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Temperature effects on the bond behavior between deformed steel reinforcing bars and hybrid fiber-reinforced strain-hardening cementitious composite

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HIGHLIGHTS

- Both steel and PVA fibers used in Hybrid-fiber reinforced SHCC.
- Rebar pullout tests used to determine bond.
- Fiber hybridization improves bond strength and pullout behavior at high temperatures.

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ABSTRACT

The authors have recently developed a hybrid fiber-reinforced strain-hardening cementitious composite (HFR-SHCC) using steel and polyvinyl alcohol (PVA) fibers. When subjected to high temperatures (up to 800 °C), this HFR-SHCC retains a higher proportion of its tensile strength compared to SHCCs containing only PVA fibers. The objective of the current study is to experimentally investigate whether the improved material properties of HFR-SHCC at high temperatures lead to better bond with conventional deformed steel reinforcing bars (rebar) compared to other SHCCs and conventional concretes. Rebar pullout specimens with a deformed rebar centrally embedded inside a SHCC/concrete cylinder were used in this study to determine the rebar-matrix bond. The bond behavior of HFR-SHCC with deformed steel rebar was compared with two concretes of different compressive strengths, a commonly used PVA-SHCC containing only PVA fibers, and a PVA-SHCC with very high content of fly ash. The rebar pullout specimens were subjected to temperatures of 100 °C, 200 °C, 400 °C, 600 °C and 800 °C and were tested after cooling down to room temperature to determine the *residual* bond strength. Results show that while the specimens made with the conventional concretes exhibit the largest bond strength at room temperature, the specimens made with HFR-SHCC retain the largest proportion of their room temperature bond strengths after exposure to high temperatures and show a more ductile pullout behavior instead of the abrupt splitting failure exhibited by the other materials.

1. Introduction

The bond between a steel reinforcing bar (rebar) and conventional concrete provides strain compatibility between these two materials in reinforced concrete structures, which is necessary for resisting the applied loads through composite action. The rebar-concrete bond governs reinforcement detailing criteria such as development length and splice length in reinforced concrete structures [1]. As discussed in Section 2 of this article, the rebar-concrete bond behavior is dependent on the properties of concrete. Therefore, the reported effects of high temperatures on the properties of concrete are reviewed below, followed by a review of the reported effects of high temperatures on the rebar-concrete bond.

1.1. Temperature effects on the properties of concrete and FRC and their bonds with rebars

The mechanical properties of concrete degrade at high temperatures due to a variety of physicochemical mechanisms [2,3]. The uniaxial compressive strength of concrete reduces by about 20% after exposure to 400 °C [4] mainly due to the physical transformation of water to steam and its expansion within the concrete

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microstructure leading to micro-cracking and spalling. A more rapid decline in compressive strength occurs at temperatures greater than 400 °C due to chemical decomposition of hydration products [4]. The tensile strength of concrete reduces approximately linearly with temperature from about 100% at 100 °C to 0% at 600 °C. The factors affecting the behavior of concrete materials at high temperature include type of aggregate, rate and duration of heating, water/cement ratio and applied compressive stress during heating [3,5]. The properties of steel also deteriorate with increasing temperature [4,6], but the relative reductions are smaller than that for concrete.

Fiber reinforced concretes (FRC) containing either polymer or steel fibers have shown greater retention of their mechanical properties at high temperatures compared to conventional concretes. Polymer fibers melt at temperatures of about 180 °C to 230 °C and create pathways for the moisture to escape without causing micro-cracking and spalling, which improves the retention of the compressive strength of polymer-FRCs at high temperatures [7,8]. On the other hand, steel fibers do not melt, and provide crack bridging at high temperatures, which improves the retention of the tensile strength of steel-FRCs [7,9,10]. Thus, both the polymer and the steel fibers improve the mechanical performance of FRCs at high temperature, but through different mechanisms.

A summary of the results of a few studies on the temperature effects on the bond between steel reinforcement and concrete/FRC is presented in Fig. 1. Various researchers have used different protocols for heating and mechanical loading. The "Residual" protocol involves mechanical testing at room temperature after cooling down from the target temperature, whereas the "Hot" protocol involves mechanical testing at the target temperature. The "Stressed, hot" protocol involves mechanical stressing of specimens to a target load, followed by heating until failure under constant load. The "stressed, hot" protocol best simulates the conditions during an actual structural fire; however, it is the most difficult protocol to achieve in a laboratory.

In Fig. 1, the y-axis shows the bond strength after exposure to an elevated temperature, normalized by the bond strength at room temperature. For specimens tested using the "hot" protocol, the percentage reduction in the rebar-concrete bond strength at a given temperature is similar to the percentage reduction in the compressive strength of concrete at the same temperature [11]. However, for specimens tested using the "stressed-hot" protocol, the percentage reduction in the bond strength at the failure temperature is greater than the percentage reduction in the compressive strength of concrete at that temperature [11-13]. The mode of failure of the rebar pullout specimens changes from ductile pullout to brittle splitting due to reduction in the tensile strength of concrete at elevated temperatures [14]. The variation of rebar-concrete bond strength with temperature depends on the temperature, type of steel (plain or deformed), and on the integrity of concrete (absence of cracking) [14-17].

There have been only a limited number of studies on the influence of high temperature on the rebar-FRC bond behavior, and their results are shown in Fig. 1(b). The residual bond strength of

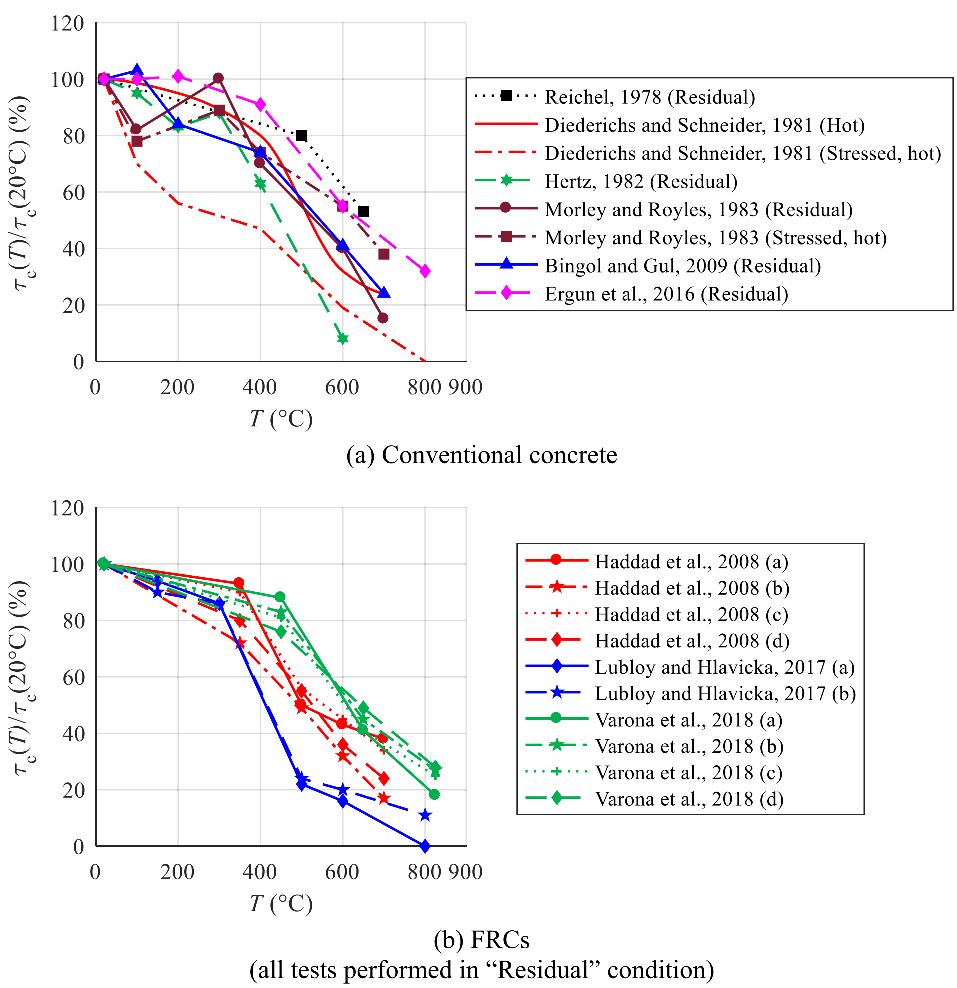

Fig. 1. Variation of bond strength with temperature. (Data for curves obtained from Refs. [11,12,14–20]).