Experimental investigation of tensile behaviour of high strength concrete

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In the design of structures, it is necessary to know about the tensile strength as well as the compressive strength and durability, which are considered to be the most important properties of concrete. In this study, 44-81 MPa high strength concretes are produced. The uniaxial tensile, split tensile and flexural tensile tests are conducted and the relationships between the respective tensile strengths are investigated.

Keywords: High strength concrete, Uniaxial tensile strength, Splitting tensile strength, Flexural tensile strength, Compressive strength.

The concrete commonly used in engineering structures is a material having high compressive strength but low tensile strength. The tensile strength of concrete whose compressive strength is in the level of about 200 MPa is between 1/8 and 1/20 of this value. So, the tensile strength of concrete is generally assumed to be zero in reinforced concrete design. But in design of some structures, the tensile strength must be known. This is a crucial design parameter especially in structures such as concrete dams, airfield runways, concrete roads and pavements, and other slabs. Therefore, many experimental and theoretical studies have been carried out to determine the tensile strength of concrete. It is known that the stress obtained by breaking a specimen which is subjected to uniaxial loading, shows the real tensile strength of concrete, but the tensile strength of concrete is obtained by indirect methods as splitting and flexural tests. A non-uniform state of stress is superimposed over the local stress fluctuations that are caused by the material structure itself. Because of this, these methods have disadvantages. However, the tensile strength obtained from the uniaxial tensile test is more reliable than that of other test methods. But this test method requires much more care compared to indirect methods. Particularly, after the production of strong epoxy based adhesives, the uniaxial tensile tests are done with few troubles.

Many experimental researches conducted in the past to determine the uniaxial tensile strength failed because of unexpected crushing which occurred as a result of local stress concentrations. Another difficulty in uniaxial tensile tests is that the test specimen is under the influence of moment effects during the tensile test due to eccentricity. Zhou reported that an increase in load eccentricity may decrease the tensile stress. The tensile strengths of concrete were investigated for traditional concretes, but with the recent developments in concrete technology, compressive strength of concrete has highly increased. Despite this, the properties of high strength concretes have not been investigated yet as well as those of traditional concretes. Especially the studies conducted to determine the tensile strength are rather limited. Zain et al. proposed some equations that indicate the splitting tensile strength of high strength concretes based on the compressive strength of concretes of any age. Swaddiwudhipong et al. studied the strain capacity in direct tension and the tensile strength of concrete produced with different types of cement at early ages in their tests. Bhanja and Sengupta investigated the effects of silica fume on the tensile strength of high strength concretes whose w/c ratios change between 0.26 and 0.42. Carrasquillo et al. studied the relationship between tensile strength and compressive strength of concrete.

The uniaxial tensile \( f_d \), splitting tensile \( f_{sp} \) and flexural tensile \( f_f \) strengths of high strength concretes were determined in this study. As the relationship of the tensile strengths with each other and with compressive strengths \( f_c \) was investigated, the secant moduli of elasticity \( E_s \) of these concretes in tension and in compression were also determined.
Experimental Procedure

Concrete materials and mix proportions

Crushed limestone aggregates were used in the production of high strength concretes. The maximum aggregate size was 16 mm. Some physical properties and granulometric composition of these aggregates are given in Table 1. Rapid hardening ordinary portland cement was used (CEM I 42.5 R)\(^{19}\) in the production of concretes. The specific density of the cement was 3.10 g/cm\(^3\). In the production of high strength concrete, silica fume containing 92% SiO\(_2\) and high range water-reducing admixtures (ASTM C-494 F type super plasticizer) were used. Silica fume, 10% of cement by weight, was added to the mixture. Super plasticizer was added in a certain ratio (1% or 2%) of binder (cement + silica fume) by weight. The mixing proportions for the concretes are presented in Table 2.

Concrete production, curing and testing age

In order to produce high strength concretes, first, the silica fume and the saturated aggregate were mixed for 3 min. Then cement and silica fume were added and this mixture was mixed without any interruption for more than 3 min by adding water and super plasticizer to it. The fresh concrete was produced in these steps and placed in moulds in three stages. The concretes were placed by applying 15 s vibrations.

The specimens taken out of their moulds one day after their production were kept in water at 22°C ± 2°C for 21 days. Until the time of the experiment, they were kept in the laboratory conditions of 18°C ± 2°C temperature and 70% relative humidity. The specimens were 28-day-old at the time of the experiment.

Specimen details and test procedure

Twelve series of the high strength concretes were produced in this study. The mix designs of the concretes are shown in Table 2. The compressive strength and the splitting tensile strength were tested using 150 × 300 mm cylinders, while the flexural strength was tested using 100 × 100 × 400 mm beams. A three point loading setup, with a beam span of 350 mm, was used for flexural tests. Also, 75 × 150 mm cylinders were used for determining the uniaxial tensile strength of concretes. Specimens were tested according to the relevant ASTM standards.

The uniaxial tensile tests were realized using a tensile loading arrangement designed for this study. Figure 1 shows the schematic test set-up of the uniaxial tensile tests. The steel discs, with a diameter of 75 mm and a thickness of 10 mm, were bonded with an epoxy based adhesive carefully onto both the upper and the lower surfaces of the uniaxial tensile cylinder specimens. These parts were connected to the

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### Table 1— Some physical properties and mixing proportions of the aggregates

<table>
<thead>
<tr>
<th>Aggregate</th>
<th>Bulk density (kg/m(^3))</th>
<th>Water absorption (%)</th>
<th>Crushed aggregate proportions (%)</th>
<th>Fine (0-4 mm)</th>
<th>Medium (4-8 mm)</th>
<th>Coarse (8-16 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine</td>
<td>2671</td>
<td>1.72</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse</td>
<td>2706</td>
<td>0.80</td>
<td></td>
<td>45</td>
<td>25</td>
<td>30</td>
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</table>

### Table 2— Mix design of the concretes (kg/m\(^3\))

<table>
<thead>
<tr>
<th>Mix no</th>
<th>W/B</th>
<th>Water</th>
<th>Cement</th>
<th>SF</th>
<th>SP</th>
<th>Aggregate</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fine</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Medium</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Coarse</td>
</tr>
<tr>
<td>A1</td>
<td>0.25</td>
<td>110</td>
<td>400</td>
<td>40</td>
<td>11.00</td>
<td>887</td>
</tr>
<tr>
<td>A2</td>
<td>0.25</td>
<td>124</td>
<td>450</td>
<td>45</td>
<td>12.80</td>
<td>851</td>
</tr>
<tr>
<td>A3</td>
<td>0.25</td>
<td>138</td>
<td>500</td>
<td>50</td>
<td>13.75</td>
<td>815</td>
</tr>
<tr>
<td>B1</td>
<td>0.30</td>
<td>132</td>
<td>400</td>
<td>40</td>
<td>8.80</td>
<td>860</td>
</tr>
<tr>
<td>B2</td>
<td>0.30</td>
<td>149</td>
<td>450</td>
<td>45</td>
<td>9.90</td>
<td>821</td>
</tr>
<tr>
<td>B3</td>
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<td>165</td>
<td>500</td>
<td>50</td>
<td>11.00</td>
<td>782</td>
</tr>
<tr>
<td>C1</td>
<td>0.35</td>
<td>154</td>
<td>400</td>
<td>40</td>
<td>6.60</td>
<td>834</td>
</tr>
<tr>
<td>C2</td>
<td>0.35</td>
<td>173</td>
<td>450</td>
<td>45</td>
<td>7.43</td>
<td>792</td>
</tr>
<tr>
<td>C3</td>
<td>0.35</td>
<td>193</td>
<td>500</td>
<td>50</td>
<td>8.25</td>
<td>749</td>
</tr>
<tr>
<td>D1</td>
<td>0.40</td>
<td>176</td>
<td>400</td>
<td>40</td>
<td>4.40</td>
<td>808</td>
</tr>
<tr>
<td>D2</td>
<td>0.40</td>
<td>198</td>
<td>450</td>
<td>45</td>
<td>4.95</td>
<td>762</td>
</tr>
<tr>
<td>D3</td>
<td>0.40</td>
<td>220</td>
<td>500</td>
<td>50</td>
<td>5.50</td>
<td>717</td>
</tr>
</tbody>
</table>

W/B : water/binder (cement + silica fume) SF: Silica fume SP: Superplasticizer
chain mechanisms, and finally, all mechanism was fixed to the jaws of the universal testing machine. The chain mechanism was used in order to eliminate the bending moment during loading. This bending moment was controlled with strain gauges of 120 mm of length and a gage factor of 2.10. The strain gauges were mutually glued in the longitudinal direction on the cylinder specimens. No moment was observed in the specimens as measured by the strain gauges during the tests. Strain gauges were also used to determine of $\sigma$–$\varepsilon$ diagrams and the secant moduli of elasticity of the concretes in compression and in tension. A load-cell with a capacity of 500 kN was used to read the applied load. The readings were recorded by a data-logger. Views from the tests conducted with a constant loading speed are given in Fig. 2. Some crack patterns from specimens after the tests are shown in Fig. 3.

Results and Discussion

The specimens were produced in this study so as to determine the tensile strength of high strength concretes. The results obtained from uniaxial compression, splitting, flexural and uniaxial tensile tests were given in Table 3. The relationships between compressive strengths and tensile strengths were shown in Fig. 4.

In this respect, in order to indicate the $f_c$ concrete’s compressive strength of 28th day, a relationship between uniaxial tensile strength and compressive strength was determined as:

$$f_t = 0.026 f_c^{1.223} \ (R=0.98)$$

The relationship between splitting tensile strength and compressive strength is

$$f_{sp} = 0.106 f_c^{0.948} \ (R=0.97)$$

and also it was determined that there existed a relationship between flexural tensile strength and compressive strength as:

$$f_{fl} = 0.034 f_c^{1.286} \ (R=0.99)$$

In Fig. 4, as the compressive strength of concrete increases, flexural strength increases more than the uniaxial tensile and the split strengths. The ratios of the compressive strength obtained in the test to the tensile strength and the variation of this ratio with
Fig. 4—Relationships between compressive strength and tensile strengths were shown in Fig. 5. It is observed from Fig. 5 that the ratios of flexural tensile strength to compressive strength and uniaxial tensile strength to compressive strength increase as compressive strength increases. On the other hand, the ratio of splitting tensile strength to compressive strength is not affected by the changes of compressive strength. Concerning this, the average ratios of compressive strengths to uniaxial tensile strength, the splitting strength and the flexural tensile strength are found as 6.60, 8.52 and 12.03, respectively. In other words, the average ratios of tensile strengths to compressive strengths of the concretes are 1/15, 1/12 and 1/8, respectively. According to this, the 1/10 value that is accepted in the technical literature for the ratio of the tensile strength/compressive strength for traditional concretes is not valid for high strength concretes.

The relationships between uniaxial tensile strength and flexural tensile strength and splitting tensile strength are given in Figs 6 and 7. And the relationship between flexural tensile strength and splitting tensile strength is given in Fig. 8. As for these relations, the ratios of $f_{dr}/f_{t} = 0.55$, $f_{dr}/f_{sp} = 0.78$...
The relationships between the splitting tensile strength and compressive strength suggested by Bhanja\textsuperscript{17}, Carrasquillo \textit{et al.}\textsuperscript{18}, ACI-363\textsuperscript{20}, CEB-FIP\textsuperscript{21} and Eurocode-2\textsuperscript{22}, were shown in Fig. 9, along with the results obtained in present study. The splitting tensile strength obtained in this study is in agreement with the tensile strength obtained from the equation proposed by CEB-FIP\textsuperscript{21}. And also the expression of splitting tensile strength obtained in this study is suitable with ACI-363\textsuperscript{20} and Eurocode-2\textsuperscript{22} recommendations on the compressive strength of around 70 MPa.

The moduli of elasticity in compression and direct tension were determined for A3, B3, C3 and D3 series specimens. The $\sigma-\varepsilon$ diagrams were obtained using the strain gauges in the longitudinal direction that

### Table 4. Secant modulus of elasticity of concretes in compression and tension

<table>
<thead>
<tr>
<th>Mix. no</th>
<th>Mean Comp. Strength (MPa)</th>
<th>Secant Modulus of Elasticity ($E_c$, in compr.) (MPa)</th>
<th>Standard deviation of Elasticity ($E_c$, in compr.) (MPa)</th>
<th>Secant Modulus of Elasticity ($E_{ct}$, in tension) (MPa)</th>
<th>Standard deviation of Elasticity ($E_{ct}$, in tension) (MPa)</th>
<th>$E_{ct} / E_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3</td>
<td>81</td>
<td>40900</td>
<td>1300</td>
<td>42200</td>
<td>1290</td>
<td>1.03</td>
</tr>
<tr>
<td>B3</td>
<td>68</td>
<td>37000</td>
<td>1220</td>
<td>39100</td>
<td>1370</td>
<td>1.05</td>
</tr>
<tr>
<td>C3</td>
<td>60</td>
<td>36400</td>
<td>1340</td>
<td>37800</td>
<td>1250</td>
<td>1.04</td>
</tr>
<tr>
<td>D3</td>
<td>54</td>
<td>34100</td>
<td>1110</td>
<td>35200</td>
<td>1230</td>
<td>1.03</td>
</tr>
</tbody>
</table>

and $f_{tu} / f_{sp} = 1.43$ were obtained based on the mean values of the tensile strengths.
were adhered to the specimens. Measurements of the secant moduli of elasticity were made according to Eurocode-2 at 40% of the mean value of compressive strength. The secant moduli of elasticity of concretes were given in Table 4. According to these values the modulus of elasticity in direct tension of concrete is nearly 1.04 times more than the modulus of elasticity in compression in average for 54 MPa ≤ f_c ≤ 81 MPa. This difference in the modulus of elasticity between these situations could be negligible.

Conclusions

Based on the experimental study on high strength concretes (44 MPa ≤ f_c ≤ 81 MPa) the following conclusions are drawn:

(i) The proposed test method for measuring direct tensile strength minimized the eccentricity during loading.

(ii) The value of 1/10 accepted in the technical literature for the ratio of the tensile to compressive strength in traditional concretes is not valid for the high strength concretes. According to the results obtained, the uniaxial tensile strength in high strength concretes having 44-81 MPa compressive strength is nearly as much as 1/15 of the compressive strength. It was determined that the uniaxial tensile strength was 45% smaller than the flexural tensile strength, and 22% smaller than the splitting tensile strength.

(iii) The ratios of flexural tensile strength to compressive strength and uniaxial tensile strength to compressive strength increased as compressive strength increased. On the other hand, the ratio of splitting tensile strength to compressive strength was not affected by the changes in compressive strength.

(iv) The splitting tensile test results are in good agreement with those obtained on high strength concretes by the CEB-FIP equation.

(v) The modulus of elasticity determined from the uniaxial tensile tests is approximately 1.04 times more than the modulus of elasticity obtained from compressive tests. This result showed that the modulus of elasticity of high strength concrete is approximately equal in compression and in direct tension.

References