Microstructure and bonding behavior of fiber-mortar interface in fiber-reinforced concrete

Li Hong[a, b], Y. D. Chen [a], T. D. Li [a], Peng Gao [a, c*], L. Z. Sun [b*]

[a]Department of Structural Engineering, Hefei University of Technology, Hefei 230009, China
[b]Department of Civil and Environmental Engineering, University of California, Irvine, CA 92697, USA
[c]Key Laboratory of Performance Evolution and Control for Engineering Structures, Tongji University, 1239 Siping Road, Shanghai 200092, China

Abstract: The interfacial properties between fiber and matrix play a critical role in the overall mechanical responses of composite materials. In this paper, the glass fiber-mortar interfacial microstructure in fiber reinforced concrete (FRC) is visualized and characterized using X-ray microscopy. Additionally, three types of fiber-mortar interface (glass fiber, high modulus polyvinyl alcohol (PVA) fiber, and basalt fiber) are analyzed by scanning electron microscopy and energy dispersive X-ray spectroscopy. The results revealed a lot of microcracks along with the glass fiber-mortar interface; moreover, the hydration product of the glass/PVA/basalt fiber-mortar interface was much lower than that of the mortar matrix. Because microcracks or lower hydration product have such a negative effect on the interfacial bonding between fiber and mortar, the objective of this paper was to provide an analysis of this problem through extensive testing of their bonding properties. Specimens made of three types of fiber were tested along with three different mortar types were tested under tensile stress and a combined stress state to investigate the interfacial bond properties between fiber and mortar. Results show that both of the tensile and shear bond strength of the interface were not only improved by stronger mortar matrix, but also significantly affected by fiber type. Furthermore, when the

*Corresponding authors: penggao@hfut.edu.cn (Peng Gao) and lsun@uci.edu (L.Z. Sun).

interface failed by slipping along the interfacial area, the interface showed an increasing shear bond strength with the increase of compressive stress. This was not the case when failure was due to the crushing of mortar. Finally, the FRC splitting tensile strength was tested to demonstrate the bonding mechanism effects on the FRC mechanical properties.

Keywords: fiber-mortar interface; microstructure; tensile bond strength; shear bond strength; compressive stress.

1. Introduction

Among the many remarkable advances in concrete material technologies, fiber reinforced concrete (FRC) has become one of the most popular because of of its tensile strength characteristics. It is generally accepted that the overall performance of FRC-based composites is dependent on the properties of the fiber and matrix interface [1]. Qu [2] found the fiber-matrix interface to not only affect the fiber and matrix bond, i.e., the strength of FRC, but also the degradation of FRC because of the defects in the fiber-matrix interface. Experiments by Gray and Johnston [3] showed that the steel fiber-matrix interfacial bond was markedly strengthened by the mechanical properties of steel-fiber reinforced mortar. Thus, the interfacial bond's uniaxial tensile first-crack flexural strengths improved when the interface zone had the correct proportions of matrix mortar mix. The mortar mix also affected interfacial bond strength based on both the ratio and concentration of the

reinforcing fibers. Recent nanoindentation freeze-thaw (F-T) test results by Zhou et al. [4] reveal that the thickness of the ultra-high performance concrete (UHPC) interface between the steel fibers and cementitious matrix slowly increased from 22/¼m/at 0 cycle to 60/¼m/at 1500/F-T cycles. Naaman's 2003 article [5] introduced the newly developed steel fiber known as Torex, which had proven to be 2-3 times stronger than the other steel fibers marketed at that time. The new fiber was able to be twisted, which helped achieve better frictional and adhesive bond forces along the fiber interface in FRC thereby improving the overall mechanical properties of FRC. The new fiber was especially helpful in improving resistance to pull-out [5].

The single-fiber pull-out test usually determines the local mechanical properties of the interface between fiber and matrix, since it measures the uniaxial tensile pull-out load and corresponding slippage [6]. Steel fiber is the most widely used fiber in the civil engineering industry [7]. For that reason, the pull-out behavior of steel fiber in a cementitious matrix has been thoroughly studied, including the geometry of steel-fiber hooks [8], fiber orientation [9], the embedded length of fiber [9, 10], and matrix strength [11-13]. Beyond steel fibers, Singh et al. [14] studied the pull-out behavior of polypropylene fiber in a cementitious matrix under seawater and salt environments to determine the maximum pull-out load of concrete under seawater. Ali et al. [15] investigated the bond strength between coconut-fiber and matrix to examine the effects of embedment length, diameter, fiber pre-treatment condition, and the mix

design ratio of concrete. Choi et al. [16] revealed that the interfacial bond improved as the compressive strength of the cement matrix and the embedment length of single fibers increased. Alberti et al. [17] found that the interfacial shear strength and the critical length of polyolefin fibers were strongly influenced by the inclining fiber angle and the matrix strength.

FRC structures can be subject to many types of loading, including tensile loading, compressive loading, and impact loading. Moreover, the distribution of fibers in FRC is not uniform. However, fiber distribution largely depends on the pouring methods and the formwork shape. This can cause failure of a fiber-matrix interface in a combined stress state but not in an area where a shear stress singularity exists. Therefore, based on the fiber alignment with respect to the applied stress, the bonds of fiber-matrix interface can be divided into tensile, shear and a combined stress state within normal and shear stress. While most research efforts on single-fiber pull-out performance focus on the direct shear or combined tensile-shear bond strength, few studies have been carried out on interfacial bond behavior under tensile stress or on a combined stress state within normal compressive and shear stress. The current study, therefore, aims to clarify the relationship between FRC and its microstructure and to characterize the fiber-mortar interface of FRC based on its microstructure and mechanical properties including tensile bond strength and combined compressive-shear bond strength. First, an X-ray nano-CT was used to scan the glass fiber-mortar interface, which can visualize and quantify the interface at a large observational scale from sub-micron to millimeters. Meanwhile, a scanning electron

microscope (SEM) and an energy dispersive X-ray spectroscope (EDX) were used to characterize the microstructural properties of three kinds of fiber-mortar interface in depth, including glass fiber, high modulus polyvinyl alcohol (PVA) fiber, and basalt fiber. Second, a special fiber-mortar interface was designed and incorporated into certain specimens to explore their tensile and compressive-shear bond strength. In these tests, three types of fiber and three different mortar strengths were considered. Tests on the interfacial bond properties were then conducted and discussed. The FRC specimens made up of three types of fibers were tested to examine the effects of the interfacial bond strength on their splitting tensile strength. The final aim of this work was to define the reliable properties of the fiber-mortar interface for a numerical simulation of FRC and to create a design to maximize the FRC materials and structural members that support the fiber-mortar interface.

2. Microstructure at the interface between glass fiber and mortar

In this section, three-dimensional (3D) X-ray nano-CT was used to visualize the glass fiber-mortar interface, followed by in-depth SEM and EDX analyses to quantify the interfacial properties between glass/PVA/basalt fiber and mortar matrix.

2.1 Samples preparation

Short glass fibers with a length of 12 mm were prepared and appear in Fig.1. Their dimensions and mechanical properties are listed in Table 1. No treatment was applied to any glass fiber surface. The glass fibers were dispersed and added into the mixtures when their composition weight ratios were 0.49:1.00:1.55:3.44 of normalized water to local Portland cement (425R) to medium sand to coarse aggregate, respectively.

Cobblestones, with diameters between 5 mm and 20 mm, were used as coarse aggregates. The mass percentages of coarse aggregates with diameters of 5–10 mm, 10–16 mm, and 16–20 mm were 23.8%, 50.5% and 25.7%, respectively. The volume fraction of glass fibers was 1.0%. FRC specimens (100 × 100 × 100 mm) were demolded and placed in a room environment maintained at 25 ± 2°C and 100% R.H. for 28 days. Sample cylinders with an 8 mm diameter and 20 mm height were removed from FRC for drilling cores. Notably, the cylinder which had mortar and fibers but no coarse aggregate was adopted for nano-CT analysis, based on its better ability to present the microstructure of fiber-mortar interface in FRC. Moreover, FRC cubic specimens were cut into 1 mm thick slices or less using a diamond saw to expose the in fiber-mortar interfaces and aggregate-mortar interfaces. The sliced surfaces were coated with gold for SEM and EDX analysis, as shown in Fig. 1.

2.2 X-ray CT analysis

The X-ray nano-CT scans of cylinder samples were performed using a ZEISS Xradia 410 Versa X-ray CT scanner with nano-CT modality(Carl Zeiss X-ray Microscopy, Inc., Pleasanton, CA A total of 1601 projections were recorded by scanning the samples from -180° to 180° with a step size angle equal to 0.225°. Data were obtained with a spatial resolution of 5 μm for a total scanning time of 2.5 hours, and the volume of interest (VOI) was limited to 972 × 1,014 × 993 voxels (x, y, z), with a physical extent of 2.99 mm × 2.99 mm × 2.99 mm to avoid edge effects. Each voxel was distinguished by its gray scale value (GSV), which is correlated to the mean value of the linear attenuation coefficient (LAC). LAC was proportional to the

material density [18].

To enhance the contrast, a mean filter with a kernel size of 2 × 2 × 2 voxels was employed to scan the images using ScanIP software. A typical “slice” image of glass FRC is shown in Fig. 2. Based on the proportional relationship between voxel intensity and material density in FRC, Fig. 2(a) clearly shows that the dark areas on the images are pores or cracks, and the white areas are fine aggregates. The light gray area represents both the cement matrix and glass fiber densities (as shown in Table 1). The glass fiber density is close to that of the cement matrix, which is about 2.32 g/cm^3 [19]. Obviously, the thin light gray rods with the large aspect ratio in Fig. 2(a) are fibers. Notably, Fig. 2(b) shows microcracks (with a width between about 7 μm and 20 μm) at the interface between the glass fiber and mortar. This may be because the surface of glass fibers is hydrophobic [20]. Microcracks were also found at the steel fiber-mortar interface [21].

2.3 SEM and EDX analysis

To further characterize the microstructure of the interface between the fiber and mortar, SEM and EDX tests were carried out. In addition to the glass fiber, PVA fiber and basalt fiber were also adopted. Their material properties are also shown in Table 1. No treatment was applied to their surfaces. Figs. 3(a) to 3(d) show typical SEM micrographs of the fiber-mortar interface and aggregate-mortar interface. Like the nano-CT scans, the SEM tests also found microcracks near or at the glass fiber-mortar interface, as shown in Fig. 3(a), but the images had more details. Typical X-ray spectra for glass, PVA, and basalt fiber-mortar interfaces, the aggregate-mortar

interface, and the mortar matrix are illustrated in Figs. 4(a) to 4(e), from which the obtained Ca/Si ratios are approximately 2.25, 1.33 and 1.59, 1.23, 1.04, respectively. Figure 4(a) shows the glass fiber-mortar interface presenting the highest Ca/Si ratio at 2.25, followed by the basalt fiber-mortar interface in Fig. 4(c) at 1.59, and the PVA fiber-mortar interface in Fig. 4(b) at 1.33, which means the glass fiber-mortar interface had the lowest amount of the hydration product, i.e., calcium silicate hydrate (C-S-H). This confirms the initiation of microcracks formed in this interfacial zone, as shown in Fig. 2. The reason may be due to the fact that glass fibers are hydrophobic [20], PVA fibers are hydrophilic which yields hydrophilic interactions between the PVA fibers and the mortar matrix [22][23], and basalt fibers have a stronger chemical bond strength with mortar matrix because of their similar chemical compositions [24].

As expected, Fig. 4 shows that the fiber-mortar interface has a lower Ca/Si ratio than either the aggregate-mortar interface or mortar matrix. This indicates that the fiber-mortar interface has a lower amount of C-S-H, which may be caused by the smoother surface of fiber than that of aggregates.

3. Experimental procedures for the bond properties of fiber-mortar interface

3.1 Fiber types and mix proportion of materials

To study the effect of fiber type on the bond properties of the fiber-mortar interface, the authors chose glass, PVA, and basalt fibers, their properties are listed in Table 1.

To investigate the influence of mortar strength on the mechanical performance of the fiber-mortar interface, three different mortar types based on three different strength grades were made by mixing water, local Portland cement (425R), and

medium sand. These three different strength-defined mortars types were also defined by the ratios between water and cement (W/C), which were 0.65, 0.49 and 0.40, respectively, and by the ratios between cement and sand (C/S), which were 1.0:2.5, 1.0:1.5 and 1.0:1.1, respectively.

FRC splitting tensile specimens were manufactured with the same W/C and C/S values as mortar specimens, the ratios between medium sand and coarse aggregates were 0.56, 0.45, and 0.38, respectively. Cobblestones were also adopted as coarse aggregates, and their mass percentages for diameters of 5-10 mm, 10-16 mm and 16-20 mm were 23.8%, 50.5% and 25.7%, respectively. The volume fraction of fibers was 1.0%.

3.2 Experimental specimens and test methods

3.2.1 Tensile bond specimens

The interface between a single fiber and mortar is too small to obtain the direct tensile bond strength. The specimens used to test the tensile bond strength in Fig. 5 were made according to the protocol in [25] and [26], which include the following steps: First, fibers of 150 mm in length were arranged in neatly ordered rows on a steel plate. Plastic cylinders were then laid on the fibers' surface and filled with the different strength mortars. The cylinder heights and diameters of the mortars were 30 mm and 50 mm, respectively. The interfacial area is equal to the top area of the mortar cylinder. Four identical interfacial tensile specimens were made for each different mortar strengths and type of fiber. All specimens were cured under conditions of at 25±2°C and 100% R.H. for 28 days.

The bond strength of the fiber-mortar interface under tension was tested using a standard test set-up, described as follows: (1) The fibers in the specimens were fastened by special fixtures, as shown in Fig. 6(a); (2) the steel disc was attached to the surface of the mortar being tested using an epoxy resin, and a tension bolt of the tester was fixed to the steel disc, as illustrated in Fig. 6(b); (3) the increasing monotonic tensile loading was provided by the tester to take up the mortar cylinder from the surface of the fibers, as presented in Fig. 6(c). The displacement rate was 0.02 mm/s. The force and displacement at the ends were recorded by a data acquisition system during the test, as shown in Fig. 6(c).

3.2.2 Compressive-shear bond specimens

Figure 7 shows specimens made to test the bond properties of fiber-mortar interface under a compressive-shear combined stress state. After the fibers were arranged in neatly ordered rows and affixed with resin (Fig. 7(a)), the mortar was cast in 40 mm × 70 mm × 70 mm steel molds (Fig. 7(b)) and removed after each specimen was separated from its mold, as illustrated in Fig. 7(c).

After 28 days of curing under conditions at 25 ± 2°C and 100% R.H, the compressive-shear bond strength was measured by the test set-up shown in Fig. 8. Fig. 8(a) shows how the fibers were affixed to the steel fixture. Fig. 8(b) shows the setup used to achieve slipping between the fibers and mortar. Additionally, steel pads with inclination angles (θ in Fig. 8(a)) of 30°, 40°, 50° and 60° were designed to determine the shear bond strength of the interface at different normal stress conditions. Then, the shear stress $\ddot{A}$ for the fiber-mortar interface and the normal stress $\tilde{A}_i$ on the

failure plane, as shown in Fig. 9, were derived as follows:

$$\begin{cases} \sigma_i = \frac{P}{A} \cdot \sin\theta \\ \tau_i = \frac{P}{A} \cdot \cos\theta \end{cases} \quad (1)$$

where A represents the interface area and P is the maximum load when the interface fails. For each kind of inclination angle and mortar grade, four identical specimens were tested, and the displacement rate was 0.04 mm/s. The loads were recorded by a data acquisition system during the test, as shown in Fig. 8(b).

3.2.3 Mortar and FRC specimens

Six cubic specimens of mortar (70.7 mm × 70.7 mm × 70.7 mm) and six prism specimens (70.7 mm × 70.7 mm × 230 mm) were made for each mortar strength to evaluate their splitting tensile strengths and compressive strengths. Further, six cubic 100 mm × 100 mm × 100 mm FRC specimens were prepared to study the effects of the bond strength of the fiber-mortar interface on their splitting tensile behavior. All specimens were cured under conditions at 25 ± 2 °C and 100% R.H. for 28 days. They were then tested by a TSY-2000 electric hydraulic pressure system.

4. Results and discussion

4.1 Strength of mortar specimens

For the mortar with W/C ratios of 0.65, 0.49 and 0.40, the splitting tensile strengths are 3.28 MPa, 4.26 MPa and 6.06 MPa, respectively, while the compressive strengths are 26.38 MPa, 37.28 MPa and 43.83 MPa. All values represent the average of six specimens. It was found that the splitting tensile strength of mortar was about 12.4%, 11.4%, and 13.8% of its compressive strength, respectively. Furthermore, both the

splitting tensile strength of the mortar and its compressive strength increased as the W/C ratio for the mortar decreased.

4.2 Bond strength of fiber-mortar interface under tension

The bond strength of the fiber-mortar interface area under tension is shown in Fig. 10, with each value representing the average of four specimens. Notably, the tensile bond strength of the interface between each kind of fiber and mortar clearly increases with the decrease in the mortars' W/C ratio. Specifically, Fig. 10 shows that the tensile bond strength of the glass, PVA, and basalt fiber-mortar interface increases by 19.8%, 25.9%, and 8.3%, respectively, when the W/C ratio of mortar decreases from 0.65 to 0.49. Additionally, the tensile bond strength of the glass, PVA, and basalt fiber-mortar interfacial areas also increases by 87.7%, 69.4%, and 78.4%, respectively, when the W/C ratio of mortar decreases from 0.65 to 0.40. These results are in accordance with previous studies by Robins et al.[8] and Wille and Naaman [27].

The results in Fig. 10 also reveals that the tensile bond strength between PVA fiber and mortar is highest, followed by basalt fiber, and glass fiber. This can be explained by the microanalysis in Section 2.3 where (1) a lot of initial microcracks formed in the glass fiber-mortar interface, as shown in Fig. 2 and Fig. 3(a), which had a detrimental effect on the interfacial bond; (2) the glass fiber-mortar interface had the lowest amount of C-S-H, followed by the fiber-mortar interfacial zone in basalt fiber, and then in the PVA fiber. More C-S-H can effectively improve the adhesion between fiber and mortar.

Notably, the tensile bond strength of each fiber-mortar interface is less than 1.0% of

the mortar splitting tensile strength. It is much less than the tensile bond strength of the coarse aggregate-mortar interface, which is 50% of the mortar's tensile strength [28]. Obviously, this can be supported directly by the micromechanical analysis results in Section 2.3; i.e., the lower tensile bond strength of the fiber-mortar interface than the aggregate-mortar interface is because it presents the higher Ca/Si ratio, as shown in Figs. 4(a) to 4(d), which means fiber-mortar interface has the lower amount of C-S-H resulting in a weak bond strength. However, the deeper cause may lie in the rougher surface of the aggregate [25] and the deeper chemical reactions between aggregate and mortar [19], both of which can produce a stronger interface between the aggregate and mortar. Therefore, it is observed in tests that the tensile bond failures all occurred in the fiber-mortar interfaces, as shown in Fig.10.

4.3 Bond strength of fiber-mortar interface under compression-shear stress state

4.3.1 Maximum load and failure of the specimens

For the interfaces between mortar and glass, PVA, and basalt fibers, the maximum load of P^{G}, P^{P}, and P^{B} (measured as the average of four interfacial compressive-shear specimens) for all mixes with various levels of the inclination angle ¸ are respectively plotted in Figs. 11(a), 11(b), and 11(c).

As expected, the higher value of the inclination angle caused a general promotion of the maximum load for all mixes. It is interesting to see in Figs. 11(a) to 11(c) that the increased rate of the maximum load becomes significant when it reaches an inclination angle value greater than 50º except for the ones between the PVA fibers and mortar with a W/C ratio equal to 0.65 in Fig. 11(b). The sharp promotion is

attributed to failure occurring in the mortar rather than the interface, as observed during the test.

Figs. 11(a) to 11(c) also show that the maximum load generally increases as the W/C decreases, except for the interface between mortar and PVA fibers with an inclination angle equal to 50º in Fig. 11(b). The general increase is because the lower value of the W/C ratio results in a higher strength of mortar, which can cause a stronger mechanical interlock and physical interaction between the fibers and mortar. This agrees with other results previously reported in [3] and [16].

Fig. 11(b) clearly shows that the interface between PVA fibers and mortar with a W/C ratio equal to 0.65 has a higher maximum load than those with a W/C ratio equal to 0.49 and 0.4 when the interface between mortar and PVA fibers have an inclination angle equal to 50º. Excessive compressive stress produced by the maximum load in the interface is a major cause of mortar crushing, which also contributes to specimen failure occurring in the mortar rather than the interface due to the lower strength of mortar when the W/C ratio equals 0.65.

According to [26], the failure modes of compressive-shear specimens can also be defined as: (1) slipping at the interface, as shown in Fig. 12(a) even though the fibers slipped along the interface, and no crushing cracks were formed in the mortar matrix. (2) By observing the crushing of the mortar, as presented in Fig. 12(b), obvious cracks can be found in the crushed mortar, but fibers have no or very limited slipping at the interface. It was observed in the test that when the inclination angle is smaller than or

equal to 50º, most of the failures occur by slipping at the interface, which is brittle. However, when the inclination angle is larger than 50º, the failure always occurs by the mortar crushing, due to the higher compressive stress caused by the maximum compressive load. In this case, the maximum load is determined by mortar's compressive strength. Therefore, it is reasonable to assume that the fiber-mortar interface will fail when the mortar is broken.

4.3.2 Effect of compressive stress on interfacial shear bond strength

For the interfaces that failed because of a slip along the interface rather than the crushing of mortar, the interfacial shear stress ($\ddot{A}^{G}$, $\ddot{A}^{P}$, and $\ddot{A}^{B}$ for the interface between mortar and glass, PVA, and basalt fibers, respectively) and compressive stress ($\tilde{A}_{i}^{G}$, $\tilde{A}_{i}^{P}$, and $\tilde{A}_{i}^{B}$) with different inclination angles under the maximum load are plotted and listed in Fig. 13, in which the non-dimensional parameters $\ddot{A}^{G}/f_{m}$, $\ddot{A}^{P}/f_{m}$, and $\ddot{A}^{B}/f_{m,}$ as well as $\tilde{A}_{i}^{G}/f_{m}$, $\tilde{A}_{i}^{P}/f_{m}$, and $\tilde{A}_{i}^{B}/f_{m}$ are adopted to avoid the influence of mortar strength, where f_{m} is the compressive strength of the mortar.

It is evident in Fig. 13 that all of the interfaces show increasing shear bond strength with increasing compressive stress. This conforms to the Mohr-Coulomb failure criterion [28]. Similar results have been found in the aggregate-mortar interface [26]. It should be noted that the maximum compressive stress in Figs. 13(a), (b), and (c) is approximately $0.033f_{m}$, $0.08f_{m}$ and $0.025f_{m}$ respectively for the interface between mortar and glass, between the mortar and PVA, and between the mortar and basalt fibers. This is because if the compressive stress is larger, the specimens will fail by the

crushing of mortar, rather than the sliding at the fiber-mortar interface. Furthermore, the experimental results also fit the Mohr-Coulomb failure criterion, as shown in Fig. 13. The fitted curves for glass, PVA, and basalt fiber-mortar interface can be expressed as

$$\frac{\tau_i^G}{f_m} = \tan 39° * \frac{\sigma_i^G}{f_m} + 0.019 \quad (2)$$

$$\frac{\tau_i^P}{f_m} = \tan 39° * \frac{\sigma_i^P}{f_m} + 0.032 \quad (3)$$

$$\frac{\tau_i^B}{f_m} = \tan 39° * \frac{\sigma_i^B}{f_m} + 0.020 \quad (4)$$

where the correlation coefficients of R^2 are 0.93, 0.96, and 0.92, respectively. This indicates that the fitted curves can express the correlativity between the interfacial compressive stress and the interfacial shear stress for each kind of fiber. Moreover, the internal friction angle derived from Eqs. (2) to (4) is 39º.

Additionally, with the same interfacial compressive stress, the interface between PVA fiber and mortar has the highest shear bond strength, followed by the basalt fiber and then the glass fiber. This can also be attributed to the amount of the Ca/Si ratio in the interface between the fiber and mortar matrix. As shown in Fig. 4, the lower amount of the Ca/Si ratio produced the stronger interfacial bond performance. Notably, the initial microcracks formed in the glass-mortar fiber interface are another reason for their weakest bond.

4.4 Splitting tensile strength of FRC with different fiber-mortar interfaces

The splitting tensile strengths (the testing results average of six specimens) of each grade of normal concrete and FRC are shown in Fig. 14. For each grade strength, the

figure shows a splitting tensile strength of each kind of FRC, which is always higher than that of normal concrete. Specifically, for W/C ratios equal to 0.65, 0.49 and 0.40, the splitting tensile strength of concrete specimens reinforced by glass fiber increased by about 1.2%, 2.5%, and 4.1%, respectively. Using the same W/C rations of 0.65, 0.49, and 0.40, the specimens reinforced by PVA increased by about 13.6%, 27.3% and 26.6% respectively and the specimens reinforced by basalt fiber increased by 8.9%, 9.9%, and 14.8%. These increases are due to the prevention of initiation and propagation of cracks provided by fibers [1].

It can also be observed in Fig. 14 that the splitting tensile strengths of FRC are different. PVA fiber-reinforced concrete shows the highest splitting tensile strength, followed by basalt and glass FRC. Both the differences in the fiber-mortar interface bond strength and the mechanical properties of fibers were considered reasons for this effect. However, for the differences in the specimens with a W/C equal to 0.65, the interface bond strength of fiber and mortar is thought to be the main reason. Because few fibers were broken in the tested specimens, the influence of the fiber's properties could be negligible. As previously mentioned, PVA fiber provides the strongest interfacial bond strength, followed by basalt fiber, and then glass fiber, which results in a silimar decrease in the splitting tensile strength of PVA, basalt and glass FRC. These results support the conclusion from Naaman [5] who reported that better bonding of the fiber-mortar interface could improve the mechanical properties of FRC.

5. Conclusions

The systematic study reported in this paper clarifies the microstructure features of the fiber-mortar interface and the interfacial bond performance between the mortar and three types of fibers with limited degrees of scatter. The specific conclusions are summarized as follows.

First, an X-ray nano-CT enabled the observation of some microcracks near or at the glass fiber-mortar interface. Meanwhile, SEM and EDX results revealed that the Ca/Si ratio for the glass/PVA/basalt fiber-mortar interface was lower than either the aggregate-mortar interface or mortar matrix.

The interfacial tensile bond tests confirmed that the tensile bond strength of the fiber-mortar interface clearly increases with decreases in the W/C ratio of mortar. Fiber type also affects the interfacial tensile bond strength, with PVA fiber providing the highest bond, followed by basalt fiber, and then glass fiber.

Furthermore, the shear bond strength of the interface between mortar and glass, PVA, and basalt fiber increases with the increase of normal compressive stress when the normal compressive stress is smaller than 3.3%, 8.0%, and 2.5% of the mortar's interfacial compressive strength, respectively. However, the larger normal compressive strength leads to crushed mortar, rather than an interface slip. The relationship of the normal and shear stress calibrated using the experimental data for each fiber reveals that the internal friction angle is approximately 39°, regardless of the fiber type.

Finally, the splitting tensile strengths for the three kinds of FRC are tested with the

results showing that PVA-fiber-reinforced concrete has the highest splitting tensile strength, followed by basalt fiber, and then, glass fiber. That is to say that the obtained interface bond properties can reflect the behavior of the fiber-mortar interface in concrete materials to some extent.

It is worth noting that the provided results can serve as the basic parameters and failure criterion for a direct and inverse future modeling analysis. Further investigations will include a 3D simulation of FRC at meso-scale for continued understanding and enhanced performance.

Acknowledgements

The authors gratefully acknowledge the funding for this work provided by the National Natural Science Foundation of China (No. 51508146) and the Key Laboratory of Performance Evolution and Control for Engineering Structures of Ministry of Education of China (No. 2018KF-1).

References

[1] V.C. Li, and H. Stang. Interface property characterization and strengthening mechanisms in fiber reinforced cement based composites, Ade. Cem. Based Mater. 6 (1) (1997) 1-20. https://doi.org/10.1016/S1065-7355(97)90001-8

[2] J. Qu. The effect of slightly weakened interfaces on the overall elastic properties of composite materials, Mech. Mater. 14 (4) (1993) 269-281. https://doi.org/10.1016/0167-6636(93)90082-3

[3] R.J. Gray, and C.D. Johnston. The influence of the fibre-matrix interfacial

bond strength on the mechanical properties of steel fibre reinforced mortars, Int. J. Cen. Compos. Lightweight Concr. 9 (1) (1987) 43-55. https://doi.org/10.1016/0262-5075(87)90036-4

[4] Z.D. Zhou, R.F. Xie, P. Z. Qiao and L.J. Lu. On the modeling of tensile behavior of ultra-high performance concrete with freezing-thawing actions. Compos. Part B Eng. 174 (2019) 106983. https://doi.org/10.1016/j.compositesb.2019.106983

[5] A.E. Naaman. Engineered steel fibers with optimal properties for reinforcement of cement composites, J. Adv. Concr. Technol. 1 (3) (2003) 241-252. https://doi.org/10.3151/jact.1.241

[6] Y.M. Abbas, and M.I. Khan. Fiber-matrix interactions in fiber-reinforced concrete: a review, Arabian J. Sci. and Eng. 41 (4) (2016) 1183-1198. https://doi.org/10.1007/s13369-016-2099-1

[7] J. Katzer. Steel fibers and steel fiber reinforced concrete in civil engineering, Pacific J. Sci. Technol. 7 (1) (2006) 53-58.

[8] P. Robins, S. Austin, and P. Jones. Pull-out behavior of hooked steel fibres, Mater. Struct. 35 (7) (2002) 434-442. https://doi.org/10.1007/BF02483148

[9] Y. Lee, S.T. Kang, and J. K. Kim. Pullout behavior of inclined steel fiber in an ultra-high strength cementitious matrix, Constr. Build. Mater. 24 (10) (2010) 2030-2041. https://doi.org/10.1016/j.conbuildmat.2010.03.009

[10] F. Isla, G. Ruano, and B. Luccioni. Analysis of steel fibers pull-out. Experimental study, Constr. Build. Mater. 100 (15) (2015) 183-193.

https://doi.org/10.1016/j.conbuildmat.2015.09.034

[11] Y. Su, J. Li, C. Wu, P. Wu, M. Tao, and X. Li. Mesoscale study of steel fibre-reinforced ultra-high performance concrete under static and dynamic loads, Mater. Des. 116 (15) (2017) 340-351. https://doi.org/10.1016/j.matdes.2016.12.027

[12] T. Abu-Lebdeh, H. Sameer, H. William, and Z. Brian. Effect of matrix strength on pullout behavior of steel fiber reinforced very-high strength concrete composites, Constr. Build. Mater. 25 (1) (2011) 39-46. https://doi.org/10.1016/j.conbuildmat.2010.06.059

[13] T. Simões, C. Octávio, J. Valen«a, H. Costa, D. Dias-da-Costa, and E. Júlio. Influence of concrete strength and steel fiber geometry on the fibre/matrix interface, Compos. Part B Eng. 122 (1) (2017) 156-164. https://doi.org/10.1016/j.compositesb.2017.04.010

[14] S. Singh, A. Shukla, and R. Brown. Pullout behavior of polypropylene fibers from cementitious matrix, Cem. Concr. Res. 34 (10) (2004) 1919-1925. https://doi.org/10.1016/j.cemconres.2004.02.014

[15] M. Ali, X. Li, and N. Chouw. Experimental investigations on bond strength between coconut fibre and concrete, Mater. Des. 44 (2013) 596-605. https://doi.org/10.1016/j.matdes.2012.08.038

[16] W.C. Choi, S.J. Jang, and H.D. Yun. Interface bond characterization between fiber and cementitious matrix, Inter. J. Polym. Sci. 2015(1) 1-11. http://dx.doi.org/10.1155/2015/616949

[17] M.G. Alberti, A. Enfedaque, J.C. Galvez, and A. Ferreras. Pull-out behavior and interface critical parameters of polyolefin fibers embedded in mortar and self-compacting concrete matrixes, Constr. Build. Mater. 112 (1) (2016) 607-622. https://doi.org/10.1016/j.conbuildmat.2016.02.128

[18] Q. Luo, D.X. Liu, P.Z. Qiao, Q.G. Feng, and L.Z. Sun. Microstructural damage characterization of concrete under freeze-thaw action, Inter. J. Damage Mech. 27 (10) (2018) 1551-1568. https://doi.org/10.1177/1056789517736573

[19] P.K. Mehta, and P.J.M. Monteiro. Concrete: Microstructure, Properties, and Materials. 3rd ed, McGraw-Hill Inc, New York, 2006.

[20] T.P. Sathishkumar, P. Navaneethakrishnan, S. Subramaniam, and R. Rajasekar. Characterization of natural fiber surfaces and natural fiber composites, Compos. Part A-Appl. S. 39 (10) (2008) 1632-1637. https://doi.org/10.1016/j.compositesa.2008.07.007

[21] Y. Geng, and C.K.Y. Leung. Microstructural study of fibre/mortar interfaces during fibre debonding and pull-out, J. Mater. Sci. 31 (5) (1996) 1285-1294. https://doi.org/10.1007/BF00353108

[22] D.J. Pinchin, and D. Tabor. Inelastic behavior in steel wire pull-out from Portland cement mortar, J. Mater. Sci. 13 (6) (1978) 1261-1266. https://doi.org/10.1007/BF00544732

[23] S.A.S. Akers, J.B. Studinka, P. Meier, M.G. Dobb, D.J. Johnson, and J. Hikasa. Long term durability of PVA reinforcing fibers in a cement matrix, Inter. J. Cem. Compos. Lightweight Concr. 11 (2) (1989) 79-91.

https://doi.org/10.1016/0262-5075(89)90118-8

[24] J. II Choi, and B.Y. Lee. Bonding properties of basalt fiber and strength reduction according to fiber orientation, Mater. 8 (10) (2015) 6719-6727. https://doi.org/10.3390/ma8105335

[25] X.L. Gu, L. Hong, Z.L. Wang, and F. Lin. Experimental study and application of mechanical properties for the interface between cobblestone aggregate and mortar in concrete, Constr. Build. Mater. 46 (2013) 156-166. https://doi.org/10.1016/j.conbuildmat.2013.04.028

[26] L. Hong, X.L. Gu, and F. Lin. Influence of aggregate surface roughness on mechanical properties of concrete, Constr. Build. Mater. 65 (29) (2014) 338-349. https://doi.org/10.1016/j.conbuildmat.2014.04.131

[27] K. Wille, and A. Naaman. Bond stress-slip behavior of steel fibers embedded in ultra high performance concrete, 18th European Conference on Fracture: Fracture of Materials and Structures from Micro to Macro Scale, 2010, Dresden, Germany.

[28] J.F. Labuz, and A. Zang. Mohr-Coulomb Failure Criterion, Rock Mech. Rock Eng. 45 (6) (2012) 975-979. https://doi.org/10.1007/s00603-012-0281-7

Figure captions

PVA fibers, and (c) basalt fibers.

Fig.14. Splitting tensile strength of normal concrete and glass/PVA/basalt fiber reinforced concrete.

Table captions

Table 1. Dimension and mechanical properties of fibers.