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Bond strength of steel bars embedded in high-performance fiber-reinforced cementitious composite before and after exposure to elevated temperatures

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ABSTRACT

Interfacial bond strengths of steel reinforcing bars embedded in a high-performance fiber-reinforced cementitious composite (HPFRCC) are investigated in this paper. Out of 303 pullout specimens, 48 HPFRCC and 3 normal concrete specimens were tested without any heat treatment, and 240 HPFRCC and 12 normal concrete specimens were heated at 200, 400, 600, or 800 °C in a furnace for 2 h prior to testing. The effects of bar shape, diameter, and length embedded in HPFRCC on the bond strength of HPFRCC specimens were investigated. The bond strength decreased with the heating temperature and with the size and embedded length of steel bars. It was reduced further when the heated specimens were cooled in water instead of air. It was disaggregated into chemical adhesion and mechanical interlock from a comparative study of plain and deformed bars. The mechanical properties and microstructures of HPFRCC specimens before and after heat treatment were compared to understand the mechanisms of interfacial bonding degradation due to heat treatment.

1. Introduction

The bond strength between deformed bars and their concrete matrix can significantly affect the mechanical behavior and performance of reinforced concrete (RC) structures [1]. Intact bond at rebar-to-concrete interfaces ensures adequate stress transfer and deformation compatibility, thus eliminating localized failure under design loads [2,3]. However, interfacial debonding sometimes happens in practice, particularly at locations that are prone to cracking, due to lack of sufficient bond strength or embedment length [4]. In order to assess the load-carrying capacity of RC structures before and after exposure to high temperature or fire hazard, the rebar-to-concrete bond behavior and performance must be investigated.

Extensive research efforts have been made to understand rebar-to-concrete bond performance through pullout or pushout tests [5–9]. In general, the bond strength is primarily associated with chemical adhesion, mechanical interlock due to impingement of deformed bar's ribs into concrete, and friction between the rebar and concrete after debonding has taken place [10,11]. Prior to debonding, the dominant effect for deformed bars is usually the mechanical interlock, which largely depends on the mechanical strength of concrete [12,13]. When rebar is pulled, its interlock effect causes the shear stress in concrete between lateral lugs of the rebar and the tensile stress in concrete that laterally confines the rebar [2,3]. As rebar is pulled out of concrete, either concrete splitting failure or concrete shear failure (pullout) occurs [2], depending on various parameters such as the shape and dimension of rebar [5], mechanical strength of concrete [6], embedded length of rebar [7,8], and thickness of concrete cover [8,9]. Hence, increasing the mechanical strength of concrete is expected to enhance the bond strength. However, the mechanical strength of concrete degrades significantly at high temperature [14,15].

In recent years, various high-performance fiber-reinforced cementitious composites (HPFRCCs) have been developed to provide enhanced mechanical strengths. For instance, ultra-high-performance concrete (UHPC) with micro steel fibers was proposed to provide high compressive strength and tensile strength [16–19]. UHPC is typically prepared with a very low water-to-cementitious materials ratio ($w/cm < 0.25$), which results in refined microstructures with low porosity and permeability, thus leading to enhanced mechanical strengths and durability. However, some researchers reported that the low permeability tended to cause accumulation of vapor pressure at elevated temperatures, potentially leading to explosive spalling [20,21]. As temperature increases, vaporization of water is promoted, greatly increasing the pore pressure and internal stresses. Moreover, decomposition of cement hydrates takes

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Abbreviations: C, S; H, Calcium silicate hydrate; CH, Calcium hydroxide; HPFRCC, High-performance fiber-reinforced cementitious composite; PVA, Polyvinyl alcohol.
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place, which increases the water content and reduces the mechanical strength of concrete [22–25]. For instance, evaporable water and a part of the bound water vaporizes at 30–105 °C, gypsum and AFt/AFm phases decompose at 110–170 °C, a part of C—S—H dehydrates at 180–300 °C, dehydroxylation of CH undergoes at 450–550 °C, and calcium carbonate decomposes at 700–900 °C [25].

Polymer fibers were also introduced into concrete to form engineered cementitious composite (ECC) and provide high tensile ductility [26,27]. Like micro steel fibers, the polymer fibers can bridge cracks at normal temperature. Unlike micro steel fibers, the polymer fibers can create channels for relief of the vapor pressure at elevated temperatures [28–32]. The thermal pyrolysis of polyvinyl alcohol (PVA) fibers starts at about 180 °C and accelerates at about 250 °C [33]. The dehydration and decomposition reactions increase the total porosity and the average pore diameter [28], thus leading to reduction in mechanical strength and stiffness. When the concrete with low permeability is heated rapidly, the existence of thermal gradient and the buildup of vapor pressure can cause significantly increased internal stresses, resulting in cracking and/or explosive spalling [25]. With the adequate use of PVA fibers that provide pathways for vapor pressure relief, spalling can be prevented or mitigated [29]. Therefore, employment of PVA fibers can potentially increase the resistance of HPFRCCs to damage at high temperature. Although steel reinforced HPFRCCs have been demonstrated successfully for their enhanced structural performance at ambient temperature [34–36], their study at high temperature is limited in the literature. So far, rebar-to-HPFRCC bond after exposure to high temperature has never been studied though the bond strength is critical for the design and evaluation of HPFRCC structures exposed to high temperature or fire hazards.

The main objective of this study is to understand the behavior of bonding between deformed bars and HPFRCCs, and evaluate the bond strength and the parameters that influence the bond strength before and after exposure to temperatures at 200, 400, 600, and 800 °C, respectively. The investigated design parameters include the type, size, and embedded length of steel bars. Out of 303 pullout specimens tested, 48 HPFRCC and 3 normal concrete specimens were tested without heat treatment and 240 HPFRCC and 12 normal concrete specimens were heated at the target temperatures for 2 h prior to testing. The mechanical properties and microstructures of HPFRCC before and after heat treatment were investigated to understand the mechanism of bond degradation at high temperature.

2. Material preparation and characterization

2.1. Raw materials and mixing procedure

In this study, a HPFRCC mixture previously developed by the authors [37] was adopted to investigate the bond strength of steel bars embedded in HPFRCCs. The mixture was proportioned with ASTM Type I portland cement, Class F fly ash, finely ground quartz sand, PVA fibers, and water. The chemical composition and physical properties of the cement and fly ash are listed in Table 1. The quartz sand has a mean particle size (d_{50}) of 115 μm, a density of 2.63 g/cm^3, and a SiO_2 content of 98.9%. The PVA fibers are 12 mm in length and 0.04 mm in diameter. The fibers had a tensile strength of 1.62 GPa. The elastic modulus and Poisson's ratio of the fibers were 42.8 GPa and 0.42, respectively. The melting point of the PVA fibers was approximately 225 °C. The water-to-binder ratio was 0.24. The sand-to-binder ratio was 0.46. The fly ash content was 60% by mass of the binder system. The PVA fiber content was 1.7% by volume of the composite. A polycarboxylic acid superplasticizer was used at a dosage of 0.1% by weight of the composite to enhance flowability during preparation of test specimens. A viscosity modification admixture was used at a dosage of 0.02% by mass of the binder in order to adjust the rheological properties of the mixture [38]. A normal concrete designated as C50 was used for comparison. The compressive strength of the normal concrete at 28 days was 50.6 MPa.

Table 1
Chemical composition and physical properties of the cement and fly ash.

	Cement	Fly ash
SiO_2 (%)	18.9	46.9
Al_2O_3 (%)	4.9	28.5
Fe_2O_3 (%)	3.6	6.2
CaO (%)	64.1	2.3
MgO (%)	0.8	1.2
SO_3 (%)	1.7	0.9
Loss of ignition (%)	3.2	2.8
Specific surface area (m^2/kg)	350	460

The HPFRCC mixture was prepared using a 19-L mortar mixer. First, the dry materials (cement, fly ash, and quartz sand) were mixed at 60 rpm for 2 min. The superplasticizer was then dissolved in water, added into the mixer, and mixed at 120 rpm for 8 min. Finally, the PVA fibers were added in 2 min at 60 rpm and mixed at 120 rpm for 2 min.

2.2. Mechanical properties and microstructures

Both cubic and dog-bone specimens were used to characterize the mechanical properties and microstructures of the HPFRCC mixture. They were cast in one lift without applying any mechanical consolidation. In order to ensure a dominant fiber orientation, each specimen was cast by pouring the HPFRCC from one end and ensuring proper flow-through of the HPFRCC to the other end [38].

The compressive strengths of the mixture were evaluated using 71 mm standard cube specimens in accordance with JGJ/T70-2009 [39]. The specimens were tested using a load frame (model: MTS, capacity: 100 kN) at a rate of 0.02 mm/min. The tensile strengths were tested using dog-bone specimens, as depicted in Fig. 1(a). The dog-bone specimens were 30 mm wide and 15 mm thick within a 100 mm gauge length. The specimens were tested using the same MTS load frame at a rate of 0.5 mm/min. The applied load was measured using the load frame; the elongation of specimen was measured using a clip-on gage. Fig. 1(b) clearly demonstrated a ductile behavior of the HPFRCC materials under tension.

In total, 15 cubes and 15 dog-bone specimens were prepared and tested at various temperatures. The specimens were covered with a wet burlap and plastic sheet immediately after casting. They were stored at room temperature (22 °C) for 24 h, and then demolded and cured in an environmental chamber at room temperature and a relative humidity of 95± 5% till the age of 28 days. The specimens were divided into five groups in terms of the treatment temperature. For each temperature, 3 cubes and 3 dog-bone specimens were tested. One group of specimens was tested at ambient temperature without any treatment. The other four groups of specimens were respectively treated at a temperature of 200, 400, 600, or 800 °C. First, the specimens were dried in a drying cabinet at 100 °C for 24 h. Then, the specimens were heated in a computer-controlled, electrically heated furnace (dimensions: 300 mm × 500 mm × 200 mm) at a heating rate of 5 °C/min until the target temperature had been reached. The target temperatures were sustained for 2 h to achieve thermal steady state in the specimens, and then naturally cooled to ambient temperature for testing.

The test results of compressive and tensile strengths are plotted in Fig. 2. As the maximum temperature was increased from 22 to 200 °C, the average compressive strength was increased from 55 to 58.8 MPa (by 7%). After that, further increasing temperature reduced the compressive strength, due to the dehydration, dehydroxylation, and decomposition of hydrates and the pyrolysis of PVA fibers. The average compressive strength was reduced to 15.2 MPa after exposure to 800 °C. Due to deterioration at elevated temperatures, the PVA fibers experienced reduced tensile strength and ductility. As temperature was increased from 22 to 600 °C, the tensile strength was reduced from 4.4 to 1.3 MPa (by 70%). After exposure to 800 °C for 2 h, the dog-bone specimens became too fragile to test their tensile strength. After exposure to 200 °C for 2 h, the tensile ductility was reduced by 75%. After the temperature