Combined effect of coarse aggregate and fiber on tensile behavior of ultra-high performance concrete

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HIGHLIGHTS

- Tensile behavior of UHPC incorporating coarse aggregate is investigated.
- Coarse aggregate brings an impairment to utilization efficiency of fiber.
- Coarse aggregate can be successfully introduced into system of UHPC.
- Fiber type has almost no effect on strain hardening behavior of this UHPC.

1. Introduction

For the design of concrete structures with good long-term performance, insight into microstructure of concretes and its relationship with performance is of paramount importance [1–2]. As result, ultra-high performance concrete (UHPC) appeared, a new class of construction material with outstanding properties. UHPC has the remarkable mechanical properties and extremely low porosity, which was obtained through dense particle packing. Therefore, it implies that UHPC performs a high durability, improved resistance against various chemicals as well as higher penetration resistance [3–5]. Presently, there has been increasing interest in the use of UHPC as a vanguard product for industrial and structural applications in the past few years, such as coupling beams in high-rise buildings, precast members, infrastructure repairs and special facilities like nuclear waste storage containers [6–7].

Basic principles of developing UHPC have been established by Richard and Cheyrezy in 1995 [3]. Normally, UHPC is designed to be a super plasticized concrete by replacement of traditional coarse aggregates with fine sand [8]. In addition, thermal treatments of UHPC are mainly preferred in order to reduce curing time and increase mechanical strengths [9–10]. The well-chosen raw material and sophisticated technical procedures make it too costly to meet the demand of large-scale project engineering. To reduce its cost, natural sand has been employed successfully as a substitute for expensive quartz sand without impairing its mechanical strengths [6,11]. Specially, coarse aggregate is recently introduced into the system of UHPC to further reduce its cost and broaden its application [12–13]. Firstly, coarse aggregate is more economic efficiency than other raw materials used. Secondly, it makes UHPC possess a better shrinkage performance and lower hydration temperature rise [14], which is attributed to the decreased binder content and its strong restraint on shrinkage of UHPC. With the inclusion of coarse aggregates, UHPC can also easily possess a high compressive strength of 180 MPa as well as excellent workability.
Unfortunately, the interface around coarse aggregate would become more weak and more flaws are accompanied [15], resulting in a poor tensile performance of concrete, especially for that with a low water to binder (W/B) ratio, i.e., UHPC [16]. Therefore, for UHPC incorporating coarse aggregate, the optimal content of coarse aggregate should be investigated carefully in order to obtain better tensile properties.

In addition to the dense microstructure obtained by maximizing packing density with very fine minerals (silica fume, slag, fly ash, etc.) [8,17–20], superior performance of UHPC is also achieved by enhancing matrix toughness with optimal steel fiber reinforcement (smooth, twist, hook, hybrid etc.) [9,21–25]. Effects of steel fiber on the tensile behavior of UHPC without coarse aggregate have been widely reported in literatures [5,21,24,26–29]. It is accepted that the tensile behavior of UHPC is controlled by bond behavior between fiber and matrix, which is attributed to matrix properties (including particle size and mechanical properties), fiber properties (including geometry, length, diameter, volume content, and mechanical properties) and interfacial properties. Some researches show that UHPC produced from macro-fibers with deformed geometry (i.e. hooked, twist) provides the excellent performance with respect to post cracking strength, strain capacity and multiple cracking behavior, which is attributed to the high utilization efficiency [21,24]. However, utilization efficiency of smooth fiber can be improved by designing ultra-high strength matrix, which allows development of high tensile stress in the smooth fiber [26]. When coarse aggregates are introduced into UHPC, the matrix should be tailored carefully to obtain a high strength and a better bond condition. Besides, fiber distribution characteristic is another critical factor influencing post-cracking behavior of UHPC [29–31]. In addition to casting method, fiber properties (i.e. geometry, shape, volume content), fluidity and shape of forms, the existence of coarse aggregates have a strong effect on fiber distribution [31–32]. Consequently, pull-out behavior of varying steel fiber in concrete behaves differently compared with that without coarse aggregates. Therefore, to use UHPC incorporating coarse aggregate in civil infrastructure, combined effect of coarse aggregate and fiber on the tensile behavior of UHPC must be carefully investigated. However, to author’s knowledge, there is little information available in literatures about the combined effect.

Accordingly, in this paper, combined effect of coarse aggregate and fiber on tensile behavior of UHPC was studied. Three types of steel micro-fibers with varying geometry and one type of steel macro-fiber were applied as reinforcement. Tests had been done to obtain overall tensile stress-strain curves of UHPC. Bonding behavior between these fibers and matrix was also performed to analyses combined effect of coarse aggregates and fibers.

### 2. Experimental program

#### 2.1. Raw materials

Portland cement, with a strength class of 52.5 conforming to the Chinese Standard GB 175-2007 [33], silica fume, ultra-fine slag and fly ash were used as cementitious materials. Their specific gravities were 3.15 g/cm$^3$, 1.87 g/cm$^3$, 2.84 g/cm$^3$ and 2.33 g/cm$^3$ respectively, and their chemical properties, determined by X-ray fluorescence (XRF) (ThermoFisher Scientific ARL QUANTX), are illustrated in Table 1. Moreover, their particle size distributions (PSD) determined by nitrogen sorption isothermal measurement (Coulter ONLNISORP 100 CX) are given in Fig. 1. River sand with an apparent density of 2.63 g/cm$^3$ and grain size below 5 mm was applied. Crushed basalt with an apparent density of 2.86 g/cm$^3$ and grain size between 5 mm and 20 mm was used as coarse aggregate. A polycarboxylate-based superplasticizer with solid content of 40% was adopted as water-reducer. To investigate effect of fiber on the tensile behavior of UHPC incorporating coarse aggregate, three types of steel micro-fibers and one type of steel macro-fiber were performed. Their properties are given in Table 2 and Fig. 2 shows images of each fiber type.

#### 2.2. Mix proportion

Table 3 provides mix proportion of the UHPC series in which binder composition is invariable and water to binder ratio is fixed at 0.18 for all mixes. The optimized UHPC binder was made with 40% cement, 10% silica fume, 30% ultra-fine slag and 20% fly ash. Single fiber pullout tests were performed on the control specimen without coarse aggregate for avoiding the effect of coarse aggregate on pullout behavior of fiber. In an attempt to optimize coarse aggregate content with respect to tensile behavior, the coarse aggregate was partially replaced in mortar at four replacement levels (0%, 15%, 25%, 35% by volume of mortar). It should be noted that the W/B ratio and superplasticizer dosage of UHPC was initially designed to be invariable for these mixes. However, as the coarse aggregate replacement level increases, a satisfied fluidity (slump >100 mm) of fresh mixture was needed to realize the well-dispersion of coarse aggregate and good homogeneity of matrix. Therefore, the superplasticizer dosage was adjusted for

![Fig. 1. Particle size distribution of cementitious materials.](image)

<table>
<thead>
<tr>
<th>Composition</th>
<th>$\text{Al}_2\text{O}_3$</th>
<th>$\text{CaO}$</th>
<th>$\text{SiO}_2$</th>
<th>$\text{Fe}_2\text{O}_3$</th>
<th>$\text{K}_2\text{O}$</th>
<th>$\text{MgO}$</th>
<th>$\text{Na}_2\text{O}$</th>
<th>$\text{SO}_3$</th>
<th>$\text{TiO}_2$</th>
<th>$\text{MnO}$</th>
<th>$\text{LOI}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>4.94</td>
<td>63.05</td>
<td>19.95</td>
<td>2.92</td>
<td>0.66</td>
<td>1.33</td>
<td>0.15</td>
<td>3.83</td>
<td>0.27</td>
<td>0.99</td>
<td>2.9</td>
</tr>
<tr>
<td>Silica fume</td>
<td>0.16</td>
<td>0.18</td>
<td>97.31</td>
<td>0.15</td>
<td>0.39</td>
<td>0.82</td>
<td>0.2</td>
<td>0.54</td>
<td>–</td>
<td>0.01</td>
<td>0.24</td>
</tr>
<tr>
<td>Ultra-fine slag</td>
<td>16.8</td>
<td>37.1</td>
<td>31.3</td>
<td>0.43</td>
<td>0.35</td>
<td>9.08</td>
<td>0.38</td>
<td>2.8</td>
<td>0.9</td>
<td>0.34</td>
<td>0.52</td>
</tr>
<tr>
<td>Fly ash</td>
<td>37.7</td>
<td>4.64</td>
<td>46.6</td>
<td>4.27</td>
<td>0.23</td>
<td>1.41</td>
<td>0.17</td>
<td>1.52</td>
<td>0.78</td>
<td>0.29</td>
<td>2.39</td>
</tr>
</tbody>
</table>

**Table 1:** Chemical composition of cementitious materials.
these mixes to achieve a satisfied workability and it has no impairment to mechanical strength of these UHPC in the latter age. The preferred formulation was further fixed to investigate effect of fiber type and dosage.

2.3. Specimen preparation and curing

The specimen preparations were conducted at temperature of 20 ± 5°C and relative humidity of about 65%. A forced single-axis mixer with a rotational speed of 45 rpm was used to prepare mixture. Cementitious materials and aggregates were first dry-mixed for about 1 min. After that, water pre-mixed with superplasticizer was then added gradually and mixed for another 2 min. Then fibers were dispersed carefully by hand into the mixture and mixed for another 2 min. The cement mixture with fibers was casted in a mold and vibrated for 10 s after workability test. Specimens were covered with plastic sheets and stored at room temperature for 1 day, then moved to a standard curing room with temperature of 20 ± 2°C and relative humidity of greater than 95%. Compressive tests were conducted after 7, 28 and 56 days curing and the tensile tests were carried out after 28 days curing.

To assess bonding strength between steel fibers and UHPC matrix, a type of dog-bone mold with a dimension of 235 mm × 25 mm × 25 mm was adopted (as shown in Fig. 3). A slot with 2 mm width was located in the middle of mold. A PVC slice with a single fiber passing through the center was insert into the slot. The embedded lengths of the single fiber on both sides of slice are both half of fiber length. Specimens were then immersed into the saturated Ca(OH)2 solution. Pullout tests were also carried out after 28 days curing.

2.4. Experimental methods and characterization

2.4.1. Fresh properties and compressive strength

Fluidity of fresh concrete, including slump and spread values, was measured with a normal 300 mm slump cone according to

![Fig. 2. Images of fibers: (a) smooth micro-fiber, (b) spiral micro-fiber, (c) hooked A micro-fiber and (d) hooked B macro fiber.](image-url)
ASTM C143. Spread refers to the average diameter of concrete spread in this paper. Air content of fresh mixes was determined by an air entrainment meter (Sanyo LS-546) according to ASTM C173. Due to the incorporation of coarse aggregate, cube specimens of 100 mm × 100 mm × 100 mm were used for compressive strength testing according to the Chinese Standard GB/T 31387-2015. At least three parallel specimens were tested at each age point.

2.4.2. Steel fiber pullout tests

Bonding strength between yarns and matrix was tested by using a CMT4103 electromechanical universal tensile machine with 10 kN load cell. The stroke-control rate was set at 0.5 mm/min. Five parallel samples of each group were tested and average values and standard deviation were presented. The curves of pull-out load \( P \) per unit remaining embedded length versus slip displacement \( D_s \) were obtained. The remaining embedded length is the difference between initial embedded length \( L \) and slip displacement \( D_s \).

2.4.3. Tensile tests of UHPC

Tensile tests of UHPC sample were performed on an electromechanical universal testing machine (MTS-801) with 500 kN load cell. The stroke-control rate was set at 0.05 mm/min. The geometry of test specimen and set-up are shown in Fig. 4. According to the previous work [24], tensile specimens with sizes of 100 mm × 100 mm × 500 mm was prepared in order to minimize the size effect of fibers, especially for the hooked-B fiber. Carbon cloth and metal plates were successively glued onto specimens by using epoxy resin to alleviate localized damage and minimize deformation of matrix at clamps. The gage length between metal plates was 100 mm. In addition, the metal frame was used to measure elongation by using two LVDTs as shown in Fig. 4(a) and averaged value from the two LVDTs was used in calculating tensile strain until peak tensile stress during tensile process. As shown in Fig. 4(b), load was transferred through a pre-embedded steel bar with a diameter of 10 mm, and steel bar was welded with 8 ribs of 5 mm length to prevent its relaxation during testing. To keep load axis straight, boundary conditions at both ends of the tensile test set-up were driven by a cardan. The average values and standard deviation of at least three parallel samples were acquired. Typical stress-strain curves of different UHPC samples were compared and first crack strength and maximum bridging stress were acquired for all samples. The first crack strength \( \sigma_{fc} \) is defined as the applied tensile stress at which a matrix crack spreads throughout the cross section of the sample under tension, and it can be adopted at the point where matrix is completely out of function. The maximum bridging stress \( \sigma_B \) is defined as the maximum stress that bridging fibers can transfer across the crack of specimen [34].

3. Results and discussion

3.1. Workability and compressive strengths

Table 4 shows the results of workability and compressive strengths of all sample series. With the increase of coarse aggregates content, UHPC mixture behaves a more poor workability as spread and slump values declined sharply. This is due to the decreased binder content [13] and the more severe interlock between coarse aggregate and steel fibers. When the replacement of coarse aggregates improves to 35%, fresh mixture exhibits a very dry condition with slump of 130 mm. In addition, the decreased binder content also results in a low air content of fresh mixture incorporated with coarse aggregate, where air content of fresh paste can be assumed to maintain unchangeable. As expected, workability of UHPC samples becomes worse with the increase of fiber dosage. With incorporation of 1.0%, 1.75% and 2.5% smooth fiber, the flowability gradually decreased by 12.0%, 32.8% and 46.0%, and it almost presents a linear tendency [35]. This phenomenon should be attributed to the increase in internal surface area that produced higher cohesive forces between fibers and concrete matrix, with the increase of additional fiber content [8]. Moreover, steel fibers are randomly distributed in the matrix and act as skeleton, and consequently hinder the flow of fresh concrete [36]. Among these fibers, the mixture with inclusion of hooked-B fiber presents a preferred workability, followed by the mixture with spiral fiber, smooth fiber and hooked-A fiber. The poor workability accompanied with deformed fibers is resulted from larger friction induced by the deformed fiber, especially for hooked fiber [22]. Besides the observed difference between hooked fibers is due
Workability and compressive strengths of UHPC samples.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Slump (mm)</th>
<th>Spread (mm)</th>
<th>Air content (%)</th>
<th>Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7d</td>
<td>28d</td>
<td>56d</td>
<td></td>
</tr>
<tr>
<td>SM2G0</td>
<td>205</td>
<td>495</td>
<td>6.6</td>
<td>96.1 ± 3.5</td>
</tr>
<tr>
<td>SM2G1</td>
<td>195</td>
<td>400</td>
<td>3.6</td>
<td>111.5 ± 5.2</td>
</tr>
<tr>
<td>SM2G2</td>
<td>168</td>
<td>380</td>
<td>2.9</td>
<td>120.2 ± 6.5</td>
</tr>
<tr>
<td>SM2G3</td>
<td>130</td>
<td>220</td>
<td>2.8</td>
<td>112.3 ± 3.9</td>
</tr>
<tr>
<td>SM0G2</td>
<td>250</td>
<td>680</td>
<td>3.6</td>
<td>85.6 ± 6.4</td>
</tr>
<tr>
<td>SM1G2</td>
<td>220</td>
<td>420</td>
<td>3.8</td>
<td>118.2 ± 6.9</td>
</tr>
<tr>
<td>SM3G2</td>
<td>135</td>
<td>240</td>
<td>2.3</td>
<td>126.4 ± 4.7</td>
</tr>
<tr>
<td>SP2G2</td>
<td>190</td>
<td>365</td>
<td>3.4</td>
<td>118.5 ± 2.3</td>
</tr>
<tr>
<td>HA2G2</td>
<td>122</td>
<td>210</td>
<td>3.6</td>
<td>117.8 ± 2.8</td>
</tr>
<tr>
<td>HB2G2</td>
<td>227</td>
<td>470</td>
<td>2.7</td>
<td>116.6 ± 3.4</td>
</tr>
</tbody>
</table>

Table 4

Table 5

Frictional bonding strengths of varying steel fibers (MPa).

<table>
<thead>
<tr>
<th>Fibers</th>
<th>Smooth</th>
<th>Spiral</th>
<th>Hooked-A</th>
<th>Hooked-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frictional bonding strength</td>
<td>8.60 ± 0.53</td>
<td>18.37 ± 0.85</td>
<td>24.65 ± 0.42</td>
<td>12.17 ± 0.31</td>
</tr>
</tbody>
</table>

In Fig. 5, steel fibers are pulled out from matrix and two different stages in curves can be observed: quickly debonding stage and gently friction one. The latter stage generally tends to be a horizontal line except deformed micro-ones, i.e. hooked-A and spiral fiber. Considering the very short region of embedded yarns that adhesive bonding strength exerts on, it is assumed that steel fibers are held in matrix only by frictional bonding strength with no adhesive bonding strength. The frictional bonding strength depends on average value of the height in the gently stage of curves [39]. The results are presented in Table 5. Due to the complex pullout behavior, the bonding strength of deformed fibers implies the average action strength during whole pullout process for the sake of comparison with straight fiber and simplicity of calculation. As shown in Table 5, it should be noted that a lower bonding strength of steel fiber in UHPC would be observed with inclusion of coarse aggregates, especially for the deformed ones. This is attributed to the fact that existence of coarse aggregate would bring more defects and micro-cracks which are impairing to the denser microstructure of matrix [15]. Additionally, the frictional bonding strength of deformed fibers are dramatically higher than that of smooth fiber, where the hooked-A micro fiber shows the highest frictional bonding strength, followed by spiral and hooked-B macro fiber. For deformed ones, mechanical deformation is accompanied with their pull-out response, thereby resulting in a strengthening shear force [22]. While, for hooked-B macro fiber, plastic deformation of the hooked end is relatively weak due to its large diameter and embedment length.

3.3. Effects of coarse aggregate replacements

Fig. 6 shows tensile responses of UHPC samples incorporating varying coarse aggregate contents (0%, 15%, 25%, 35% by volume of mortar), where the strain is only valid up to peak stress of fiber pull-out. Irrespective of coarse aggregate content, all UHPCs behave similarly and two different stages are clearly identified in the tensile stress-strain curves as shown in Fig. 6: strain based elastic part and fiber pullout part. In all cases, together with a steady-state cracking, a sudden drop in load-bearing capacity is followed by first crack of UHPC samples, which indicates that a strain hardening and multiple cracking behaviors is not occur in these samples. This is because the first-crack strength of these samples is higher than the corresponding maximum fiber-bridging stress. As reported by Li et al. [34], the presence of...
multiple cracking is determined by first-crack strength, which in turn is dependent on crack size. Furthermore, according to the founding provided by Wille et al. [26], a value of energy absorption capacity $g$ prior to tension softening $g \geq 50 \text{kJ/m}^3$ is suggested to describe strain-hardening behavior. The energy absorption capacity $g$ is mainly dominated by matrix toughness and fiber-bridging effect, which is related to the fiber properties (including fiber length, radius, volume content, elastic modulus and distribution), matrix properties (including tensile behavior and the corresponding elastic modulus) and interface properties (including bonding behavior and strength) [40]. In post-cracking curves, it can be seen that a lower fiber-bridging stress is observed for UHPC incorporating coarse aggregate and it is almost independent of coarse aggregate content. This verified that coarse aggregate would bring impairment to the microstructure of UHPC and result in a poor fiber bonding stress. However, in addition to the microstructure of fiber–matrix interfacial zone, fiber-bridging stress is also contributed by dispersion of fibers, which is influenced by the existence and amount of coarse aggregate. With the addition of coarse aggregate, a severe interlock between fiber and coarse aggregate may be obtained and uniform dispersion of fibers becomes hard to reach. Consequently, resulting in a more complex microstructure of UHPC sample.

Fig. 7 summarizes values of first-crack strength and maximum bridging stress obtained for the UHPC incorporating different coarse aggregate content. As shown in Fig. 7, with incorporation of 15%, 25% and 35% coarse aggregate, the first-crack strength of UHPC samples gradually declines by 4.7%, 5.0% and 6.1%, respectively. This may be due to increased flaws associated with the increase of coarse aggregate content. However, difference between first-crack strengths is relatively small. Additionally, it can be seen that maximum fiber-bridging stresses show a high scattering. Although the effect of coarse aggregate on maximum fiber-bridging stress is not clear, coarse aggregate content should be carefully tailored. Because a large replacement level will lead to a severe overlay of steel fiber and a lower bonding strength, this will bring a serious impairment to fibers pullout behavior. Hence, it can be summarized that coarse aggregate can be successfully introduced into the system of UHPC to further reduce its cost without almost impairing to its tensile properties, regarding tensile properties of UHPC.

Because of its satisfactory tensile properties and relative low cost, the binder system containing 25% coarse aggregate was selected as optimized formulation of UHPC for the following studies.

3.4. Effects of fiber dosage

It is accepted that another key parameter affecting tensile behavior of UHPC sample is fiber dosage. In this section, with the coarse aggregate replacement level fixed at 25%, four smooth fiber dosages were adopted as shown in Table 3 (0, 1.0%, 1.75%, 2.5%) to study the influence of fiber dosage on tensile behavior of UHPC incorporating coarse aggregate. Their tensile responses are presented in Fig. 8 and tensile properties are summarized in Fig. 9 and Table 6.

As a comparison, only an elastic part is presented in tensile curve of the unreinforced UHPC sample and its first crack strength reaches around 6.65 MPa, which is apparently lower than that of UHPC samples with introduction of steel fiber. As shown in Figs. 8 and 9, both first-crack strength and fiber-bridging stress improve as fiber dosage increases. To evaluate utilization of steel fiber, a utilization factor $\eta$, which is defined as the ratio of tensile properties to the ultimate tensile strength of UHPC sample [39], is introduced as Eq. (1). The results are given in Table 6.
be used to characterize strain hardening behavior [24,34]. This ratio is strongly dependent on fiber dosage for UHPC incorporating coarse aggregate, where $\frac{\sigma_f}{\sigma_{f/f}}$ is the utilization efficiency of fiber.

Table 6: Tensile properties of UHPC samples with varying fiber dosage and corresponding utilization efficiency of fiber.

<table>
<thead>
<tr>
<th>Notation</th>
<th>$V_f$ (%)</th>
<th>$\sigma_t$ (MPa)</th>
<th>$\sigma_{f/f}$ (MPa)</th>
<th>$\eta$</th>
<th>$\eta^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM0G2</td>
<td>0</td>
<td>2940</td>
<td>$\sigma_f$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM1G2</td>
<td>1.00</td>
<td>2940</td>
<td>7.26 ± 0.11</td>
<td>0.34</td>
<td>0.585 ± 0.19</td>
</tr>
<tr>
<td>SM2G2</td>
<td>1.75</td>
<td>2940</td>
<td>7.34 ± 0.17</td>
<td>0.22</td>
<td>6.41 ± 0.31</td>
</tr>
<tr>
<td>SM3G2</td>
<td>2.50</td>
<td>2940</td>
<td>8.28 ± 0.18</td>
<td>0.19</td>
<td>8.10 ± 0.21</td>
</tr>
</tbody>
</table>

$\eta = \frac{\sigma_f}{\sigma_m + 2\sigma_f/\sigma_f^*}$ (1)

where $\sigma_t$ is tensile properties of UHPC sample, i.e. $\sigma_{f/f}$ and $\sigma_m$ is tensile strength of matrix, it is equal zero for calculating the utilization factor during fiber pullout stage, $a$ is an orientation factor and fixed at 0.5 for a three-dimensional orientation [21], $V_f$ is the volume fraction of steel fiber, $\sigma_f$ is the ultimate tensile strength of steel fiber.

It can be seen from Table 6 that utilization efficiency of fibers becomes worsen with the increase of fiber dosage, whatever at first crack and peak stress in post-cracking curves. This result is disagreed with the finding reported by Wille et al. [21], where utilization efficiency of fibers in UHPC sample without coarse aggregate is almost unchangeable as fiber dosage increases from 1.5% to 2.5%. As mentioned above, with the fiber dosage increases, interlock between fiber and coarse aggregate and overlay of steel fibers become severe, which consequently leads to a lower utilization efficiency of fiber. Furthermore, it can be seen that the utilization efficiency of fiber at peak stress in postcracking curves is slightly higher than that at first crack, which indicates that steel fiber is more effective at enhancing maximum fiber-bridging stress than first-crack strength. This is attributed to that the first-crack strength is mainly contributed by matrix toughness, whereas contribution of fiber reinforcing effect is relatively weak [34].

In addition, it is interesting to note that the gap between first-crack strength and maximum fiber-bridging stress is gradually bridged with fiber dosage increases as shown in Fig. 9 and Table 6. Ratio of maximum fiber-bridging stress to first-crack strength can be used to characterize strain hardening behavior [24,34]. This ratio is strongly dependent on fiber dosage for UHPC incorporating coarse aggregate as shown in Table 6. If the fiber dosage further increases, maximum fiber-bridging stress is undoubtedly stronger than first-crack strength and this ratio should be larger than 1.0, thereby a phenomenon of strain hardening and multiple cracking behavior of UHPC samples incorporating coarse aggregate could also be triggered. This indicates that fiber dosage will be a critical factor that enhancing strain hardening and multiple cracking behaviors for UHPC sample incorporating coarse aggregates. Moreover, due to the low utilization efficiency of fiber in this paper, an alternative method of realizing strain hardening and multiple cracking behaviors would be to further improve bond behavior in order to increase the fiber utilization efficiency, which would then result in a higher fiber-bridging stress for a given low fiber volume fraction such as surface treatment or fiber type.

3.5. Effects of fiber type

As mentioned above, another key parameter affecting tensile behavior of UHPC samples is fiber type. In this section, four different steel fibers with dosage fixed at 1.75% were adopted as shown in Fig. 2 to investigate influence of fiber type on tensile behavior of UHPC samples incorporating coarse aggregates. The tensile responses are given in Fig. 10 and tensile properties are summarized in Table 7.

As shown in Fig. 10, the overall shape of tensile-strain curves of all samples are identical, irrespective of fiber type. However, fiber type has a strong effect on first crack strength and fiber-bridging stress, especially in the post-cracking curve. For micro-fibers, the UHPC with deformed fiber shows a higher tensile properties, compared with that with smooth fiber. Among these, UHPC with hooked-A fiber has the highest tensile properties. Differences observed in tensile properties are attributed to different bonding properties associated with fiber geometry. As shown in Table 5, the frictional bonding strength of hooked-A fiber is highest and it is almost three times higher than that of smooth one. While UHPC with macro-fiber, i.e. hooked-B fiber, exhibits the lowest tensile properties and its first crack strength is only slightly higher than that without fiber. This is attributed to two aspects: one is the lower frictional bonding strength as shown in Table 5, the other is the lowest fiber number introduced into UHPC, compared with other micro-fibers at same dosage. However, due to its long anchor length, the macro-fiber can significantly improve strain capacity of UHPC samples, where the tensile strain at maximum bridging stress is largest as shown in Fig. 10. This phenomenon is also observed by Wille et al. [21], Park et al. [24], and Wu et al. [36]. Thus, UHPC tensile performances with respect to post cracking.
strength, strain capacity and multiple micro-cracking behavior can be successfully tailored by hybrid fiber system [24,41].

As shown in Table 7, ratio of maximum fiber-bridging stress to first-crack strength for UHPC with different fibers presents a very small fluctuation, which is located between 0.86 and 0.87. This phenomenon is not agreed with UHPC without coarse aggregate [24], as Park et al. reported that this ratio is strongly dependent on fiber type. Difference observed may be attributed to the combined effect of fiber bridging and coarse aggregate, where existence of coarse aggregate has a strong effect on fiber distribution and interface microstructure between fiber and matrix [31–32]. Because of the limit distribution space, overlay fiber become severe for deformed ones and deformed fibers bring more flaws around the coarse aggregate. Although single fiber pullout behavior is significantly influenced by fiber type as shown in Fig. 5, pullout behavior of overall fibers bridging across matrix crack plane for UHPC with introduction of coarse aggregate cannot simply integrate over the contribution of individual fibers like UHPC without coarse aggregate.

It also can be seen from Table 7 that the utilization efficiency of deformed fibers is higher than that of smooth fiber. This can be attributed to the additional pullout force induced by mechanical deformation of deformed fiber. Furthermore, fiber geometry with respect to length and diameter has a more stronger effect on the utilization efficiency, where the utilization efficiency of hooked-B fiber shows an increase of 16% and 25% at first crack strength and maximum fiber-bridging stress, compared to that of hooked-A fiber. Therefore, coupled with micro-fiber, macro-fiber provides the feasibility of improving bonding behavior through increasing fiber utilization, which may result in a higher tensile properties. The result can be confirmed by the bonding strength result and the favorable results of blending fiber reinforcement UHPC [24,41].

4. Conclusions

In this study, tensile behavior of UHPC incorporating coarse aggregates was investigated. Three types of steel micro-fibers, including smooth, spiral and hooked, and one type of steel macro-fiber of hooked were applied as reinforcement. Bonding behavior between these fibers and matrix was also performed. Combined effect of coarse aggregate and fiber properties, including fiber dosage and type, on the overall tensile stress-strain curves and tensile properties of UHPC was analyzed. The following conclusions can be drawn.

(1) With inclusion of coarse aggregate, the UHPC mixture behaves a more poor workability due to the decreased binder content. With respect to compressive strength, the replacement level of coarse aggregate has a critical value of 25% and different fibers act similarly.

(2) Coarse aggregate brings impairment to the bonding strength of steel fiber in the UHPC matrix incorporating coarse aggregate, especially for deformed ones. Among these, the hooked-A micro fiber shows the highest frictional bonding strength, followed by spiral and hooked-B macro fiber, whereas the smooth fiber shows the lowest frictional bonding strength.

(3) At a favorable replacement level (<25%), coarse aggregate can be successfully introduced into the system of UHPC to further reduce its cost without almost impairing to its tensile properties, regarding first-crack strength and maximum fiber-bridging stress.

(4) Unlike UHPC without coarse aggregate, a lower utilization efficiency of fiber is observed as fiber dosage increases from 1.0–2.5%, due to the fact that interlock between fiber and coarse aggregate and overlay of steel fibers become severe. In addition, the phenomenon of strain hardening and multiple cracking behaviors of UHPC incorporating coarse aggregate can be also triggered by further increasing fiber dosage to larger than 2.5%, where it can bridge the gap between first-crack strength and maximum fiber-bridging stress of UHPC incorporating coarse aggregate.

(5) Compared with smooth fiber, UHPC with deformed fiber shows better tensile properties except macro-deformed fiber. Different from UHPC without coarse aggregate, fiber type has almost no effect on strain hardening behavior, due to combined effect of fiber bridging and coarse aggregate. Utilization efficiency of fiber is strongly dependent on the fiber geometry, especially for length and diameter.

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References


Table 7

Tensile properties of UHPC with different fibers and corresponding utilization efficiency of fiber.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Vf (%)</th>
<th>sf (MPa)</th>
<th>σf (MPa)</th>
<th>ffc (%)</th>
<th>σB (MPa)</th>
<th>γB (%)</th>
<th>σf/σB (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM2G2</td>
<td>1.75</td>
<td>2940</td>
<td>7.34 ± 0.17</td>
<td>0.22</td>
<td>6.41 ± 0.31</td>
<td>0.24</td>
<td>0.874</td>
</tr>
<tr>
<td>SF2G2</td>
<td>1.75</td>
<td>2860</td>
<td>7.95 ± 0.21</td>
<td>0.25</td>
<td>6.97 ± 0.24</td>
<td>0.28</td>
<td>0.877</td>
</tr>
<tr>
<td>HA2G2</td>
<td>1.75</td>
<td>2940</td>
<td>8.53 ± 0.22</td>
<td>0.26</td>
<td>7.32 ± 0.26</td>
<td>0.29</td>
<td>0.859</td>
</tr>
<tr>
<td>HB2G2</td>
<td>1.75</td>
<td>1980</td>
<td>6.70 ± 0.16</td>
<td>0.29</td>
<td>5.80 ± 0.19</td>
<td>0.35</td>
<td>0.866</td>
</tr>
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