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Pull-out behaviour of straight and hooked-end steel fibres under elevated temperatures

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ABSTRACT

This paper presents the results of an experimental investigation into the effect of elevated temperature on the steel fibre-matrix bond characteristics. A series of pull-out tests on straight and hooked-end fibres embedded in four different cementitious matrixes, namely normal strength concrete (NSC), medium strength concrete (MSC), high strength concrete (HSC) and ultra-high performance mortar (UHPM) were performed. Ninety days after casting, the specimens were heated to target temperatures of 100, 200, 300, 400, 500, 600, 700 and 800 °C, respectively. The initial and residual thermal and mechanical properties of the concrete were investigated. It was shown that while the variation in compressive strength and pull-out response for different temperatures is relatively small up to 400 °C, further increase in temperature results in a reduction in the pull-out strength, especially for the temperature > 600 °C. At 800 °C, the maximum pull-out load of the hooked-end fibres with NSC, MSC and HSC decreased by 54%, 64% and 56%, respectively.

1. Introduction

Fire remains one of the major hazards for high-rise buildings, tunnels and other infrastructure. For this reason, many researchers have spent considerable effort towards understanding the effects that elevated temperatures have on building materials and elements [1]. This is particularly true in more recent times for newer materials, such as steel fibre reinforced concrete (SFRC). SFRC is now widely used as a primary construction material in a variety of applications due to its excellent performance in improving the tensile response of concrete and also its ability to control crack propagation [2–4]. However, like most other construction materials, the exposure of SFRC to high temperature results in a significant deterioration of the physical and mechanical properties of both component materials and their inter-relationship (i.e. bond) [5]. Bond is the mechanism through which tensile forces are transmitted between the steel fibres and the surrounding cement paste. A part of these forces are resisted by the cement paste, whilst the remainder is resisted by the fibres. The interfacial bond properties between the fibres and cement paste play a crucial role in controlling the mechanical properties of SFRC at both room and elevated temperatures. Therefore, the knowledge of the bond relationship is the first key step towards understanding the behaviour of SFRC structural elements at an elevated temperature. The bond characteristics are commonly assessed using the single fibre pull-out test, which is able to determine the interfacial properties between the fibres and the surrounding cementitious matrix [6].

The mechanical properties of SFRC at room temperature have received considerably more attention from the research community compared to those at the elevated temperature [7]. More recent attempts on the SFRC under the elevated temperature mainly focus on the mechanical rather than the thermal properties [8–10]. The primary mechanical properties that influence the fire performance of SFRC members are the compressive strength, tensile strength, elastic modulus and the stress-strain response in compression. Although steel fibres may not offer any obvious advantage from a fire-endurance point of view, it has been shown that steel fibres can be considered as an effective way in delaying the spread of cracking, and hence potentially improve the performance of concrete after exposure to high temperature [11]. However, due to variations in concrete strength, test methods and heating conditions, there is a lack of consensus on the SFRC behaviour under an elevated temperature in the available literatures.

The degradation of the mechanical properties of concrete at high temperature is mainly due to the physicochemical bond changes that occur in the cement paste and aggregate as well as thermal incompatibility between the cement paste and the aggregate [12]. The temperature-dependent properties also vary with the concrete strength. For example, researchers have found that high strength concrete (HSC) is more likely to experience dramatic spalling failure at a given elevated temperature compared with normal strength concrete (NSC), mainly owing to the finer pore structure in HSC [13]. It has also been shown that the occurrence of explosive spalling is more likely in HSC than NSC at similar levels of elevated temperature [14]. There are a number

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of measures which can be taken to effectively alleviate spalling under high temperatures for HSC such as the addition of polypropylene fibres [15], steel fibres [16] or hybrid fibres (steel and polypropylene fibres) [7], as well as protecting the exposed concrete surface with a thermal barrier [12].

As stated before, it is essential to have a proper understanding of the bond relationship between the steel fibres and the concrete matrix at elevated temperature in order to evaluate the deterioration in mechanical properties of SFRC; nevertheless, little information on this topic is available in the literature. In this context, the current paper presents an experimental study into the pull-out behaviour of both straight and hooked-end steel fibres under a range of elevated temperatures. The main objective is to investigate the bond mechanisms associated with the pull-out behaviour, and how these are affected by elevated temperatures. Four groups of cementitious mixtures with an initial compressive strength ranging between 33 and 148 MPa are included in the study. The results are essential in order to develop a better understanding of the effect of high temperature on the bond-slip characteristics and to further assess the degree of deterioration in mechanical properties of SFRC after high temperature exposure. The results of the experiments are presented and discussed in detail, with particular attention given to the most salient parameters such as concrete strength and fibre type.

2. Experimental program

2.1. Materials and sample preparation

Table 1 presents the four grades of concrete which were included in the experimental programme, namely normal strength concrete (NSC), medium strength concrete (MSC), high strength concrete (HSC) and ultra-high performance mortar (UHPM). The NSC mix design was prepared using ordinary Portland cement whilst the other three mixes all employed high strength Portland cement (i.e. CEM II 32.5R and CEM III 52.5N, respectively, in accordance with European standard EN 197-1 [17]). Silica fume, ground quartz and fly ash were also used for the preparation of the MSC, HSC and UHPM mixtures. Around 60% of the crushed granite aggregates were 6 mm in size and the remaining 40% were 10 mm. Two types of sand were used in experimental programme. As presented in Table 1, coarse grain sand (C.G.S., 0–4 mm) was used in the NSC, MSC and HSC mix design and very fine grain sand (F.G.S., 150–600 μm) was used in the UHPM concrete. A superplasticizer called TamCem23SSR was used to enhance the workability of the HSC and UHPM mixtures.

The geometrical properties of hooked-end fibres are depicted in Fig. 1a. The steel fibres used in this study were the commercially-available Dramix hooked-end fibres (3D 65/60 BG fibres) which were 60 mm in length (l_f), 0.90 mm in diameter (d_f) and had an aspect ratio of 65 and a yield tensile strength (f_y) of 1150 N/mm^2. The measured values of the hook geometry, namely l_1, l_2, α and β (as shown in Fig. 1) are given in Table 2. For the tests using straight fibres, the same samples were used with the hooked-ends cut off, as illustrated in Fig. 1b.

The pull-out tests on single steel fibres were performed using cubes with a side dimension of 100 mm for NSC, MSC and HSC, and cylinders with a diameter of 100 mm and height of 50 mm for the UHPM samples (this is because of the finer aggregates). In each test specimen, a single steel fibre was carefully placed through a hole which was made in the bottom of moulds. The embedded length (l_E) was one half of the overall fibre length (i.e. 30 mm). For each concrete mix, three additional cubes (again 100 mm in size) were prepared in order to determine the compressive strength of the mixture. The concrete was prepared using a laboratory pan mixer for the NSC, MSC and HSC, and a hobart mixer for UHPM (which is only used for fine materials without coarse aggregates). During preparation, the dry components were firstly mixed for approximately 1 min before water and the superplasticizer (for the HSC and UHPM) were added. This was then mixed for 11 min, which experience has shown is appropriate to result in a homogenous mixture. After casting and vibration, the specimens were covered with a thin polyethylene film to avoid retain the escaping moisture and left for 24 h at room temperature. The specimens were then removed from moulds and cured for a further 28 days in the conditioning chamber, where the temperature was held at 20 ± 2 °C and the relative humidity 96 ± 4%. All specimens were tested at an age of 90 ± 2 days and the average value of three specimens was adopted, both for the compressive strength and pull-out tests.

2.2. Heating scheme

After 90 days, the pull-out and compressive strength specimens were directly placed in the electric furnace. The free end of the steel fibre for the pull-out specimens was covered with heat insulation before placed in the furnace. A controlled furnace was used which is capable of achieving a maximum temperature of 1100 °C and a maximum heating rate of 36 °C/min. In this study, the specimens were heated to a maximum temperature of either 100, 200, 300, 400, 500, 600, 700 or 800 °C at a constant rate of 20 °C/min, based on the recommendations of Haddad and Shinnas [18]. Once the target temperature was reached, it was held constant for 1 h and then the specimens were allowed to cool in the furnace for 1 day before the compressive strength and pull-out tests were conducted. The temperature-time curve is presented in Fig. 2.

2.3. Test setup

The pull-out tests were performed on the cooled specimens using a specially designed grip system, as illustrated in Fig. 3, which was attached to an Instron 5584 universal testing machine. The grips were designed such that the forces applied to the fibre provided a true reflection of the real situation experienced by fibres bridging a crack. The body of the gripping system was machined in a lathe using mild steel and had a tapered end to allow the insertion of four M4 grub screws (Fig. 3). These were then tightened around the steel fibre to an equal torque for an even distribution of gripping pressure to minimize the deformation of the fibre ends and avoid breakage at the tip. Two linear variable

Table 1
Mix design of mixtures.

Matrix type	Cement (kg/m^3)	Silica fume (kg/m^3)	Fly ash (kg/m^3)	Quartz (kg/m^3)	Aggregate (kg/m^3)			Superplasticizer (kg/m^3)	Water (kg/m^3)	W/B (−)
					C.A	F.A				
						C.G.S	F.G.S			
					6–8 mm	0–4 mm	150–600 μm			
NSC	364[a]	–	–	–	979	812	–	–	200	0.55
MSC	350[b]	–	107	–	660	1073	–	–	205	0.45
HSC	480[b]	–	45	–	850	886	–	6	210	0.40
UHPM	710[b]	230	–	210	–	–	1020	30.7	127	0.11

[a] Portland-limestone cement CEM II 32,5R.
[b] Portland cement CEM III 52.5 N.