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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.

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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

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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 [16] reported that the coefficients of variation (COVs) of the residual strengths of unheated fibre-reinforced shotcrete and concrete measured by the third-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 within the range of the considered mid-span deflections (for normal-strength concrete beams with 50 kg/m^3 fibre) was 10–35%.

The mechanical properties of SFRC degrade after exposure to high temperatures due to (a) a combination of dehydration and decomposition of hydrated pastes, (b) deterioration of the aggregates and fibres, and (c) different thermal expansion between the matrix and the fibres. The behaviour of SFRC exposed to high temperatures is also dependent on its composition, including the type, aspect ratio, and volume fraction the fibre, which are considered to be important factors [18–21]. Therefore, the results recorded for heated SFRC vary more greatly than those of unheated SFRC, because their mechanical responses are dependent on more factors. For these reasons it is necessary to examine heated SFRC using tensile test methods that give results that are not highly scattered, to allow exact investigation of the effects of each relevant factor on the concretes' mechanical properties.

Several methods are available to evaluate the tensile properties of fiber reinforced concrete [15,22,23]. Chen [24] proposed the double punch test (DPT), also known as the Barcelona test. This test method is an indirect test method to measure the tensile strength of cylindrical plain-concrete specimens and recently recovered by Chao et al. [25] and Malatesta et al. [26] for quality control of the tension behaviour of SFRC. A cylindrical specimen is subjected to compression loadings at the centres of its top and bottom surfaces by two steel punches. The main advantages of the DPT are its ease of procedure, relatively simple specimen preparation, and the lower variability in the measured results than those resulting from other test methods such as three- or four-point bending tests using beam specimens [27]. Chao et al. [25] reported that the COV of the results was less than 12%. Therefore, the DPT for assessing SFRC performance is more attractive than other methods.

In this study we discuss the influence of the type, aspect ratio, and volume fraction of the fibre on the mechanical properties of SFRC exposed to high temperatures. The tensile strength and rupture energy capacity of the heated samples were measured with high accuracy by the DPT. Following previous works [28,29], the changes in the tensile strength of SFRC under high temperature are discussed; a more comprehensive discussion is accomplished here 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 1.0%)—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 [4]. In total 240 cylindrical specimens (diameter 150 mm; height 150 mm) were prepared, six specimens for each test parameter. The average compressive strength was found to be 31.1 MPa at 28 days by compressive testing as per the ASTM C39 method [30].

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_{ct}) can be estimated as follows:

$$f_{ct} = \frac{F_{P\,max}}{2\pi A}\frac{\cos\beta - \mu_k \sin\beta}{\sin\beta + \mu_k \cos\beta} \tag{1}$$

$$A = \frac{hd}{4} - \frac{d'^2}{4\tan\beta}$$

Table 1
Test variables.

Fibre type	Tensile strength (MPa)	Fibre (mm)		l/d	Exposed temp. (°C)	Exposure time (h)	Mix ratio (Vol.%)
		Diameter	Length				
Hooked fibre	1050	0.5	30	60	Amb.	2	0
		0.75	60	80	300		0.25
Twist fibre	2450	0.5	40	80	500		0.50
					700		1.0