties of UHPFRC. Kang & Kim [3] investigated the effect of the fiber orientation on the tensile behavior of UHPFRC. According to this study [3] the effect of the fiber orientation found to be negligible in the pre-
cracking behavior, but this significantly affected the post-cracking behavior. Mahmud et al. [4] conducted a numerical investigation and based on the numerical results the ‘size effect’ is negligible for beams up to 300 mm. Nguyen, et al. [5] investigated the size effect on flexural behavior of UHPFRC with hybrid fibres. Specimens of different sizes tested under flexural loading. The beams had different, depth and width while the fiber content was 1.5% and 2% per volume. It was found that the size of the beams affected not only the flexural strength but also parameters as the energy absorption, the deflection capacity and the crack spacing at the modulus of rupture. More specifically, the authors reached a conclusion that as the size decreased the flexural parameters, as the energy absorption and the deflection capacity are increased.

The main findings of the previous studies indicate that further investigation is required on the ‘size effect’ of UHPFRC. Also, even if there are available models for the correlation of the tensile strength with the flexural performance of steel fiber reinforced concrete, there are not any published models on UHPFRC. The main aim of this study is to investigate the effect of the depth of beams UHPFRC flexural strength and to propose a model for the correlation of flexural with the tensile strength. The results of an extensive experimental investigation of direct tensile tests and beams under bending loading are presented and these results have been used for the development of a model for the estimation of the flexural strength of beams with various depths.

2. EXPERIMENTAL INVESTIGATION

2.1 Material Preparation

UHPFRC is characterized by enhanced homogeneity and high density. In the mix design of the present study, silica sand with maximum particle size of 500μm was used together with high strength cement 52.5 N, silica fume and slag. High percentage of steel fibers (3%) with diameter 0.16 mm and 13 mm length were added in the mix. The mix design is based on a previous study [6] and the mix proportions are presented in Table 1.

Table 1: Mix Design for UHPFRC

<table>
<thead>
<tr>
<th>Material</th>
<th>Mix proportions (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (52.5N)</td>
<td>657</td>
</tr>
<tr>
<td>GGBS</td>
<td>418</td>
</tr>
<tr>
<td>Silica fume</td>
<td>119</td>
</tr>
<tr>
<td>Silica Sand</td>
<td>1051</td>
</tr>
<tr>
<td>Superplasticizers</td>
<td>59</td>
</tr>
<tr>
<td>Water</td>
<td>185</td>
</tr>
<tr>
<td>3% Steel fibres</td>
<td>236</td>
</tr>
</tbody>
</table>

Regarding the mixing procedure, the dry ingredients (silica sand, GGBS, silica fume and cement) were mixed first for 3 minutes. Then the water and the superplasticizer were added to the mix and finally the steel fibers were mixed gradually through sieving. A high shear mixer Zyklons (Pan Mixer ZZ 75 HE) was used for the mixing of the materials.

Direct tensile specimens (dog-bone) together with prisms were cast from the same batch of concrete. The geometry and dimensions of the dog-bone specimens are presented in Figure
1a. Beams were also cast with four various depths 25 x 100 x 500 mm, 50 x 100 x 500 mm, 75 x 100 x 500 mm, and 100 x 100 x 500 mm (Figure 1b).

![Figure 1: a) Dog Bone and b) prism specimens](image)

After the de-moulding all the specimens were placed in a steam curing tank for 3 days in 90 °C, and the specimens were tested 14 days after casting.

3. TESTING SETUP AND EXPERIMENTAL RESULTS

3.1 Direct Tensile Tests

Direct tensile tests of 6 dog bone shaped specimens were conducted using the setup presented in Figure 2. The tests were performed under displacement control using a constant loading rate of 0.007 mm/sec and Linear Variable Differential Transformer (LVDT) was used to measure the average extension over a gauge length of 105 mm.

![Figure 2: Experimental setup for direct tensile tests](image)

A number of specimens were also monitored using LaVision Digital Image Correlation System. Indicative results of one of the examined specimens are presented in Figure 3. From this system additional strain measurements were taken during the test and the crack opening was also measured. The results indicate that in the first elastic part (strain values below 0.001), the strain is uniformly distributed along the specimen. Then, in the second phase (strain between 0.001 and 0.005) there is a combination of crack opening and elastic strain in the neck of the dog bone specimen, while for a strain value higher than 0.005, all the extension of the specimen is due to the crack opening (Figure 3).
The stress-strain results of all the direct tensile tests are presented in Figure 4. In this graph, the strain value has been calculated by the total extension during the test divided by the gauge length.

The experimental results indicate a variation of the tensile strength from 11.74 MPa to 14.20 MPa. An average stress-strain curve has been calculated and the average strength was found equal to 12.10 MPa.

### 3.2 Flexural Prism Tests

For the investigation of the size effect on the flexural strength of UHPFRC beams, three flexural tests were performed for each different depth value. The tests were conducted under four point loading with a span length of 300 mm and distance between the two loading points 100 mm. Two LVDTs were used to record the deflection of the beams in both sides and the
tests were conducted using a displacement control of 0.001 mm/sec. An external yoke (Figure 5) was used in order to exclude any additional displacement at the support. The testing setup is presented in Figure 5.

Figure 5: Experimental setup for the flexural testing of the prisms

The majority of the specimens failed in the middle of the span with a typical vertical flexural crack. The typical failure mode for the specimens with the different thickness values are presented in Figure 6.

Figure 6: Characteristic failures of a) 25 mm, b) 50 mm, c) 75 mm, and d) 100 mm thickness beams

The load-deflection results for all the examined specimens together with the average curves are presented in Figure 7.
The results of Figure 7 indicate that there is a scatter in the experimental results, since for 25 mm depth beam the maximum load was ranged between 5.3 kN and 8.1 kN, for 50 mm depth the maximum load was between 19.3 kN and 26.7 kN, for 75 mm beam depth the maximum load was between 35 kN, and for 100 mm depth beam the range was between 50.5 kN and 80.3 kN. The average maximum load calculated from the average load-deflection curves (Figure 7), and the average values were found equal to 6.5 kN for 25 mm, 22.3 kN for 50 mm, 43.1 kN for 75 mm, and 66.7 kN for 100 mm depth.

The flexural strength of each specimen was determined according to JSCE-SF4 [7] (Equation 1).

\[
f_u = \frac{PL}{bd^2}
\]

where:
- \(f_u\) is the flexural strength (MPa),
- \(P\) is the peak load (kN),
- \(L\) is the effective span length (300 mm),
- \(b\) is the width of specimen (100 mm), and
- \(d\) is the depth which varies from 25 to 100 mm.

The flexural strength results for all the different examined thicknesses are presented in Table 2 and these values have been calculated using the average maximum load values.
Table 2: Experimental results for the different depths

<table>
<thead>
<tr>
<th>Beam Depth (mm)</th>
<th>Flexural strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>31.2</td>
</tr>
<tr>
<td>50</td>
<td>26.8</td>
</tr>
<tr>
<td>75</td>
<td>23.0</td>
</tr>
<tr>
<td>100</td>
<td>20.1</td>
</tr>
</tbody>
</table>

The results of Table 2 indicate that there is an increment of the flexural strength values as the depth is reduced. In order to correlate the average tensile strength of UHPFRC (12.1 MPa), calculated from the direct tensile tests (Figure 4), the following equation is proposed (Equation 2).

$$\sigma_t = \frac{f_u}{2.85 \times (1 - 4.2 \times h)}$$  \hspace{1cm} (2)

where:

- \(\sigma_t\) is the tensile stress (MPa),
- \(h\) is the cross section height (in m), and
- \(f_u\) is the flexural tensile strength.

The proposed equation is applied for the examined specimens and the results are compared with the experimental data of Table 2 (Figure 8).

Figure 8: Application of the proposed model for the flexural strength versus experimental results

The proposed model could be used to correlate the flexural with the direct tensile strength of UHPFRC for specimens with depth up to 100 mm thickness. Further experimental work is needed in order to check the reliability of the model for specimens with depths higher than 100 mm.

4. CONCLUSIONS

In this study the direct tensile strength and the flexural performance of UHPFRC has been investigated. Direct tensile tests of dog-bone shaped specimens and prisms with various section depths were tested under flexural loading. From the direct tensile tests, the stress–strain distribution was obtained, and at the same time the crack opening and the strains were
monitored. Three different phases were illustrated (Figure 3) based on measurements with a digital image correlation system.

From the flexural testing of beams with various thicknesses, it was evident that the flexural strength is affected by the section depth. The flexural strength values were reducing as the section depth was increasing and they were found to be between 31.2 MPa and 20.1 MPa for beams with depths in the range of 25 mm to 100 mm. From the direct tensile tests the average tensile strength was found equal to 12.1 MPa. Using these results, a model is proposed to correlate the tensile with the flexural strength for the examined range of prisms’ depths.

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BIBLIOGRAPHY


