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Evolution of the bond strength between reinforcing steel and fibre reinforced concrete after high temperature exposure

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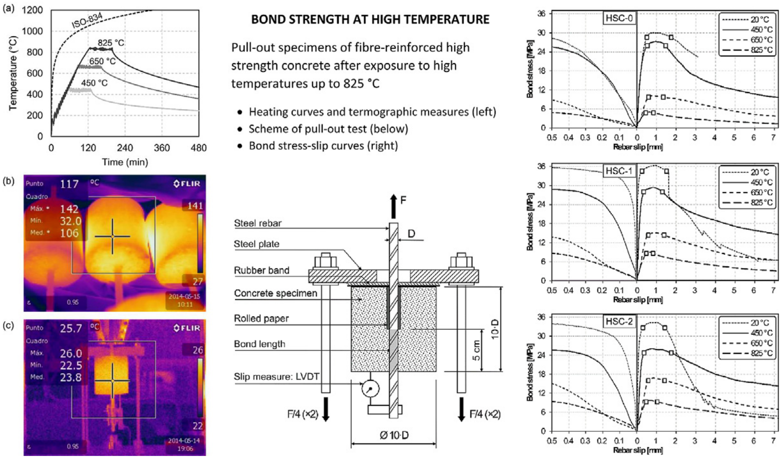
HIGHLIGHTS

- Influence of hybrid fibre addition on steel to concrete bond strength is studied.
- Compressive strength and pull-out tests made after high temperature exposure.
- Hybrid fibre addition proved beneficial to the peak bond strength up to 825 °C.
- Bond strength at elevated temperatures decreases due to loss of mechanical properties and degradation of bond condition.
- An adaptation of the local bond stress-slip curve given in Model Code 2010 has been presented.

GRAPHICAL ABSTRACT



BOND STRENGTH AT HIGH TEMPERATURE

Pull-out specimens of fibre-reinforced high strength concrete after exposure to high temperatures up to 825 °C

- Heating curves and termographic measures (left)
- Scheme of pull-out test (below)
- Bond stress-slip curves (right)

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ABSTRACT

Reinforced concrete structural strength depends on the bond between steel rebars and concrete. This mechanism can be compromised during a fire, but may be one of the least investigated phenomena in concrete research, and is not addressed in concrete design codes. This paper is focused on the characterization of the bond strength after exposure to temperatures up to 825 °C, by means of pull-out tests carried out in normal and high strength concrete, with polypropylene and steel fibres. Compressive and pull-out tests were performed after exposure to high temperature and cooling down to room temperature. Hybrid fibre addition including steel fibres with a high aspect ratio proved beneficial to the peak bond strength at the highest temperatures tested. However, high strength concretes exposed to 450 °C presented higher bond strength losses if steel fibres were added. Finally, equations are proposed for predicting the bond strength after high temperature exposure.

1. Introduction

Reinforced concrete (RC) became a structural material during the second half of the 19th century. Reportedly, one of several reasons was its good behaviour exposed to the high temperatures in accidental fire situations, especially when compared to other construction materials of that age, e.g. wrought iron. Concrete exhibits better fire performance than structural steel and recent history provides some notable though dramatic examples for this assertion: the fire in Windsor Tower (Madrid, 2005) and the fire in Grenfel Tower (London, 2017).

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The development of nuclear power plants in the 1970's and some industrial processes (e.g. the gasification tanks of carbon thermal power plants, where temperature might reach 1000 °C or even 2000 °C [1]) shifted the focus of concrete research to the evolution of its physicochemical and mechanical properties during or after exposure to elevated temperatures [2,3].

Research on the performance of high strength concrete (HSC) at high temperatures was carried out since the late 1970's. High strength and self-compacting (SCC) concretes have a more compact microstructure than normal strength concrete (NSC) and their internal structure make HSC and SCC more sensitive to the sloughing off or even the explosive spalling of the concrete cover in the hottest elements [4–11]. One of the causes of spalling is the thermal gradients and the thermal incompatibility of the different components of the reinforced concrete elements: the cement paste, the aggregates, the steel rebars and tendons [12–14], which have different coefficients of thermal expansion. Another cause of spalling is the dehydration of the C-S-H gel and the portlandite (400–600 °C), which generates water steam and provokes an increase of the pore pressure within the concrete. And yet another cause suggested in [15] is the calcination of $CaCO_3$ (600–900 °C) when calcareous aggregates are used; this chemical process expels CO_2 and may contribute to the pore pressure increase. Spalling is one of the greatest concerns when dealing with concrete structures exposed to fire. In the last two decades research has been focused on studying fibre-reinforced concrete (FRC) subjected to high temperatures. Polypropylene fibres, which melt at approximately 170 °C, have been proven adequate to control the spalling of concrete. Their melting creates an additional capillary pore network inside the concrete, which allows the release of the water steam generated by dehydration reactions [16–22]. Thus, the main objective of polypropylene fibres is not the structural reinforcement but rather the improvement of the fire resistance of concrete. On the other hand, steel fibres may be used in order to increase the residual strength of concrete after exposure to elevated temperatures [23–25]. However, some research [19] argues that the benefit of adding steel fibres may not be so obvious, since they contribute to speeding up the heating of the concrete and may be prone to producing internal micro-cracking because of thermal incompatibility with the concrete matrix. Hybrid fibre addition (steel and polypropylene) has been addressed in some recent research [16–19,26–28] and the experimental evidence suggest a synergy between both types of fibre, enhancing the mechanical properties of concrete.

Concrete fire design is covered by international codes and standards, such as the Model Code 2010 [29] and the Eurocode 2 [30]. Simplified approaches are proposed as well as more advanced methods based on tables or curves that describe the evolution of the compressive strength of concrete and other properties at high temperatures. Basis for advanced numerical modelling methods is also provided. Nonetheless, the loss of bond between the steel reinforcement and the concrete during or after exposure to elevated temperatures is not addressed in those standards. The structural strength of a RC element highly depends on an appropriate bond between steel rebars and concrete. This mechanism can be compromised during a fire, because important temperature gradients within the structural element may appear due to the difference in thermal conductivity of concrete and steel. Steel to concrete bond at high temperatures may be one of the least investigated phenomena in concrete research. Amongst the few references that have reported on this issue the following studies should be mentioned: Milovanov and Salmanov [31], Kasami et al. [32], Reichel [33], Diederichs and Schneider [34], Hertz [35], Morley and Royles [36], Ahmed et al. [15], Haddad and Shannis [37], Haddad et al. [38], Bingöl and Gül [39], Botte and Caspeele [40] and Lublóy and Hlavička [41]. Most of these studies focused on NSC but four of them [34,37,38,41] addressed HSC. Moreover, bond of rebars to FRC was studied in two of them [38,41]. Although RILEM pull-out test [42] is carried out in cubic or prismatic specimens, in most cases the bond strength at high temperature was nevertheless obtained through cylindrical specimens. Moreover, the bond strength was measured after heating to the reference temperature and cooling to room conditions (residual properties). According to the existing literature [1] residual properties are always lower than those measured in stressed tests or unstressed tests at high temperature. Hence the experimental evidence provided in the aforementioned papers is potentially conservative. Numerical models for studying the bond of reinforcement to concrete at high temperatures have been proposed [43–45]. These models use many of the experimental references given above for calibration.

This paper is focused on the characterization of the bond strength after exposure to high temperatures up to 825 °C, by means of pull-out tests carried out in six different batches of concrete, including normal and high strength concrete and the addition of polypropylene and steel fibres. The pull-out tests were carried out on cylindrical specimens after exposure to high temperature and cooling down to room temperature. Slips up to 7 mm were obtained to characterise and discuss not only the peak bond strength, but also the bond-slip curve and the potential increase of the ductility due to the addition of fibres. The evolution of the compressive strength of concrete after exposure to high temperature was also tested. The results are discussed and contrasted to some of the aforementioned experimental research.

2. Experimental procedure

2.1. Materials and specimen preparation

Six different fibre reinforced concrete (FRC) batches were prepared, divided into two different types of concrete: three of them were designed to obtain normal strength concrete (NSC), while the other three were high strength concretes (HSC). Limestone aggregates were used for both coarse and fine fractions; CEM II/B-M (S-L) 42.5R according to UNE-EN 197-1:2011 [46] was used for NSC, while a combination of silica fume and CEM I 52.5R was used for HSC. In order to obtain an adequate workability of the fresh mix, different water reducing agents were used and even combined: a modified hydroxycarboxylic agent (type A) was used for the NSC batches, whereas a mixture of a modified lignosulphonate agent (type B) and a polycarboxylate (type C) was used for HSC. Table 1 includes the dosages of these two reference concretes.

In previous experimental campaigns explosive spalling was observed in NSC, even with slow heating ratios [20]. Therefore, polypropylene (PP) fibres were used in the six batches to avoid integrity problems due to explosive spalling. On the other hand, two different steel fibres with diameters of 0.75 mm (type S1) and 0.35 mm (type S2) were used to prepare hybrid fibre reinforced concretes. The properties of these three types of fibres are given in Table 2. To sum up, the following six concrete types were prepared:

- NSC-0: control NSC, including PP fibres.
- NSC-1: hybrid fibre reinforced NSC, with PP fibres plus S1 steel fibres.
- NSC-2: hybrid fibre reinforced NSC, with PP fibres plus S2 fibres.
- HSC-0: control HSC, including PP fibres.

Table 1
Concrete dosages for normal (NSC) and high strength (HSC) concretes.

Material	NSC	HSC
CEM II/B-M (S-L) 42.5R	290 kg/m^3	–
CEM I 52.5R	–	450 kg/m^3
Silica fume	–	45 kg/m^3
w/c ratio	0.6	0.35
Fine aggregate (0–4 mm)	800 kg/m^3	865 kg/m^3
Coarse aggregate (5–11 mm)	1090 kg/m^3	865 kg/m^3
Water reducing agent type A	3.2 kg/m^3	–
Water reducing agent type B	–	4.95 kg/m^3
Water reducing agent type C	–	9.9 kg/m^3
PP fibres	1.5 kg/m^3	2.5 kg/m^3
Steel fibres*	20 kg/m^3	20 kg/m^3

* Only in hybrid fibre reinforced NSC and HSC.