Evaluation of mechanical properties of steel-fibre-reinforced concrete exposed to high temperatures by double-punch test

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Highlights

- The factors influencing the tensile properties of heated steel-fibre-reinforced concrete (SFRC) were investigated.
- The tensile properties of heated SFRC were measured by the double-punch test.
- Tensile properties of the heated SFRC were more sensitive to volume fraction and aspect ratio of fibre than to its type.
- The relative loss was highest in tensile strength, followed by compressive strength and rupture energy.

Abstract

The aim of this investigation was to study the factors influencing the mechanical tensile properties of steel-fibre-reinforced concrete exposed to high temperatures. The properties were estimated by the double-punch test having a high accuracy. Specimens reinforced with fibres of two types (twisted or hooked), two aspect ratios (l/d = 60 or 80), and three fibre contents (volume fractions of 0.25%, 0.5%, or 1%) were tested after exposure to four different maximum temperatures (room temperature, 300 °C, 500 °C, and 700 °C). Test results show that the residual compressive strength, DPT tensile strength and rupture energy of the specimens decreased with their increased heating. After the SFRC was exposed to the high temperatures, the relative loss in tensile strength was higher than that in compressive strength, but the relative loss of rupture energy was comparatively lower. After exposure to high temperature, the behaviour of the samples was more sensitive to the volume fraction and aspect ratio of the fibre than to its type. The coefficients of variation (COVs) of the rupture energy for SFRC specimens heated to higher temperatures is similar to those of the tensile strength, although the results are considerably more scattered than the compressive strength. A model predicting the residual tensile strength of heated SFRC measured by the DPT was proposed based on the test results.

1. Introduction

Fires in concrete structures such as tunnels and buildings expose the concrete to very high temperatures; its surface can reach above 1000 °C, and heat transfers can raise the interior of the concrete to 300–700 °C. Hot concrete suffers chemical and physical reactions such as dehydration and decomposition, which degrade its material properties (e.g., strength and modulus of elasticity) [1,2]. Such deterioration can induce cracking, and the rapid increase of vapour pressure and thermal stresses in the concrete after the heat exposure result in spalling of concrete and perforation [3,4]. To overcome these problems, steel fibre can be incorporated to reinforce the concrete. Steel fibre improves the properties of high-strength concrete after exposure to high temperatures and controls the cracking behaviour [5]. Therefore, steel-fibre-reinforced concrete (SFRC) is commonly used to construct such as tunnel linings, precast segments, flat slabs, and road paving; it is also used in various repairs.

Various works have studied the fire resistance and mechanical properties of SFRC after its exposure to high temperatures [6–12]. Poon et al. [6] reported the effects of elevated temperatures (600 °C and 800 °C) on the compressive strength stress–strain relationship (stiffness) and energy absorption capacities (toughness) of concrete reinforced with steel fibres in compression. Lau and Anson [7] investigated the loss of compressive strength and flexural strength of SFRC exposed to maximum temperatures of 105 °C and 1200 °C. Colombo et al. [8] discussed the decay of peak
and post-cracking strengths versus the increase in temperature for uniaxial compression, uniaxial tension, and bending. Tai et al. [9] discussed the compressive strength, elastic modulus, and peak strain of steel-fibre-reinforced reactive powder concrete in quasi-static loading after its exposure to high temperature (200–800 °C).

As outlined above, various studies have presented the effect of high temperatures on the mechanical properties of SFRC, with attention paid to the strength and toughness in compression, and to the splitting and flexural strengths. However, little information is available on the energy absorption capacity (or toughness) of heated SFRC in tension, despite the importance of tensile resistance as a benefit of SFRC. Sukontasukkul et al. [13] reported the changes in flexural toughness of SFRC exposed to high temperatures of 400 °C, 600 °C and 800 °C via four-point bending tests using a beam specimen [14,15]. They described that the post-peak strength and the toughness increased after exposure to relatively low temperatures near 400 °C, while these properties decreased with further heating. However, they did not report the degree of dispersion of their data acquired using the four-point bending method—which is a popular method for testing the quality of concrete and fibre-reinforced concrete (FRC) due to its simple methodology, but has a drawback in that the resulting strength and toughness values are considerably scattered. For example, Bernard et al. [16] reported that the coefficients of variation (COVs) of the residual strengths of unheated fibre-reinforced shotcrete and concrete measured by the three-point bending test method are typically greater than 20% in post-crack performance. Barr et al. [17] reported a round robin test program for the notched beam-bending test recommended by the RILEM TC 162-TDF methodology. They found that the COVs for SFRC beams are higher than those for plain concrete beams and that the variability of the measured load increases as the beam aspect ratio increases. A major problem in using these test methods is that they are based on additional experimental data, including the rupture energy of the heated SFRC.

2. Experimental programme

2.1. Materials and specimen preparation

The main variables investigated here are listed in Table 1. The hooked steel fibres (aspect ratios 60 and 80) and the twisted steel fibres (aspect ratio 80) used in the SFRC are depicted in Fig. 1. The fibres were applied at three volume contents (0.25%, 0.5%, and 1%): representative of SFRC used in tunnel linings—to cover a majority of the range of practically used volume fractions. The tensile responses of normal concrete were also compared with those of the different SFRCs. The properties of the steel fibres are listed in Table 1, and the details of each specimen’s composition were presented in Table 2.

All cast specimens were stored in air at ambient temperature for two days prior to demolding. After demolding the specimens, they were cured in a water bath for 26 days. After drying the specimen taken from the water bath for 14 days, they were exposed to high temperature. Because the mechanical properties of concrete subjected to high temperatures are dependent on the moisture content of the specimen, temperature for 24 h. Their physical properties were then tested.

The DPT assessed cylindrical specimens using punches of 38 mm diameter and 25 mm thickness, as recommended by Malatesta et al. [26]. A universal testing machine of capacity 2000 kN running in displacement control was used to conduct the tests (Fig. 2). The speed of displacement during testing was 0.3 mm/min. Six specimens of each type were tested to examine the dispersion of the results.

2.2. Test set-up and procedure

The SFRC specimens were heated in an electric furnace capable of heating up to 1000 °C, and exposed to a maximum temperature of room temperature, 300 °C, 500 °C, or 700 °C. The furnace was heated to the required temperature 1 h before the heating of the samples. Once the temperature was reached, the specimens were held in the furnace for 2 h before being removed and left to cool naturally to room temperature for 24 h. Their physical properties were then tested.

The DPT assessed cylindrical specimens using punches of 38 mm diameter and 25 mm thickness, as recommended by Malatesta et al. [26]. A universal testing machine of capacity 2000 kN running in displacement control was used to conduct the tests (Fig. 2). The speed of displacement during testing was 0.3 mm/min. Six specimens of each type were tested to examine the dispersion of the results.

To examine the effects of the fibre (its type, aspect ratio, and volume fractions) on the mechanical properties of SFRC exposed to high temperatures, direct tensile strength proposed by Blanco et al. [31] and rupture energy were used. The rupture energy is determined from the area under the curve of applied load versus total circumferential opening displacement (TCOD). The direct tensile strength (f ut) can be estimated as follows:

\[ f_{ut} = \frac{F_{p max} \cos \beta - \mu_s \sin \beta}{2EA \sin \beta + \mu_s \cos \beta} \]

where:

- \( A \) is the cross-sectional area of the cylinder
- \( d \) is the cylinder diameter
- \( b \) is the punch diameter
- \( E \) is the elastic modulus
- \( F_{p max} \) is the maximum load
- \( \mu \) is the friction coefficient
- \( \beta \) is the angle between the load line and the horizontal

Table 1: Test variables.

| Fibre type     | Tensile strength (MPa) | Diameter (mm) | Length (mm) | l/d | Exposed temp. (°C) | Exposure time (h) | Mix ratio (Vol.%)
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hooked fibre</td>
<td>1050</td>
<td>0.5</td>
<td>30</td>
<td>60</td>
<td>Amb.</td>
<td>2</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.75</td>
<td>60</td>
<td>80</td>
<td>300</td>
<td>0.25</td>
<td>0.50</td>
</tr>
<tr>
<td>Twist fibre</td>
<td>2450</td>
<td>0.5</td>
<td>40</td>
<td>80</td>
<td>500</td>
<td>0.50</td>
<td>1.0</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>700</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A transducer (LVDT) was mounted in the frame. Power microscope (100× magnification) (Fig. 4). Both types of fibre visibly deteriorated after heating to 300°C and above. They showed significant colour change caused by oxidation, and their surface damage is more apparent with increasing of heating temperatures. The result indicates that thermal damage to the fibres caused the deterioration of their bonding in the concrete matrix, and then mechanical property of SFRC is degraded.

2.3.3. Fracture patterns

Fig. 5 illustrates the failure patterns of SFRC specimens exposed to high temperatures. Specimens failed by cracks propagate from the edge on compressive section formed by steel wedges to cylinder border. The fracture patterns of specimens exposed to room temperature and 300°C specimens were characterized by two or three main cracks forming an angle of approximately 120°, as shown in Fig. 5. A similar pattern is also reported in the literature [26]. After exposure to high temperatures of 500°C and 700°C, specimens showed clear color change and damage: the occurrence of cracks increased with the increasing maximum temperatures. Specimens heated to above 500°C began increasingly to crack and appeared whites owing to the effects of dehydration or chemical reactions. The three or four main cracks, with minor radial cracks, which were randomly distributed (Fig. 5d, h and l) were observed. These failure modes are considered to be influenced by the deterioration of the matrix properties of the SFRC and the damage of fibres.

2.3.4. Change in DPT tensile strength

Residual tensile strength of the heated SFRCs measured by DPT (and their COVs) and the relative strength to the strength of unheated specimens are summarized in Table 3. It was found that there is a steady loss in tensile strength with an increase in temperature. The tensile strength of the SFRC specimens heated at 300°C, 500°C, and 700°C were respectively about 75–65%, 65–39%, and 46–22% compared to the value before heating. These differences are mainly attributed the deterioration of the matrix properties of the SFRC and the damage of fibres.

Table 2
Compositions of SFRC mixtures.

<table>
<thead>
<tr>
<th>Mix ratio (Vol.%)</th>
<th>Compressive strength $f'_c$ (MPa)</th>
<th>W/B (%)</th>
<th>S/a (%)</th>
<th>Unit weight (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>31.1</td>
<td>46.65</td>
<td>39.36</td>
<td>189.44</td>
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<tr>
<td>0.25</td>
<td></td>
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<td></td>
<td>406.07</td>
</tr>
<tr>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td>652.78</td>
</tr>
<tr>
<td>1.0</td>
<td></td>
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<td></td>
<td>1005.54</td>
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<td>Steel fibre</td>
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<tr>
<td></td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

where $A$ is the area of the cracked radial surface, $h$ and $d$ are the height and radius of the cylinder specimen, respectively, and $l'$ is the radius of the punch. $F_{\text{max}}$, $\beta$ and $\mu_b$ are the maximum load and failure angle and kinetic friction coefficient. In this study, 25° and 0.7 were considered as $\beta$ and $\mu_b$, respectively.

To measure TCOD at half the height of the cylindrical specimens, a special steel frame was attached to the specimen (see Fig. 2), and a linear variable differential transducer (LVDT) was mounted in the frame.

2.3. Test results and general discussion

2.3.1. Change in residual compressive strength of SFRC at elevated temperatures

The residual compressive strengths (average of three results) of SFRC specimens exposed to 15°C (room temperature), 300°C, 500°C, and 700°C are plotted in Fig. 3. As expected, exposure to higher temperatures degraded the compressive strength of the SFRC. A significant loss of strength occurred above 300°C. The residual strengths of SFRC heated to 300°C, 500°C, and 700°C were respectively about 92%, 60%, and 30% of the value at the room temperature. The losses in compressive strength of specimens changes in structure and composition of concrete during heating. The COVs of the residual compressive strength of all SFRC specimens are less than 5%. The dashed line in the graph plots the results predicted by the model for normal concrete designed to withstand fire [32]. Although the residual compressive strengths of SFRC predicted by the model were comparable with the test results, the predicted values are somewhat larger than those observed.

2.3.2. Damaged fibres

Heated fibres pulled from the tested specimens were examined under a high-power microscope (100× magnification) (Fig. 4). Both types of fibre visibly deteriorated after heating to 300°C and above. These differences are mainly attributed the deterioration of the matrix properties of the SFRC and the damage of fibres.

Fig. 1. Steel fibres used to reinforce concrete; (a) hooked fibres ($l/d = 80$), (b) hooked fibres ($l/d = 60$), and (c) twisted fibres ($l/d = 80$).

Fig. 2. Double punch testing.

Fig. 3. Comparison of residual compressive strength of SFRC specimens exposed to 15°C, 300°C, 500°C, and 700°C.

Fig. 5 illustrates the failure patterns of SFRC specimens exposed to high temperatures. Specimens failed by cracks propagate from the edge on compressive section formed by steel wedges to cylinder border. The fracture patterns of specimens exposed to room temperature and 300°C specimens were characterized by two or three main cracks forming an angle of approximately 120°, as shown in Fig. 5. A similar pattern is also reported in the literature [26]. After exposure to high temperatures of 500°C and 700°C, specimens showed clear color change and damage: the occurrence of cracks increased with the increasing maximum temperatures. Specimens heated to above 500°C began increasingly to crack and appeared whites owing to the effects of dehydration or chemical reactions. The three or four main cracks, with minor radial cracks, which were randomly distributed (Fig. 5d, h and l) were observed. These failure modes are considered to be influenced by the deterioration of the matrix properties of the SFRC and the damage of fibres.

2.3.3. Fracture patterns

Fig. 5 illustrates the failure patterns of SFRC specimens exposed to high temperatures. Specimens failed by cracks propagate from the edge on compressive section formed by steel wedges to cylinder border. The fracture patterns of specimens exposed to room temperature and 300°C specimens were characterized by two or three main cracks forming an angle of approximately 120°, as shown in Fig. 5. A similar pattern is also reported in the literature [26]. After exposure to high temperatures of 500°C and 700°C, specimens showed clear color change and damage: the occurrence of cracks increased with the increasing maximum temperatures. Specimens heated to above 500°C began increasingly to crack and appeared whites owing to the effects of dehydration or chemical reactions. The three or four main cracks, with minor radial cracks, which were randomly distributed (Fig. 5d, h and l) were observed. These failure modes are considered to be influenced by the deterioration of the matrix properties of the SFRC and the damage of fibres.
(a) Hooked fibres ($l/d = 80$).

(b) Hooked fibres ($l/d = 60$).

(c) Twisted fibres ($l/d = 80$).

**Fig. 4.** Damaged fibres exposed to 15 °C, 300 °C, 500 °C, and 700 °C.

(a) Twisted fibres: 0.25%, 15 °C
(b) Twisted fibres: 0.25%, 300 °C
(c) Twisted fibres: 0.25%, 500 °C
(d) Twisted fibres: 0.25%, 700 °C

(e) Twisted fibres: 1%, 15 °C
(f) Twisted fibres: 1%, 300 °C
(g) Twisted fibres: 1%, 500 °C
(h) Twisted fibres: 1%, 700 °C

(i) Hooked fibres: 0.5%, 15 °C
(j) Hooked fibres: 0.5%, 300 °C
(k) Hooked fibres: 0.5%, 500 °C
(l) Hooked fibres: 0.5%, 700 °C

**Fig. 5.** Cracking behaviour of SFRC exposed to 15 °C, 300 °C, 500 °C, and 700 °C.
The tensile responses of the heated SFRC specimens with 1% volume fraction twisted fibres are illustrated in the load–TCOD curves in Fig. 6. Each curve represents averaged data from three specimens. Significantly different load-carrying capacities were observed for the different maximum temperatures, with specimens being increasingly weak and increasingly less stiff with their increased heating up to 700 °C. The slopes of the ascending and descending curves varied with temperatures. The SFRC specimens exposed to 700 °C were less than 17%. However, the corresponding coefficients for samples heated to higher temperatures were about 10.1–32.8%. These results indicate that heating affects the residual tensile strength more greatly than it does compressive strength of SFRC.

### 2.3.5. Change of rupture energy in SFRC

The tensile responses of the heated SFRC specimens with 1% volume fraction twisted fibres are illustrated in the load–TCOD curves in Fig. 6. Each curve represents averaged data from three specimens. Significantly different load-carrying capacities were observed for the different maximum temperatures, with specimens being increasingly weak and increasingly less stiff with their increased heating up to 700 °C. The slopes of the ascending and descending curves varied with temperatures. The SFRC specimens exposed to 700 °C produced the lowest slope in load reduction after peak load, because the different thermal expansion coefficients of the matrix and the fibres caused microcracks to emerge upon heating. Fig. 6 also shows that after exposure to the elevated temperatures, the CTOD values at the peak loads of SFRC specimens are increased.

![Load–TCOD curves for SFRC specimens with twisted fibres 1% Vol.](image)

Fig. 6. Load–TCOD curves for SFRC specimens with twisted fibres 1% Vol.

The rupture energies of the heated SFRCs measured by DPT and their COVs, and relative rupture energy to the energy prior to the exposure to the high temperature are summarized in Table 4. The rupture energy also decreased with increasing maximum exposure temperature. After exposure to temperatures of 300 °C, 500 °C, and 700 °C, the rupture energy of the SFRC specimens were about 100–67%, 100–55%, and 78–51% of the value at room temperature. These percentages were higher than those for tensile strength. These results indicate that the loss of rupture energy was slower than that in residual tensile strength. The reason of the difference is that rupture energy of heated SFRC specimens is affected by both the internal microcracking in the matrix and the interfacial bonding behaviour between the steel fibre and the matrix [6,33]. The COVs values of DPT rupture energy for SFRC specimens heated to higher temperatures is similar to those of the tensile strength, although the results are considerably more scattered than the compressive strength.

### 2.4. Effect of fibre volume fraction

Residual DPT tensile strength relative to the strength prior to the exposure to the high temperature is plotted in Fig. 7 against the volume fraction of steel fibres in the variously heated SFRC specimens. As the fibre volume fraction increased from 0% to 1%, it was found that the residual DPT tensile strength of the heated SFRC specimens increased and its relative loss was decreased. These results indicate that the incorporation of steel fibres in concrete can improve the tensile properties of concrete exposure to high temperatures.

![Load–TCOD curves for SFRC specimens with hooked fibres 1% Vol.](image)

Fig. 8 shows load–TCOD curves for specimens with hooked fibres (l/d = 80) at 300 °C. All the tested fibre volume fractions (0.25–1%) exhibited a gradual drop after the peak load. The heated SFRC specimen with 1% fibre volume fraction exhibited the highest rupture energy capacity, because the fibre strengthened it. However, no significant differences were found in the stiffness of the SFRC specimens after exposure to 300 °C. Overall, results show that with increasing fibre content, the rupture energy of the heated SFRC specimens increased, but its relative loss increased (see Fig. 9), in contrast with the results for tensile strength. These results indicate that the deterioration of their bonding in the SFRC, caused by thermal damage to the fibres, was more pronounced for rupture energy than DPT tensile strength.

### 2.5. Effect of fibre type

Figs. 10 and 11 compare the DPT tensile strengths and rupture energies of heated specimens reinforced with two types of steel fibre (hooked and twisted fibres with aspect ratio of 80). Fig. 12 shows load–TCOD curves for specimens containing hooked or twisted fibres of 1% volume fraction after exposure to 700 °C. In general, the behaviour of the unheated SFRC specimens depended considerably on

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**Table 3** Residual DPT tensile strength results of SFRC.

<table>
<thead>
<tr>
<th>ID</th>
<th>l/d</th>
<th>Mix ratio (Vol.%):</th>
<th>15 °C Mean (MPa) COV (%)</th>
<th>300 °C Mean (MPa) COV (%)</th>
<th>500 °C Mean (MPa) COV (%)</th>
<th>700 °C Mean (MPa) COV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No fibre</td>
<td>-</td>
<td>-</td>
<td>3.02 (100%) 12.4</td>
<td>1.96 (65%) 5.0</td>
<td>1.40 (46%) 11.4</td>
<td>0.67 (22%) 20.8</td>
</tr>
<tr>
<td>Hooked fibre</td>
<td>0.25</td>
<td>3.49 (100%) 10.0</td>
<td>2.06 (59%) 10.5</td>
<td>1.64 (47%) 11.1</td>
<td>0.99 (28%) 32.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>3.35 (100%) 5.6</td>
<td>2.18 (65%) 16.8</td>
<td>1.62 (48%) 10.1</td>
<td>0.89 (27%) 18.1</td>
<td></td>
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<tr>
<td></td>
<td>1</td>
<td>3.21 (100%) 9.0</td>
<td>2.36 (75%) 12.0</td>
<td>2.10 (65%) 16.0</td>
<td>1.45 (45%) 19.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60 0.25</td>
<td>3.33 (100%) 9.4</td>
<td>2.19 (66%) 9.6</td>
<td>1.41 (42%) 24.5</td>
<td>0.83 (25%) 18.1</td>
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<tr>
<td></td>
<td>0.5</td>
<td>3.17 (100%) 4.9</td>
<td>2.12 (67%) 10.9</td>
<td>1.64 (52%) 11.8</td>
<td>0.90 (28%) 11.8</td>
<td></td>
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<tr>
<td></td>
<td>1</td>
<td>3.02 (100%) 6.0</td>
<td>2.12 (70%) 12.9</td>
<td>1.63 (54%) 14.7</td>
<td>1.03 (34%) 17.8</td>
<td></td>
</tr>
<tr>
<td>Twisted fibre</td>
<td>0.25</td>
<td>3.62 (100%) 8.5</td>
<td>2.12 (59%) 13.8</td>
<td>1.41 (39%) 18.5</td>
<td>0.90 (25%) 13.4</td>
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</tr>
<tr>
<td></td>
<td>0.5</td>
<td>3.31 (100%) 7.2</td>
<td>2.20 (66%) 9.3</td>
<td>1.61 (49%) 18.3</td>
<td>1.04 (31%) 24.8</td>
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<tr>
<td></td>
<td>1</td>
<td>3.11 (100%) 3.8</td>
<td>2.25 (72%) 14.5</td>
<td>1.66 (53%) 18.0</td>
<td>1.44 (46%) 29.5</td>
<td></td>
</tr>
</tbody>
</table>

(1): Relative residual tensile strength expressed as a percentage of strength before exposure.

---

**Table 4** Residual DPT rupture energy results of SFRC.

<table>
<thead>
<tr>
<th>ID</th>
<th>l/d</th>
<th>Mix ratio (Vol.%):</th>
<th>15 °C Mean (kN mm) COV (%)</th>
<th>300 °C Mean (kN mm) COV (%)</th>
<th>500 °C Mean (kN mm) COV (%)</th>
<th>700 °C Mean (kN mm) COV (%)</th>
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<tbody>
<tr>
<td>No fibre</td>
<td>-</td>
<td>-</td>
<td>3.39 (100%) 24.44</td>
<td>102.23 (3016%) 47.20</td>
<td>154.68 (4563%) 25.00</td>
<td>119.66 (3450%) 35.91</td>
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<td>Hooked fibre</td>
<td>0.25</td>
<td>221.12 (100%) 13.81</td>
<td>221.43 (100%) 16.75</td>
<td>222.35 (101%) 8.38</td>
<td>171.59 (78%) 12.2</td>
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<tr>
<td></td>
<td>0.5</td>
<td>287.35 (100%) 30.79</td>
<td>191.1 (67%) 36.34</td>
<td>221.63 (77%) 7.28</td>
<td>155.87 (54%) 13.93</td>
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<tr>
<td></td>
<td>1</td>
<td>330.93 (100%) 30.26</td>
<td>321.91 (97%) 10.87</td>
<td>387.17 (117%) 9.34</td>
<td>253.14 (76%) 10.49</td>
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<tr>
<td></td>
<td>60 0.25</td>
<td>233.39 (100%) 8.00</td>
<td>216.44 (93%) 10.63</td>
<td>185.19 (79%) 30.04</td>
<td>150.16 (64%) 8.33</td>
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<td></td>
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<td>272.14 (100%) 19.12</td>
<td>211.47 (85%) 22.86</td>
<td>226.56 (83%) 12.72</td>
<td>168.62 (62%) 4.7</td>
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<tr>
<td></td>
<td>1</td>
<td>274.59 (100%) 32.55</td>
<td>216.9 (79%) 17.88</td>
<td>238.76 (87%) 27.04</td>
<td>175.27 (64%) 15.78</td>
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<tr>
<td>Twisted fibre</td>
<td>0.25</td>
<td>217.66 (100%) 17.89</td>
<td>214.96 (99%) 32.00</td>
<td>185.95 (85%) 11.91</td>
<td>143.79 (66%) 15.9</td>
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<td>0.5</td>
<td>319.05 (100%) 5.26</td>
<td>264.02 (83%) 20.18</td>
<td>234.09 (73%) 19.65</td>
<td>161.91 (51%) 6.09</td>
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<td>409.71 (100%) 13.72</td>
<td>305.27 (75%) 14.48</td>
<td>224.08 (55%) 10.10</td>
<td>254.66 (62%) 32.93</td>
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</tbody>
</table>

(1): Relative residual rupture energy expressed as a percentage of strength before exposure.
the fibre type; the concrete reinforced with the twisted steel fibre showed better energy capacities than that reinforced with the hooked steel fibre [19]. In this study, there was no clear increasing or decreasing trend in the tensile strength and rupture energy of the heated SFRC specimens that depended on whether the fibre was hooked or twisted, at all the tested fibre volume fractions. These results indicate that there is no noticeable effect of fibre type on the tensile resistance and energy absorption capacity of SFRC specimens after their exposure to high temperatures.

2.6. Effect of fibre aspect ratio

Figs. 13 and 14 showed that the aspect ratio of the steel fibre significantly influenced the enhancement of the tensile performance of the SFRC exposed to high temperatures. After heating, at all tested temperatures and fibre contents, all the test series with hooked \((l/d = 60 \text{ and } 80)\) and twisted fibres \((l/d = 80)\) exhibited a gradual drop after the peak load. SFRC with fibres of aspect ratio \(l/d = 80\) (hooked or twisted) presented a higher DPT tensile strength and rupture energy capacity than that containing hooked fibres of \(l/d = 60\) owing to the favourable effects of the large aspect ratio. The differences in the strength and rupture energy were more
significant at high temperatures and at high fibre volume fractions. Therefore, steel fibres having high aspect ratio should be used to improve the tensile strength and rupture energy of SFRC exposed to high temperatures.

3. Model for prediction of the residual DPT tensile strength

3.1. DPT residual tensile strength model for SFRC under high temperatures

As above mentioned, tensile strength decreased as the maximum temperature increased from 300 °C to 700 °C and the slope of the curves in Fig. 7 decreased as the volume fraction of fibre (either twisted or hooked) increased. Consideration of the effect of the aspect ratio of hooked fibre reveals that the slope of the curve decreased with the increasing aspect ratio of the fibre. These
results indicate that the DPT tensile strength of heated SFRC specimen can be predicted as a function of the fiber volume fraction. Therefore, Eqs. (2) and (3) were developed to estimating the tensile strength of the hooked fiber and twisted fibers, respectively. Eq. (2) is based on the fiber volume fraction and aspect ratio of fiber and Eq. (3) is the function of the fiber volume fraction.

\[
f_{\text{DPT}}; T = 0.0008 \frac{l}{d} - 0.03 \left( F - 0.113 \right) T + 100 f_{\text{DPT,amb}}, \tag{2}
\]

\[
f_{\text{DPT}}; T = 0.033 F - 0.117 T + 100 f_{\text{DPT,amb}}, \tag{3}
\]

where \(f_{\text{DPT}}; T\) is the DPT tensile strength (MPa) of the heated SFRC at temperature \(T\), \(F\) is the fibre volume fraction (%), and \(T\) is the maximum temperature (°C). \(f_{\text{DPT,amb}}\) is the DPT tensile strength (MPa) of SFRC at ambient temperature, \((T = 15^\circ C)\). The aspect ratio of fibre is denoted by \(l/d\). Note that the equations for the tested fibres are valid when the fibre volume fraction is varied between 0.25% and 1% and the maximum heating temperature is 300–700 °C.

### 3.2. Comparison of the proposed model with experimental results

The proposed model was compared with the experimental data reported in Colombo et al. [8] and Ding et al. [33]. Experimental conditions such as aspect ratio, mix ratio, and temperatures are summarized in Table 5. The strength of specimens with twisted fibers was not compared due to lack of experimental data.

Fig. 15 shows their experimental results and the predicted strength variations using Eq. (2). As shown in Fig. 15a, the analytical prediction (solid line) shows a reasonable agreement with the regression curve (dashed line) which was based on the experimental data at high temperature condition ranged from 200 °C to 700 °C.
600 °C. In Fig. 15b, the predicted strength values is 5–15% higher than that measured values, while the strength reduction rate of the two values is almost identical within the temperature ranges of 300–700 °C. Ding et al. [33] reported that the residual strength of the SFRC specimens with a fiber volume ratio of 0.69 is about 5–10% lower than that with a fiber volume ratio of 0.50 in the range of 300–600 °C. However, the residual strength with a fiber volume ratio of 0.69, predicted by the proposed model, is slightly higher than that with a fiber volume ratio of 0.50. Such results may be caused by the differences in the compressive strength of the SFRC and testing method. It is noted that the experimental data were obtained from the four-point bending test with a great scattering, compared to DPT tests. Therefore, the evaluation with the proposed model, which can consider the effect of mix ratio and aspect ratio of steel fibers, should be based on the experimental data with a small scattering like DPT tests which is used for normal strength test of SFRC.

4. Conclusions

The aim of this study was to investigate the effects of the type, aspect ratio, and volume fraction of fibre reinforcement in concrete on its mechanical properties after its exposed to high temperatures. The tensile strength and rupture energy capacity (toughness) of SFRC were measured by the DPT with high accuracy. Four different maximum temperatures were compared: room temperature, 300 °C, 500 °C, and 700 °C. Cylindrical specimens of 150 mm height and 150 mm diameter were reinforced with either twisted or hooked fibres of aspect ratio l/d = 60 or 80. The fibres were present at volume fractions of 0%, 0.25%, 0.5%, or 1%. The main findings of this study are as follows.

1. As the maximum temperature increased from room temperature to 700 °C, the SFRC weakened, lost stiffness, and showed reduced rupture energy, with the degradation depending on the type, aspect ratio, and volume fraction of the fibre. The tensile behaviour of the SFRC specimens was more sensitive to the volume fraction and the aspect ratio of the fibre than to its type. It was found that after the SFRC was exposed to high temperatures, there is a loss in mechanical properties relative to the properties prior to heating. The relative loss in tensile strength was higher than that in compressive strength, but the relative loss of rupture energy was comparatively lower. Furthermore, as increasing fibre content, the relative loss in DPT tensile strength of unheated specimens decreased, while that of rupture energy increased.

2. The COVs values of DPT rupture energy for SFRC specimens heated to higher temperatures is similar to those of the tensile strength, although the results are considerably more scattered than the compressive strength. These findings indicate that high temperatures affect the tensile properties of SFRC more greatly than they do the compressive strength, which is to be expected given that the tensile properties is directly correlated with internal microcracking as well as the behaviour of the interfacial bonding between the steel fibre and the matrix.

3. A model predicting the residual tensile strength of heated SFRC measured by the DPT was proposed based on the test results. The fibre volume fraction, in particular, and also the aspect ratio of the hooked fibre were considered in the model. However, additional research is needed to demonstrate the validity of the model for water/cement ratio and different aspect ratio of fibre.

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References


