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How do fiber shape and matrix composition affect fiber pullout behavior and flexural properties of UHPC?

Zemei Wu[a,b,*], Kamal Henri Khayat[a,b,**], Caijun Shi[a,***]

[a] College of Civil Engineering, Hunan University, Changsha 410082, PR China
[b] Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, Rolla, MO, 65401, USA

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ABSTRACT

The use of steel fiber is essential to secure high strength and ductility in producing ultra-high performance concrete (UHPC). In this study, the interfacial bond properties between embedded steel fibers with different shapes (straight, hooked, and corrugated fibers) and UHPC matrices proportioned with either 15% or 20% silica fume, by mass of binder, under different curing times were investigated. Flexural properties of UHPC reinforced with 2% different shaped fibers were also evaluated. Test results showed that corrugated and hooked fibers significantly improved the bond properties by three to seven times when compared to those with straight fibers. The flexural strength of UHPC with corrugated and hooked fibers were enhanced by 8%–28% and 17%–50%, respectively. Microstructural results from MIP, BSEM, and TG confirmed the change in bond properties. The bond strength of straight fibers exponentially increased with the decrease of calcium hydroxide content. Based on the composite theory, the flexural strengths of UHPC made with different shaped fibers can be efficiently predicted using the fiber-matrix bond strength, the flexural strength of the UHPC matrix (non-fibrous matrix), and the parameters of fibers. The ratios of predicted to measured flexural strengths ranged between 0.8 and 1.1, in which straight fibers showed a larger discreteness due to higher sensitivity of flexural strength associated with the orientation of fibers.

1. Introduction

Non-fiber-reinforced concrete is a quasi-brittle material that can undergo brittle failure under tensile load. The brittleness of concrete increases with the increase of concrete strength. In order to use it in structural elements subjected to tensile, fatigue, and impact loads, the design of this composite material should be optimized to ensure adequate strength, ductility, and energy absorbing capacity [1,2]. Ultra-high performance concrete (UHPC) is a new class of materials typically characterized by high content of cementitious materials (800–1200 kg/m^3), water-to-cementitious material (W/CM) ratio of 0.20 ± 0.02, use of 1%–4% steel fibers by volume of concrete [3]. The inclusion of short and randomly distributed fibers can significantly improve its strength and toughness [4,5].

The bond at the interface between the fiber and the matrix can greatly affect mechanical properties of the composite material, including that of UHPC. When a composite material is subjected to external loads, the matrix would initially sustain the load and then the fiber through stress transferring at the fiber-matrix interface [6]. When a fiber is pulled out from the matrix, two failure modes would occur: a debonding or a fracture of the fiber [12]. Fiber rupture will be observed if the pullout load that corresponding to the tensile strength of the fiber is lower than that of the shear strength of the matrix. This failure mode is not ideal from the point of view of reinforcement because of limited energy dissipation and underutilization of the potential mechanical property of the fiber [7,13]. Besides, the energy is released abruptly, which can dramatically decrease the toughness of the composite material. However, if appropriate high tensile strength approaching to the ultimate tensile strength of fiber is exerted, higher energy dissipated associated with the fiber-matrix interface could be obtained.

Several strategies can be used to improve bond properties at interfacial transition zone (ITZ) between the embedded fibers and the matrix, including: (1) densification of the cementitious matrix [8–10]; (2) use of deformed fibers [11]; (3) surface treatment of fibers, such as plasma treatment for polyethylene fibers [12]. The increase level of bond resulting from the use of deformed fibers appears to offer the highest degree of bond improvement [12,13]. The bond mechanism between embedded fibers and surrounding matrix typically includes

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[*] Corresponding author. College of Civil Engineering, Hunan University, Changsha 410082, PR China.
[**] Corresponding author. College of Civil Engineering, Hunan University, Changsha 410082, PR China.
[***] Corresponding author.
E-mail addresses: zemianmian@gmail.com (Z. Wu), khayatk@mst.edu (K.H. Khayat), cshi@hnu.edu.cn (C. Shi).

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three parts: (1) adhesion or chemical bond; (2) friction; and (3) mechanical anchorage and interlock of the fiber [14]. Adhesion is initially solicited during pullout testing and is closely correlated with the properties of the ITZ. After full debonding is attained, friction and/or mechanical anchorage between the fiber and matrix play a dominant role through the slippage of fibers [15,16]. The use of deformed fibers can efficiently enhance bond given additional mechanical interlocking provided by the fiber geometry [17,18], and hence tensile and flexural properties of UHPC [19,20]. Extensive research has been done by far about the effect of fiber shape on either fiber pullout behavior or mechanical properties of UHPC. However, there is a perceived lack of information on relationship between fiber pullout behavior and flexural properties of UHPC. How do fiber shape and matrix composition affect fiber pullout behavior and hence mechanical properties of UHPC remains an interesting topic.

This study aims at investigating the bond properties between different shaped fibers and matrix as well as its relationship with microstructure and flexural properties of UHPC. The influence of straight, corrugated, and hooked fibers on fiber-matrix bond properties and flexural properties of UHPC with 2% of these fibers were evaluated. Advanced materials characterization techniques, including mercury intrusion porosimetry (MIP), backscattered scanning electron microscopy (BSEM), and thermal gravimetry (TG) were employed to characterize the microstructure of the matrix and/or fiber-matrix interface. The bond strength related to either calcium hydroxide content of the UHPC matrix or flexural strength of UHPC was established.

2. Experimental program

2.1. Materials

Portland cement (P.I. 42.5), according to the Chinese Standard was used. The silica fume (SF) has a particle size in the range of 0.02–0.28 μm and SiO_2 content of 93.9%. Its BET surface area was 18,500 m^2/kg. Natural river sand with a maximum particle size of 2.36 mm and a fineness modulus of 3.0 was used. A polycarboxylate-based superplasticizer (SP) was used. Its solid content was approximately 20% and water-reducing efficiency was greater than 30%.

As shown in Table 1, three brass-coated steel fibers, including straight, hooked, and corrugated fibers with diameters of 0.2 mm and lengths of 13 mm, were selected for investigation. The tensile strength is approximately 2800 MPa.

2.2. Mixture proportion and sample preparation

Based on the previous study from the authors [21,22], UHPC mixture with 15%–25% silica fume, by mass of cementitious materials, can obtain denser microstructure and better bond to fiber. Therefore, 15% and 20% silica fume were incorporated in UHPC mixtures, which were designated as U15 and U20, respectively, to study the fiber pullout behavior and microstructure of matrix. Table 2 shows the mixture proportion. A water to cementitious materials (W/CM) ratio of 0.18 was adopted, and the dosage of a liquid-based SP in UHPC matrix with no fiber was fixed at 2%, by total mass of cementitious materials. In calculating the total water content in the mixture, the liquid phase in the SP was considered. For the investigation of flexural properties of UHPC, 2% straight, corrugated, and hooked fibers were incorporated alone using the U20 matrix (designated as UHPC in Table 2). In order to ensure good flowability of the UHPC mixture without vibration, 4% SP was adopted.

Table 1
Geometries of three selected fibers.

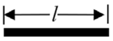
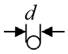
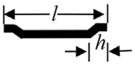
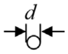
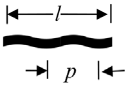
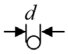
Shape	Geometry	Section	Details
Straight			l = 13 mm, d = 0.2 mm
Hooked			l = 13 mm, d = 0.2 mm, h = 0.2 mm
Corrugated			l = 13 mm, d = 0.2 mm, p = 6 mm

Table 2
Mixture proportion of matrix and UHPC.

No.	W/CM	Mass of ingredient (kg/m^3)					
		Cement	Sand	Water	SF	SP	Fiber
U15	0.18	917	1079	177	162	21.6	0
U20	0.18	863	1079	177	216	21.6	0
UHPC	0.18	863	923	166	216	43.2	156

Mixture ingredients were dry-mixed at a low speed for 3 min, then water and superplasticizer were slowly added. The materials were mixed for approximately 6 min at a low speed then 1 min at a high speed. The mixture was then cast into the mold. The specimens were demolded 24 h after casting and cured in lime-saturated water until 3, 7, 28, and 91 d.

2.3. Experimental methods

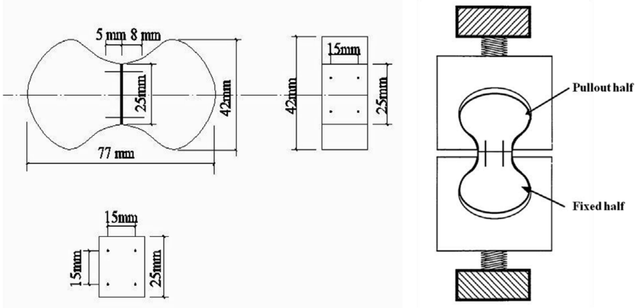
2.3.1. Fiber pullout testing

Dog-bone shaped specimens were used to measure the pullout behavior of four embedded fibers within the UHPC matrix. The fiber embedment lengths were 5 and 8 mm in the pullout and fixed half, respectively, from the center of the dog-bone sample, as shown in Fig. 1 (a). Plastic clips measuring 25 × 25 mm (Fig. 1(a)) with a thickness of 0.5 mm were used. This corresponds to the cross section at the center of the dog-bone shaped specimens. The clips were punched to get four holes with an evenly distributed space of 15 mm. The fiber length (5 mm in the pullout half) and orientation were ensured by using a thin bamboo substrate with four vertical holes at a depth of 5 mm. The fibers were then vertically fixed in the clips using glue. Detailed information for preparation of dog-bone shaped specimens and fiber pullout testing can be found in Ref. [21].

An MTS testing machine with 20 kN load cell was used. The loading rate was 1 mm/min. Pullout load-slip relationship was recorded. Five specimens were prepared for each group. To ensure the reliability of results, only the results of those specimens with all four fibers pulled out from the pullout half of specimen were used. The bond strength can be calculated as follows:

$$\tau_{max} = \frac{P_{max}}{n\pi dl} \tag{1}$$

where $\tau_{\max}$ (MPa) is the bond strength of the embedded fibers; $P_{\max}$ (N)



(a) Geometry of dog-bone shaped specimen (b) Pullout testing

Fig. 1. Illustration of dog-bone shaped specimen and pullout testing [21].