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Bond-slip behaviour of steel fibres in concrete after exposure to elevated temperatures

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HIGHLIGHTS

- Bond-slip behaviour of straight and hooked fibres in concretes after exposure to elevated temperatures is investigated.
- Hooked-end fibres showed better bond strength than straight fibres.
- Explosive spalling has been occurred above 500 °C and destroyed all UHPM's specimens.
- The reduction in bond strength at elevated temperatures is strongly related to the degradation of the constituent materials.

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ABSTRACT

The bond-slip mechanisms, associated with the pull-out behaviour of steel fibres embedded in concrete after exposure to elevated temperatures, are experimentally investigated. A series of pull-out tests have been performed on straight and hooked-end steel fibres embedded in four different types of concrete, namely, normal strength concrete (NSC), medium strength concrete (MSC), high strength concrete (HSC) and ultra-high performance mortar (UHPM). Ninety days after casting, the specimens were heated to a target temperature of either 100, 200, 300, 400, 500, 600, 700 or 800 °C. The effect of temperature on the mechanical and thermal properties of the steel fibres and concrete was also studied. The results showed that the bond behaviour of straight fibres is significantly influenced by heating. The influence of elevated temperatures on the bond characteristic of hooked-end fibre was twofold: the bond strength does not vary significantly for all matrixes in 20–400 °C, while the bond dramatically degraded in 400–800 °C, especially at temperatures greater than 600 °C. The reduction in bond strength at elevated temperatures is found to be strongly related to the degradation in properties of the constituent materials, i.e. the fibres and concrete.

1. Introduction

Steel fibre reinforced concrete (SFRC) is increasingly common in structural engineering owing to its ease of construction, structural performance and efficiency. Steel fibres are incorporated into cementitious materials in order to improve their ductility and energy absorption, and to resist or delay the development of cracks [1,2]. The main contribution of the fibres is to enable the concrete element to continue carrying loads after cracking has occurred, the so-called post-cracking behaviour [3]. SFRC is vulnerable to severe environmental conditions such as those which occur during a fire. At a high temperature, the mechanical and physical properties of the concrete and reinforcing steel fibres, as well as the bond characteristic between these materials, may significantly deteriorate. Hence, the strength of SFRC under various elevated temperatures can vary, depending mainly on the fibre-matrix bond strength. Therefore, the bond characteristic between the steel fibre and surrounding concrete subject to high temperatures urgently needs to be understood and quantified, especially for hooked-end fibres, which are amongst the most widely used of the various fibres available on the market.

There are two main mechanisms through which bonds develop between the concrete and fibres, namely physiochemical bond (i.e. adhesion and friction) and mechanical bond (i.e. interlock) [4]. The former is predominantly determined by the properties of the interfacial transition zone (ITZ) as well as the fibre surface properties [5]. This type of bond is the first mechanism to be activated in the pull-out process and mainly controls the pull-out resistance of straight fibres. For very plain fibres, with no deformities or bends, this is the only bond mechanism that is present. The second type of bond, mechanical interlock, is determined by the geometric

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deformations due to the fibre straightening with increasing tensile stress.

Numerous investigations have been conducted to improve the understanding of the bond-slip characteristics between steel fibres and concrete. The most effective mechanism for developing bond strength is through the presence of mechanical deformations in the fibre [6–8]. Whereas the bond characteristics between steel fibres and concrete at ambient temperature have been the subject of intensive investigation by researchers [9–11], for the high-temperature behaviour, information is much more limited, particularly in terms of experimental data. Much of the current knowledge of the high-temperature behaviour of SFRC is based on thermal and mechanical properties tests [12,13].

The behaviour of structural elements and materials in fire conditions is of paramount importance and carefully considered in structural design, particularly for high-rise buildings and other infrastructure. In these construction forms, SFRC is regularly used as a primary structural material [14–17]. The main concern from the structural performance point of view is the condition and integrity of the constituent materials (i.e. steel fibre and concrete) and also the bond characteristics between them, as the temperature increases. It is well established that concrete undergoes significant change in its chemical composition, physical structure and water content when subjected to elevated temperature [18,19]. These physical and chemical changes cause the aggregate to expand, whilst the surrounding cement paste experiences shrinkage. As a result of these transformations, the cement paste-aggregate bond is the weakest point in the concrete mix in fire [20,21]. This thermal mismatch between the aggregate and the cement paste cause the concrete to crack [22]. An assessment of the degree of deterioration in physical and mechanical properties of SFRC after exposure to high temperatures can be achieved by investigating the bond-slip characteristics. The fibre-matrix bond properties are commonly assessed using the single-fibre pull-out test [23].

This paper presents a series of experimental pull-out tests on both straight and hooked-end steel fibres; A total of four groups of concrete mixtures were investigated, which had an initial compressive concrete strength ranging between 33 and 148 MPa. The main objective of this research was to experimentally investigate the bond-slip mechanisms of both straight and hooked-end fibres at ambient and elevated temperature. The results of this experimental investigation are essential to better understand the effects that elevated temperature have on the bond-slip characteristics, and further to predict the post fire-resistance of SFRC structural elements.

2. Experimental programme

2.1. Materials

Four different concrete grades were investigated in these experiments, namely normal strength concrete (NSC), medium strength concrete (MSC), high strength concrete (HSC) and ultra-high performance mortar (UHPM). All were prepared using two classes of Ordinary Portland Cement (i.e. CEM II 32.5R and CEM III 52.5 N) according to European standard EN 197-1 [24]. Silica fume, ground quartz and fly ash were also used for the preparation of the MSC, HSC and UHPM mixtures. The aggregates consisted of crushed granite with a maximum size of 10 mm. Coarse sand (0–4 mm) was used in the NSC, MSC and HSC mix design and very fine sand (150–600 μm) was used in the UHPM mix design. A superplasticizer called TamCem23SSR was used to enhance the workability of the HSC and UHPM mixtures. The mix proportions are summarised in Table 1.

Both straight and hooked-end steel fibres were used in the pull-out tests. The commercial Dramix hooked-end fibres were 60 mm in length (L_f) and 0.90 mm in diameter (D_f), had an aspect ratio (L_f/D_f) of 65, and had tensile strength of 1150 N/mm^2. The geometrical properties of the hooked end fibres are depicted in Fig. 1 and detailed in Table 2. To study the anchorage effect of the hook, straight fibres were obtained by cutting the end hooks of the hooked fibres to ensure the consistency (see Fig. 1b). The cut fibres were examined to ensure only no deformed fibres were selected for experiments.

2.2. Specimens

The pull-out test specimens prepared were 100 mm cubes for NSC, MSC and HSC and 100 × 50 mm cylinders for the UHPM specimens (this is because of the finer aggregates in this mixture). The steel fibre was carefully embedded in the cement mixes. The fibre embedment length was 30 mm, which is half the length of the fibre used in this investigation. For each concrete mix, three additional 100 mm cubes were prepared in order to determine the compressive strength and mass loss of the mixture for each thermal level. Immediately after casting and vibration, the specimens were covered with a thin polyethylene film in order to minimise moisture loss and left for 24 h at room temperature. The specimens were demoulded after 24 h and then cured for a further 28 days in the conditioning chamber, which was controlled to have a temperature of 20 ± 2 °C and relative humidity of 95 ± 5%.

2.3. Heating scheme

At 90 days after casting, the specimens for the pull-out and compressive strength tests were placed in an electrical high-temperature furnace. For the pull-out specimens, the free end of the steel fibre was protected with heat insulation before the specimens were placed in the furnace. The specimens were then heated to a maximum target temperature of 100, 200, 300, 400, 500, 600, 700 or 800 °C, at a heating rate of 20 °C/min [18,25]. The target temperatures were maintained for 1 h, following which the specimens were allowed to cool down naturally before being tested at room temperature. It is noteworthy that for specimens heated to higher temperatures; the overall exposure duration was greater than for specimens heated to relatively lower temperatures as the specimens also follow the "heating up" period. The temperature-time curve of the furnace compared with the standard curve recommended in ISO 834 [26] and RWS [27] is presented in Fig. 2.

2.4. 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 to ensure an even distribution of gripping pressure and to minimise deformation or breakage of the fibre ends.

Two linear variable differential transformer transducers (LVDT) were used to measure the distance travelled by the steel fibre relative to the concrete surface during testing (i.e. the pull-out distance). They were held in place using aluminium sleeves on either side of the main grip body (Fig. 3). The LVDT had ball bearings at the tips to allow for accurate readings on the surface of the