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REINFORCEMENT MECHANISMS OF FIBERS IN UHPC COMPOSITES

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ABSTRACT

Incorporation of appropriate discrete fibers is an efficient way to improve the ductility of concrete. However, agglomeration issue, reduction in flowability, and high cost would be encounted if excessive amount of fiber is used. This paper discusses the effects of fiber on some properties, including compressive, flexural, tensile, and dynamic properties, of ultra-high performance concrete (UHPC) and fiber reinforcing mechanisms. The investigated factors affecting these properties include fiber content, shape, type, distribution, orientation, and hybrid fibers. Finally, some typical applications of UHPC in worldwide are presented. Steel fiber can increase the compressive strength to some extent, but significantly improve the tensile and flexural behaviour. Fiber hybridization is a promising way to reduce cost and enhance mechanical properties. It aims at summarizing the recent progresses and to enhance the economic efficiency and practicability of UHPC.

KEYWORDS:

Ultra-high performance concrete; Fiber; Mechanical properties; Fiber reinforcing mechanism; Application

INTRODUCTION

The development of ultra-high performance concrete (UHPC) has attracted a lot of research interest and has been used for a number of applications. Until now, UHPC structures have been built in Canada, France, China, Japan, Korea, and America, etc (Graybeal 2008; Rebentrost and Wight 2008). The design and production of UHPC is based on four main theoretical principles, including reduction in porosity, improvement in microstructure, enhancement in homogeneity, and increase in toughness (Shi et al. 2015a; Wang et al. 2015). Appropriate addition of steel fibers can endorse UHPC not only high strength, but also high toughness and cracking resistance with a strain hardening behaviour (Park et al. 2012; Habel et al. 2006).

High amount of cementitious materials and fiber and use of special curing for UHPC can lead to low production efficiency and high energy consumption. Extensive researches have been conducted to optimize the performance of UHPC with the help of incorporation of supplement cementitious materials and/or nano-particles (Tafraoui et al. 2009; Wu, et al. 2016a, Wu, et al. 2016b). Fiber, as the most important part in UHPC, can not only enhance the mechanical properties but can also restrain the shrinkage of UHPC (Hassan et al. 2012; Harish et al. 2013; Nguyen et al. 2013; Wu et al. 2016c). Until now, steel, carbon, glass, and synthetic fibers, such as polypropylene and polyethylene fibers, have been used in UHPC. They were incorporated as a mono fiber or blended with other fibers. Different shapes of steel fiber have also been used to improve the mechanical properties due to high mechanical anchorage associated with the shaped fibers (Kim et al. 2011; Markovic 2006). The mechanical properties of UHPC can vary with the type, content, shape, and orientation of fiber, and casting method, etc.

In this paper, the commonly used fiber in UHPC and its role is firstly summarized. Two fiber reinforcing mechanisms based on composite mechanics and fiber space theories are introduced. The mechanical properties, such as compressive, flexural, tensile, and dynamic properties, which are affected by content, shape, type, distribution, and orientation of fiber, fiber hybridization, are then analyzed. Finally, some typical applications of UHPC structures are presented. It aims to summarize the recent progresses and to enhance the economic efficiency and practicability of UHPC.

TYPES OF FIBER AND UHPC

Historically, horsehair was used in mortar and straw in mud bricks. In the 1900s, asbestos fibers were used in concrete. However, health risks associated with asbestos were discovered. By the 1960s, steel, carbon, glass, and synthetic fibers, such as polypropylene and polyethylene fibers, have been adopted in concrete. Table 1 shows the typical properties of the commonly used fibers in cementitious materials. Due to the high tensile strength and Young modulus, steel and carbon fibers are the most used ones in UHPC (Shi et al. 2015).

Table 1 Typical properties of fibers (ACI, 1973; Shi et al. 2015)

Type	Diameter (μm)	Relative density ($g \cdot cm^{-3}$)	Tensile strength (MPa)	Young modulus (GPa)	Elongation (%)
Asbestos	≤0.5	2.75	500-980	84-140	0.3-0.6
Acrylic	5-17	1.18	800-950	16-23	9-11
Polyester	10-80	1.38	735-1200	6-18	11-15
Polyethylene	800-1000	0.96	200-300	5-6	3-4
Polypropylene	20-70	0.91	300-770	3.5-11	15-25
Nylon	23	1.16	900-960	4.2-5.2	18-20
PVA	1.30	1.30	600-2500	5-50	6-17
Aramid	10-12	1.44	2500-3100	60-120	2.1-4.5
Rock Wool	2.7	2.7	490-770	70-119	0.6
Glass	10-16	2.74	1400-2500	70-80	2.5-3.5
Wood	25-400	1.40	50-1000	15-40	-
Carbon	7-18	1.75	1800-4000	200-480	1.2-1.6
Steel	250-1000	7.80	280-2800	200-250	0.5-4.0

Current UHPCs can be classified into two groups according to the type of fiber used. In the first group, high strength smooth or deformed steel mono-fibers with very fine diameter ($d_f \leq 0.2$ mm) and relatively short length ($l_f \leq 30$ mm) were incorporated in the UHPC matrices (Wuest et al. 2008; Abu-Lebdeh et al. 2011). In the second group, two or three different types of fibers were blended in (Wille et al. 2011). Long and short fibers, or smooth and hooked steel fibers, or steel and synthetic fibers were blended together. The fiber volume is often in the range from 1% and 4%. Due to the high cost and reduction in flowability, the large amount of fibers is still one of the main difficulties in the application of UHPCs.

Role of fiber in UHPC

Concrete is a typical quasi-brittle material with low tensile strength, strain capacity, and fracture toughness. Incorporation of fibers into concrete can prevent and control initiation, propagation or coalescence of cracks. When a load acts on fiber reinforced concrete, the fibers do not sustain the load directly, but the matrix does. The load is transferred to the fibers through the interface between the fibers and the matrix. Fig. 1 demonstrates how fibers absorb energy and control the growth of crack (Zollo 1997). Starting from the leftmost fiber element and proceeding along the crack towards the right in the figure, they represent fiber rupture, pullout, bridging by tension through the fiber, and debonding at the fiber-matrix interface.

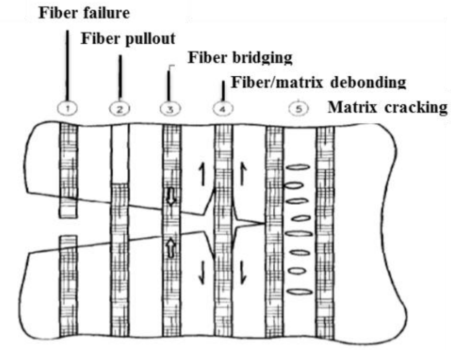


Fig. 1 Energy-absorbing mechanisms of fiber-matrix

FIBER REINFORCING MECHANISM OF CONCRETE

Theory of the composite mechanics

Based on the blending theory of the composite material, the composite mechanics theory was adopted in the fiber reinforced concrete. By using this theory, the formulas of stress, elastic modulus, and the intensity can be calculated. In this theory, the concrete heterogeneity of the valid volume along the stretching orientation and the length and the orientation modification of the nonlinear short fibers cannot be ignored. Fig. 2 shows some the detailed information of matrix and fiber under stress.

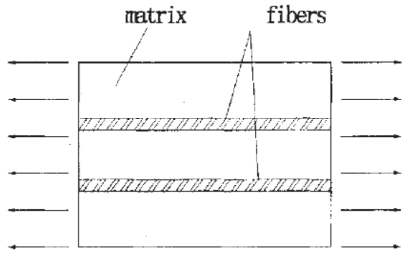


Fig. 2 Illustration of a composite material under stress

The properties of the composite material are the sums of effect from each component. The hypotheses are stated as follows:

(a) Fibers are continuously and homogenously arrayed in the matrix. Their orientations are parallel to the direction of loading force.

(b) Good bond exists in the fiber and the matrix, in which same strain with no relative slide is assumed.

(c) Both the fiber and the matrix present elastic deformation and have the same lateral deformation.

According to the basic hypotheses above, when force is applied along the fibers, the maximum stress and the elastic modulus can be calculated according to Equations (1) and (2), respectively:

$$f_c = f_f V_f + f_m V_m = f_f V_f + f_m(1-V_f) \tag{1}$$

$$E_c = E_f V_f + E_f V_m = E_f V_f + E_m(1-V_f) \tag{2}$$

where f_c *and* E_c are the maximum stress and the elastic modulus of the fiber reinforced concrete, respectively; f_m, E_m, and V_m are stress, elastic modulus, and volume of the matrix, respectively; f_f, E_f, and V_f are the stress, elastic modulus, and volume of the fiber, respectively.

The equation (2) indicates that the deformation of the fiber equals to that of the matrix in the elastic range. Hence, when the orientation of the fiber is similar to the loading direction of the load, the stress (or the elastic modulus) of the concrete is equal to the sum of the matrix stress and the fiber stress (or the elastic modulus of the matrix and steel fiber) multiplying the respective volume.

However, the hypotheses are ideal, which applies to the composite materials with specified aligned fibers only. In practice, fiber is randomly and disorderly oriented. In this case, the orientation and length of the fiber and the bonding properties between fiber and matrix should be taken into account. Therefore, an improved model was carried out by Naaman (1991). It was assumed that the stress of the composite is the superimposed stresses of the fiber and the matrix under different strains. The cracking strength could be calculated by Equation (3):

$$f_c = f_m(1-V_f) + \eta\tau V_f \frac{l}{d} \tag{3}$$

where f_c is the average stress of the composite material; f_m is the stress of the matrix; V_f is the fiber volume; l/d is the aspect ratio; τ is the average interface shear stress, which can be determined by fiber pullout testing; η is the reduction factor, $\eta=\eta_1\eta_2\eta_3$; η_1, η_1, and η_1 are the direction coefficient, effective coefficient in the forced direction, and reduction factor of fiber, respectively. The stress after cracking of concrete is sustained by the fiber. The ultimate stress could be expressed in Equation (4):

$$f_c = \eta\tau V_f \frac{\mathrm{l}}{\mathrm{d}} \tag{4}$$

Fiber space theory

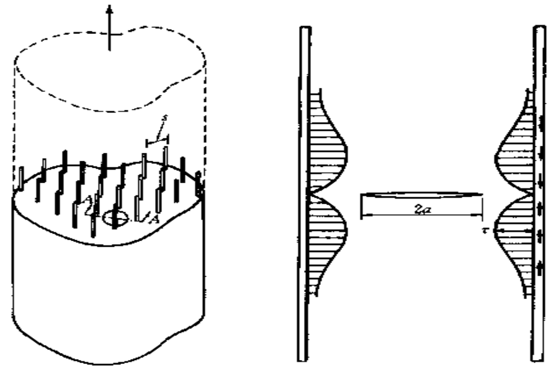
The fiber space theory was proposed by Romualdi et al. (1963, 1964), which is based on the linear elastic fracture mechanics. It explains how the fiber prevents the cracking from occurring and developing. This theory assumes that the damage of concrete results from interior defects, such as micro crack and initial porosity, which would produce crack tip stress concentration under external forces. With the increase of stress, the cracks would further extend and transform into large cracks, resulting in destruction of concrete members. Romualdi et al. assumed that continuous fibers are evenly distributed along the direction of pullout with a chessboard-shaped in the matrix, as illustrated in Fig. 3. As shown in Fig. 3(a), a crack with radius of a is surrounded by four fibers with a spacing of S. Under the tensile loads, regions of the cracks around the fiber will produce the cohesive force distribution of τ, as shown in Fig. 3(b). The cohesive force on the crack tip yields reverse stress field, which can reduce the degree of stress and eventually constraints the development of cracks. In this case, a stress intensity factor is generated at the crack tip in contrary to that of the crack tip of matrix, and the total stress intensity factor is reduced to:

$$K_T = T_\sigma - K_f \tag{5}$$

or

$$K_T = \frac{2\sqrt{a}}{\pi}\left(f_{fc} - Q\right) \le K_{1c} \tag{6}$$

where K_T is the actual strength intensity factor of the composite material; K_a is the strength intensity factor of the composite material without fiber under external force; K_f is the generated opposite power intensity factor due to the incorporation of fibers; K_{1c} is the critical power intensity factor; K_{fc} is the uniform tensile stress along the fiber direction; Q is the maximum shear stress of fiber to cracking concrete after additional strain resistance in the fiber-matrix interface.



(a) Fiber constraint model (b) A-A section

Fig. 3 Fiber constraint model for composite materials

When $K_T \ge K_{1c}$, fracture can occur in the composite material. According to this theory, Romualdi et al. considered that fiber spacing s has a significant influence on tensile strength of concrete. Assuming 2a=s $\sqrt{a}$, the tensile strength of fiber reinforced concrete can be calculated in terms of Equation (7):

$$f_{cu} = \frac{K_{1c}}{Y\sqrt{a}} = \frac{0.83K_{1c}}{Y\sqrt{s}} = \frac{K}{\sqrt{s}} \tag{7}$$

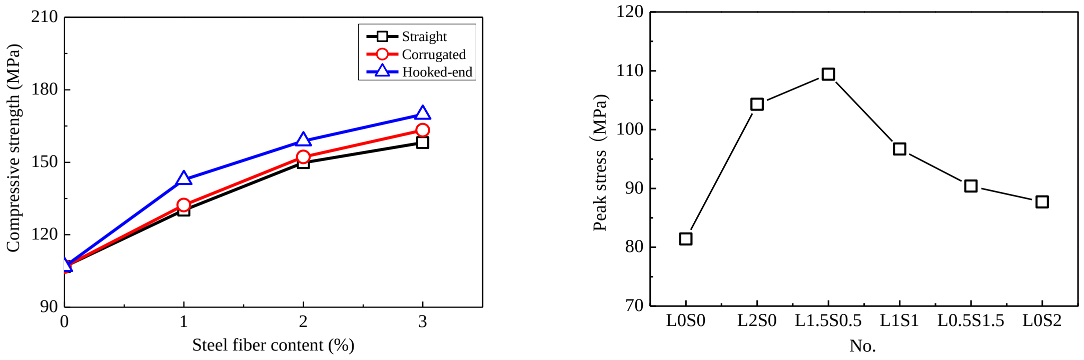
where f_{cu} is the tensile strength of the fiber reinforced concrete; K is a constant related to K_{1c} and Y; Y is a constant related to the shape of crack; S is the average spacing of directional long fiber.

The fiber spacing is related to fiber shape, length, volume, orientation, etc. Therefore, the actual fiber spacing can vary with those factors. Others factors, such as material composition, mixing and vibrating processes, curing conditions, interface bonding properties between fiber and matrix, and steel fiber dispersion technology, should also affect the fiber spacing.

COMPRESSIVE PROPERTIES

The compressive strength is an important parameter of cement-based materials related to structure and component design. Hannawi et al. (2016) investigated the effect of different types of fibers on the uni-axial compression of UHPC. It was shown that the mineral and synthetic fibers had a relatively slight influence on the compressive strength and elastic modulus of concrete. However, the steel fiber improved the strength because of its intrinsic rigidity. Generally, with the increase of steel fiber, the compressive strength of green reactive powder concrete (GRPC) could increase by 30-50 MPa compared to that without any fiber (Zhang et al. 2008). Hassan et al. (2012) indicated that steel fiber had a relatively small effect on the pre-cracking compressive strength. However, its influence on the post-cracking behavior and failure mechanism were significant. The reference UHPC specimens with no fiber behaved elastically until peak strength and then followed by a sudden strain softening. In contrast, UHPC specimens behaved elastically up to approximately 90%-95% of their compressive strength, followed by strain hardening behavior up to peak strength.

Fiber shape also affects the compressive strength of UHPC. It was indicated that UHPC with hooked-end fibers had the highest compressive strength, followed by corrugated fibers and then straight fibers, as illustrated in Fig. 4(a) (Wu et al. 2016a). When 2% hooked-end, corrugated and straight fibers were incorporated, the compressive strengths increased by 48.7%, 44.3%, and 40.3%, respectively, compared to that without any fiber. When hybrid fibers (long and short fiber) were incorporated, the uniaxial compressive strength increased first and then decreased with the increase of the short fiber volume, as shown in Fig. 4(b). The highest compressive strength was achieved for UHPC with 1.5% long fibers and 0.5% short fibers (L1.5S0.5), whereas those with 2% short fibers (L0S2) showed the worst properties (Wu et al. 2016d).



(a) Fiber shape (Wu et al. 2016a)

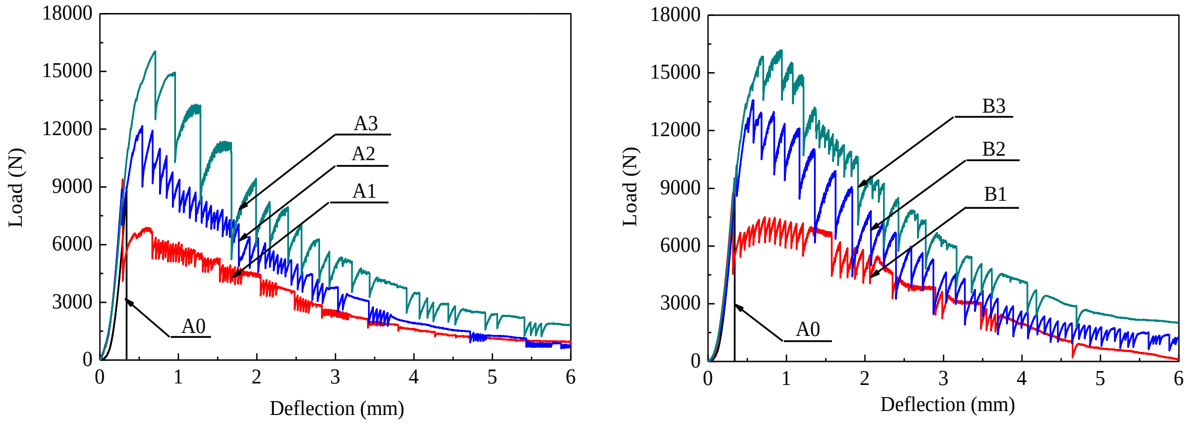
(b) Volume of fiber hybridization

Fig. 4 Effects of fiber shape and volume of hybridization fiber on compressive strength of UHPC (L0S0: no fiber; L2S0: 2% long fibers with length of 13 mm; L1.5S0.5: 1.5% long fibers with length of 13 mm and 0.5% short fibers with length of 6 mm; L1S1: 1% long fibers and 1% short fibers; L0.5S0.5%: 0.5% long fibers and 1.5% short fibers; L0S2: 2% short fibers)

FLEXURAL PROPERTIES

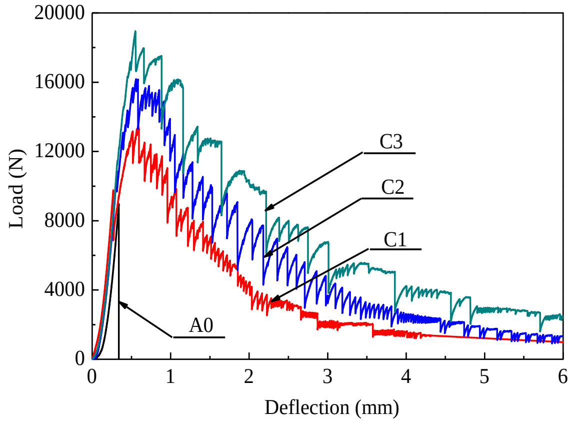
Fiber has significant effect on flexural properties of UHPC. Huang et al. (2014) showed that 2% polyethylene fibers increased the flexural strength by 47.3% compared to the reference sample. Yoo et al. (2016) observed obvious enhancements in flexural strength and energy absorption capacity when longer fiber was used, whereas insignificant effect of fiber length on the first cracking properties. Birol et al. (2016) proposed that fiber type was decisive in characteristic of the load- deflection curve. However, the fiber volume amplified this effect with an increasing trend after the first cracking region. Wu et al. (2016c) investigated different fiber dosages (0, 1%, 2%, and 3%) and shapes (straight, corrugated, and hooked-end) of steel fiber on flexural properties of UHPC. The results are shown in Fig. 5. Steel fiber content had limited effect on the first crack strength and first crack deflection of flexural load-deflection curve of UHPC. However, considerable effect on the peak load was observed. When 2% straight, hooked-end, and corrugated fibers were used, the peak load increased by 46.3%, 81.1%, and 61.4%, respectively, compared to the reference specimen. The peak deflection increased by 76.7%, 153.3%, and 123.3%, respectively.

Fiber blending is a promising method to improve the flexural performance of UHPC, which makes macro and micro fibers or fibers with different shapes play a role at different levels. It was found that the fiber hybridization in normal strength matrices produced favorable hybridization effect on the ductility in comparison with that with one type of fiber (Sivakumar, 2007). Kim et al. (2011) found that the enhancements in modulus of rupture, deflection capacity, and energy absorption capacity were different according to the types of macro fiber as the amount of micro fiber blended increased. The order of flexural performance of hybrid ultra-high performance fiber reinforced concrete (H-UHPFRC) according to the types of macro fiber was as follows: hooked fiber > twisted fiber > long smooth fiber. Real non-uniform fiber distribution can decrease the strengthening effect of fiber. Hai et al. (2016) showed that steel and polyvinyl alcohol fibers efficiently improved the bending properties of UHPC. The flexural and compression ratio, tension and compression ratio increased by 40%.



(a) Straight steel fiber

(b) Corrugated steel fiber



(c) Hooked-end steel fiber

Fig. 5 Effects of steel fiber shape and content on flexural load-deflection curve of UHPC at 28 days (A1, A2, and A3 represent UHPC with 1%, 2%, and 3% straight fibers, respectively; B1, B2, and B3 denotes UHPC with 1%, 2%, and 3% corrugated fibers, respectively; C1, C2, and C3 denotes UHPC with 1%, 2%, and 3% hooked fibers, respectively)

Several researches proved that the placing methods affected the fiber distribution in short-fiber reinforced concrete, and hence the mechanical performance (Toutanji and Bayasi 1998; Toutanji et al. 2010). Kang et al. (2011) evaluated the fiber distribution characteristic on the flexural strength of UHPFRC under two different placing directions. It was found that the initial cracking and ultimate flexural strengths of UHPC placed parallel to the longitudinal direction of model were 5.5% and 61%, respectively, larger than that placed transversely.

TENSILE PROPERTIES

Generally, tensile properties of concrete are determined by using three types of test methods, such as direct tension tests, splitting tests, and flexural tests. These tests are usually performed by using dog-bone shaped, cylinder, and prism specimens.

Kang et al. (2011) studied the tensile fracture properties of UHPC with fiber volume ratio varying from 0 to 5% through notched 3-point bending testing. It was reported that the tensile strength of UHPC linearly increased with the increase of fiber volume ratio.

Park et al. (2012) investigated the effects of blending fibers on the tensile behavior of ultra high performance hybrid fiber reinforced concrete (UHP-HFRC). Four types of steel macro-fibers (different lengths or geometries) and one type of steel micro-fiber were considered. The volume of the macro-fiber was held at 1.0%, whereas the volume of the micro-fiber varied from 0 to 1.5%. The overall shape of tensile stress-strain curves of UHP-HFRC was primarily dependent upon the type of macro-fiber, although the addition of micro-fibers favorably affected the strain hardening and multiple cracking behaviors. UHP-HFRC produced with twisted macro-fibers showed the best performance with respect to post-cracking strength, strain capacity, and multiple micro-cracking behavior, whereas UHP-HFRC produced with long smooth macro-fibers exhibited the worst performance, as shown in Fig. 6. The hybrid combinations of a synthetic fiber with high strength, such as PE and steel fibers, could improve the tensile behavior of UHPC (Kang et al. 2016).

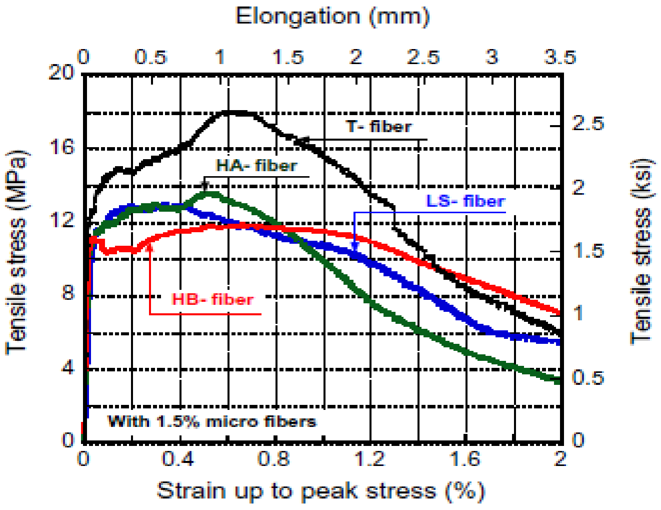


Fig. 6. Tensile responses of UHP-HFRCs with 1.5% micro fibers and 1.0% macro-fibers

UHPC with only 2.5% short smooth steel fibers (d_f = 0.2 mm, L = 13 mm) also showed tensile strain hardening behavior (Wille et al. 2011). Its post-cracking strength was 14.2 MPa and strain capacity was 0.24%. UHPCs with 2% high strength deformed steel fibers, such as hooked and twisted steel fibers, showed good tensile properties. Nonetheless, it is still difficult to obtain strain capacity more than 0.5% using one type of fiber in UHPC, as well as tensile post-cracking strength more than 15 MPa.

DYNAMIC PROPERTIES

The superior performance of UHPFC allows its potential applications in structures that suffer high speed impact and explosive loads (Lee et al. 2007), including explosion and penetration resistant structures, protective shelter of military engineering, and nuclear waste treatment. There are two common methods, the drop weight and split Hopkinson pressure bar (SHPB) testing, to measure the dynamic behavior of concrete. The drop weight testing has the ability to reproduce conditions under which real life component would be subject to impact loading (Ku et al. 2005). Habel et al. (2016) studied the impact performance of UHPC by the drop weight tests and stimulated the dynamic response using a two mass-spring model. It was shown that the analytical two mass-spring model of the drop weight configuration was in good agreement with the experimental results. The UHPC strength increased with increasing strain rate and continued to exhibit strain hardening characteristics up to approximately $d\varepsilon/dt = 2\ s^{-1}$. Multiple cracking was also observed. The bending resistance increased by more than 25% and the corresponding uniaxial tensile strength was increased by more than 15% relative to static behavior. Because impact performance is greatly influenced by configuration, such as drop weight and speed, specimen size, and support stiffness, some researchers used the SHPB testing instead.

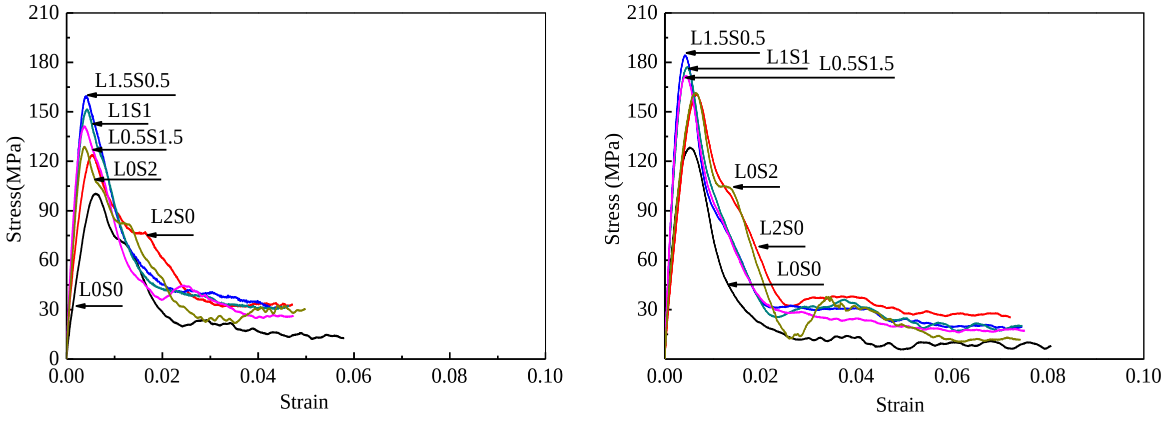
Rong et al. (2010) found that the dynamic compressive strength of UHPC was improved with the increase of fiber volume and was significantly sensitive to the strain rate. Under the same compressive loading, the UHPC matrix was crushed while the UHPC with 3% or 4% of steel fibers remained essentially intact. For dynamic tensile strength, Zhang et al. (2008) found that it increased obviously with the increase of impact velocity ranging from 4 to 14 m/s, which showed high strain rate sensitivity. The minimal dynamic tensile strength was higher than the quasi-static strength, especially for GRPCs with high fiber content.

Figure 7 shows the dynamic compression stress-strain curves of UHPC with hybrid steel fibers under the same impact velocity (He 2015). The reference mixture L0S0 showed the lowest dynamic compressive strength and toughness, while the L1.5S0.5 mixture exhibited the highest corresponding values followed by the L1S1 and L1.5S0.5 mixtures. However, UHPC mixtures with mono fiber (L0S2 and L2S0 mixtures) showed comparable dynamic peak stress, which was lower than that of the L0.5S1.5 mixture.

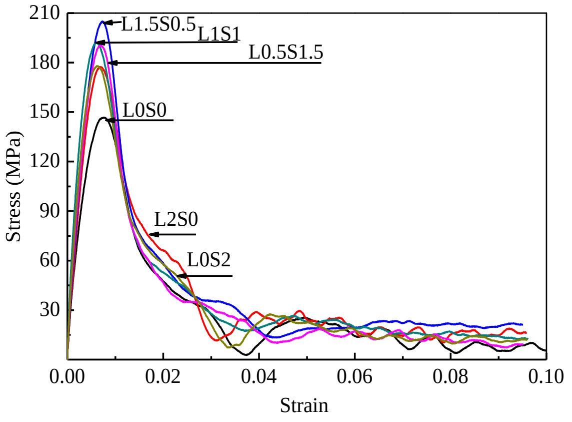
APPLICATION OF UHPC

Bridges and footbridges

The world's first designed UHPC structure is the Sherbrooke footbridge in Sherbrooke, Quebec, which was built in 1997 (Perry and Seibert, 2008). This precast and prestressed pedestrian bridge is a post-tensioned open-web space RPC truss, with 4 access spans made of high performance concrete (HPC). In the early 2000, several remarkable road bridges, such as Shepherds Bridge in Australia, bridge of Wapello in Iowa (USA), bridge of the expressway in Japan, and five pedestrian bridges like Korea, Sermaises in France, Sakata Mirai, and Akakura in Japan, have been constructed by Ductal (Resplendino, 2012).



(a) 8.9 m/s (b) 11.7 m/s



(c) 13.9 m/s

Fig. 7 Effects of hybrid fibers on dynamic compression stress-strain curves of UHPC at 28 days

The first German large scale application was the “Gaertnerplatzbridge” in Kassel (Harries and Roberts-Wollmann, 2008) that built in 2007 (Fig. 8). This very slender structure was made of prefabricated and prestressed fiber-reinforced UHPC elements, which consists of a 3D steel truss in combination with longitudinal girders and deck slabs. Due to the high adhesive tensile strength, the slabs were glued to the girders with an epoxy resin without any additional mechanical fitting device (Spasojevic 2008).

Recently, an assembly precast UHPC bridge was built in Changsha, China, as shown in Fig. 9. It has three spans of 27.6, 36.8, and 6.4 m. Due to its advantages in technical, economic, and social aspects, UHPC will has a broad market demand in China in the following years.

Fig. 8 Gaertnerplatzbridge in Kassel

Fig. 9 Assembly precast UHPC bridge in Changsha

Building equipment

In the areas of building equipment, numerous applications of UHPC can be found (Stoeux, 2011). These applications can ensure cost-effective and sustainable structures with varied architectural forms (Figure 10). The UHPC interest in this area is clear, related to the finesse and variety of geometric shapes allowed by the absence of passive reinforcement sunshades. The superior mechanical properties of UHPC structure, which is competitive with steel or aluminum alloy, can produce very slender, durable, aesthetic, and durable structures.

Fig. 10 Ultra-high performance fiber reinforced concrete (UHPFRC) perforated panels

Thin shell structure and lightweight roofing

Figure 11(a) shows the Millau toll in France. This is a bulky structure, representing a total weight of 2300 tons implemented on site. The structure had a length of 98 m and a width of 28. Two thin slabs of 10 cm thick were made, which were connected by 12 prestressed beams. It was built using 53 match-cast pasted prefabricated segments assembled on a hanger with a longitudinal prestressing. This project highlighted the following aspects: (1) Being able to produce UHPC structure with complex shapes and thin membrane; (2) Perfect control of the rheological properties for the production of UHPFRC in high volume.

One of another famous application is the Shawnessy LRT station in Calgary, Canada, as shown in Fig. 11(b). The design flexibility afforded by UHPC allowed the architect to fulfil their desire for a free-flowing form design for this structure. Full-scale load tests were used to ensure the satisfactory behaviour of the 24 UHPC architectural shell canopies that were used for the station prior to their installation. The canopies were only 20 mm thick and shield waiting passengers from the weather. Each pair of canopy pieces was supported on a single UHPC.

(a) Overview of the coverage of Millau toll, France (b) Shawnessy LRT station in Calgary, Canada

Fig. 11 Applications of UHPC in thin shell structure and lightweight roofing

Other applications

UHPC cannot only be used for construction of precast structure to ensure beauty of city (Fig. 12 a and b), but can be also utilized to repair and enhance the performance of existing structures (Fig. 12 c). These materials are required to be increasingly more energy-efficient, environmentally friendly, sustainable, affordable, and resilient. They need to meet multi-performance design criteria and be easily produced and incorporated into construction methods and practice.

(a) Precast structure (b) Precast structure (c) Repaired structure

Fig. 12 Other UHPC applications

CONCLUSIONS

There is a great potential for the application of ultra-high performance fiber reinforced concrete in structural elements and structures exposed to severe mechanical or environmental loading. Based on the literature review and discussions above, following conclusions can be drawn:

(1) Incorporation of mineral and synthetic fibers have little influence on the compressive strength of UHPC, whereas steel fiber can increase the compressive strength to some extent. The addition of micro-fibers favorably affect the strain hardening and multiple cracking behaviors. Blending fiber is an effective method to enhance the tensile strength and strain capacity. Deformed fiber can significantly increase the flexural and tensile strength. However, the large amount of fibers prone to cause fiber agglomeration issue and lead to high cost. Therefore, design UHPC incorporated with appropriate steel fiber content with effective orientation is essential to enhance mechanical properties, efficiency, and sustainability.

(2) UHPCs are sensitive to strain rate. Incorporation of steel fiber effectively improves the dynamic properties. Under the same compressive loading, the sample of UHPC matrix is crushed while the sample made of UHPC with steel fibers remains essentially intact. UHPC with hybrid steel fibers showed better impact performance than those with single type of fiber.

UHPC has been applied, often as precast structure, in the several countries. In order to apply it more wildly, requirements, such as energy-efficient, environmentally friendly, sustainable, affordable, and resilient, should be met. There is significant research need to understand the mechanical and structural behavior of UHPC under complex combined loads as encounter in the field. To be able to fully utilize the superior qualities of this new material, it will be necessary to develop a realistic, reliable performance-based design concept for such structures.

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