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Steel fibers pull-out after exposure to high temperatures and its contribution to the residual mechanical behavior of high strength concrete

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HIGHLIGHTS

- The effect of high temperatures up to 500 °C on fiber reinforced concrete is analyzed.
- A numerical model that reproduces test results and is useful for design is presented.
- Degradation of the different mechanisms contributing to pull-out behavior is studied.
- Reduction of pull-out strength is lower than decrease of matrix compressive strength.
- Great part of post-peak flexure strength is preserved.

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ABSTRACT

Many concrete structures are exposed to high temperatures that produce material deterioration involving stiffness and strength loss. Although residual mechanical behavior of steel fiber reinforced concrete subjected to high temperatures has been studied in the last decades, the effect of the deterioration of each component of the composite behavior has not been assessed. This information together with a meso-mechanical model can be very useful for the design of steel fiber reinforced concrete to be used in structures that are expected to be exposed to high temperatures.

This paper analyzes the effect of temperature on steel fibers pull-out mechanism from a high strength concrete matrix and its contribution to the residual mechanical behavior of Steel Fiber Reinforced High Strength Concrete (SFRHSC). Pull-out tests of straight and hooked end fibers and uniaxial tension tests on the fiber filaments exposed to room and high temperature (300 °C, 375 °C and 475 °C) were performed. Additionally, two SFRHSC incorporating 30 kg/m^3 and 60 kg/m^3 of hooked end steel fibers and a plain High Strength Concrete (HSC) exposed to the same temperatures were studied. Uniaxial compression tests and bending tests on notched prisms were used to characterize the composite material. The experimental results were analyzed with the aid of a pull-out model and a meso-model for SFRHSC, both developed by the authors. It is shown that hooked end fibers pull-out strength was reduced after the exposure to high temperatures. Since concrete strength only contributes in a small region surrounding the hooks, the pull-out strength reduction can be mainly attributed to the reduction of steel strength and frictional effects due to high temperature exposition. HSC tension strength reduction begins earlier and it is proportionally greater than pull-out strength reduction. As a consequence, HSC bending strength decreases faster than SFRHSC strength.

1. Introduction

Many structures like industrial plants or nuclear power plants are expected to be exposed to high temperatures due to their functions. In addition, other structures can be accidentally exposed to thermal risk (e.g. tunnels, tall buildings) that threat personal and property safety.

Nowadays, cementitious composites are increasingly being used in construction and they are normally designed for specific applications [1] with special characteristics like high strength, low permeability and improved durability [2]. The counterpart of

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these superior performance cementitious materials are brittleness and higher vulnerability to high temperature exposure [3]. The addition of fibers can help counteracting these disadvantages and improving the composite behavior of Fiber Reinforced Concrete (FRC).

It is well known that FRC failure is strongly related to the fiber pull-out mechanism. Thus, a comprehension of the factors affecting the pull-out mechanism combined with other significant variables as the density and orientation of fibers in FRC is required to model FRC behavior [4]. Steel fiber pull-out involves fiber/matrix debonding and frictional sliding, but pull-out strength is mainly due to mechanical interlocking introduced by fiber conformation [4]. Pull-out tests made by Naaman and Najm [5] on different types of steel fibers (smooth, deformed and hooked end) embedded in mortar matrices with compressive strengths from 33 to 60 MPa indicate that deformed fibers resist pull-out in an oscillatory way, while hooked end fibers resistance decreases as the hook is straightened and travels along the matrix tunnel. As expected, pull-out load strength increases with the fiber embedded length but increments are more evident in straight fibers than in hooked end fibers [6,7]. Pull-out tests of fibers with an inclination of 30° show an increase of strength with respect to aligned fibers but the pull-out strength decreases for inclinations greater than 45° [6,8]. It was usually found that the lower the w/c ratio, the higher the concrete failure load. However, the w/c ratio plays a minor role in the pull-out behavior [9,10]. It was also observed that the fluidity of the matrix improves bond strength of straight and twisted steel fibers [11]. Results of single fiber pull-out tests for deformed and smooth steel fiber embedded in very-high strength concrete matrices confirm that the maximum pull-out load and the total pull-out energy increase as matrix strength increases for smooth, flat end and hooked end fibers that did not rupture [12–14].

The residual response of FRC after exposure to high temperatures strongly depends on fibers material. Many researchers have studied the behavior of fiber composites incorporating steel fibers, polypropylene fibers or a combination of both, after the exposure to high temperatures. Steel fibers improve residual mechanical properties [15] of concrete exposed to high temperature [16,17], being the gain more marked in tension [18,19] than in compression [20,21].

The reductions in flexural strength are lower in steel FRC (SFRC) than in plain concrete and the post-peak strength is less affected than first-crack strength. Bozkurt [22] showed that steel macro fibers provide better flexural strength to self-compacting lightweight concrete exposed to high temperatures than hybrid fibers. Khaliq and Kodur [18] also found that steel fibers improve tensile strength of self-compacting concrete tested at temperatures up to 400 °C.

Some SFRCs exposed to high temperatures exhibit strain hardening and keep an almost constant load capacity during the post-peak [23]. Similar results were obtained for slurry infiltrated fiber concrete (SIFCON) over 300 °C [24]; flexure strength decreases with temperature but behavior is more plastic due to the fiber-slip mechanism. For more severe exposure conditions, the degradation of the material is reflected by an increase in non-linearity [23]. Beglarigale et al. [24] attributed the stiffness and strength loss of SIFCON at high temperatures to the effect of micro-cracks that are formed at the areas of unhydrated grains and the $Ca(OH)_2$ concentration, the decomposition of calcium hydroxide that can lead to a damage as a result of lime expansion during the cooling period, increase in porosity, decomposition of hydration products (above 400 °C), destruction of C–S–H structure and decomposition of the limestone aggregate and powders ($CaCO_3$) around 750 °C. Moreover, the deterioration of SIFCON under temperatures higher than 600 °C can be attributed to the oxidation of external surface of steel fibers that produces a reduction of fibers cross section and fiber–matrix bond strength [24].

Like in plain concrete, the Young's modulus of fiber reinforced reactive powder concrete decreases with increasing temperature and the stiffness loss is faster than the compressive strength loss [25,26]. The compression stress–strain relationship of SFRC after temperature exposure presents increasing strength in the 200–300 °C range, then decreases in the 300–700 °C range and the stress–strain curves become flatter. Similar results were verified in the case of steel fiber reinforced recycled aggregate concrete [27] and hybrid steel and polyvinyl alcohol fiber reinforced concrete [28]. Favorable effects of steel fibers in residual compressive strength and surface cracking of concrete subjected to high temperatures were observed for thin fibers and not for thick fibers [29]. The residual behavior depends more on the volume fraction and aspect ratio than on fiber's axis shape (straight, hooked end, twisted) [21].

It was proved that testing conditions, i.e. performed while the specimens are still hot or after cooling (residual state), influence concrete mechanical behavior [1]. Nevertheless, the differences in mechanical properties are insignificant [30]; thus, residual mechanical properties can be safely used.

Some negative effects of steel fibers addition in the response of FRC after very high temperature exposure have been observed. Cracks between matrix and steel fibers appeared as a result of different thermal expansion coefficients and oxidation darken FRC [25]. At 750 °C steel fibers suffer partial melting and morphology and composition of fibers core can be affected. Partially melted fibers fill concrete cracks, fibers diameter is increased by oxide layer and they become brittle. All these phenomena result in a compromise of fiber pull-out mechanism [31]. Nevertheless, some of the benefits of adding steel fiber to concrete are retained after the exposure to high temperatures up to 1200 °C [16,32].

The research concerning the behavior of SFRC after heating have focused the attention on the composite behavior. Although there are experimental results from pull-out tests [33] available in the literature and the deterioration produced by other phenomena like corrosion [34,35] or alkali silica reaction [36–39] has been studied, the effect of temperature on a single fiber pull-out has usually been indirectly analyzed from FRC tension tests results [31,38,39]. Recently, Abdallah et al. [40] studied the pull-out behavior of steel fibers embedded in concrete after exposure to elevated temperatures. They found that pull-out behavior of straight fibers is significantly influenced by high temperature. In contrast, pull-out behavior of hooked end steel fibers is practically not affected by temperature up to 400 °C, while the pull-out strength shows a strong reduction for higher temperatures.

A comprehensive numerical study of the effect of temperature on the pull-out mechanism and on SFRC residual behavior is not yet available. Considering that fiber pull-out is the main mechanism responsible of FRC behavior, this paper experimentally and numerically analyzes the effect of high temperature on steel fiber pull-out response and identifies its impact on Steel Fiber Reinforced High Strength Concrete (SFRHSC) residual mechanical behavior.

2. Experimental program

Pull-out tests were performed on single hooked end and straight smooth steel fibers embedded in High Strength Concrete (HSC) matrix. These specimens were divided in four groups and three of them were exposed to high temperatures. In addition, individual steel fibers were also exposed to the same temperatures to characterize their residual tension behavior. The residual properties of a base HSC and two SFRHSC, under uniaxial compression and flexure were also evaluated.