Mechanical properties and corrosion resistance of high performance fiber-reinforced concrete with steel or amorphous alloy fibers

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Abstract

In the present study, steel fiber and amorphous alloy fiber were applied either single-added or hybrid-added to produce high performance fiber-reinforced concrete (HPC). The results showed that the flowability of fresh concrete was reduced and the compressive, splitting and flexural strength was increased by adding fibers to the mixture. However, the effect of amorphous alloy fiber was more pronounced due to the higher aspect ratio compared to steel fiber. Addition of amorphous alloy fiber improves the interfacial structure and results in a greater maximum pull-out load and bond strength, whereas, a smaller interfacial toughness as compared to crimple steel fibers. After wet/dry cycles, the flexural strength and bond strength was raised about 8% and 10% after 3 days experimental period, but reduced 10% and 15% after 30 days experimental period for steel fiber-reinforced concrete (SFRC), however, has little difference for amorphous alloy fiber concrete (AAFRC). Additionally, the hybrid-fiber-reinforced concrete showed superior performance, especially the flexural property as compared to their single-fiber-reinforced counterparts due to combination effect of the two types of fibers which delay the formation of micro-cracks and macro-cracks, respectively.

1. Introduction

Concrete is widely used as building materials [1, 2]. With the building structure development to high-rise and long-span, the requirement for the strength and toughness of concrete has become increasingly high [3]. However, the concrete will become fragile with the increasing of its strength [4]. It is known, the existence of fibers in concrete composites can effectively block micro-cracks and macro-cracks expanded [5], remarkably raised the concrete matrix tenacity, ductility and impact resistance properties [6].

For many decades, research works have focused on the benefit from fiber-reinforcement, a series of fiber type, including steel, glass, synthetic, and natural fiber have been applied. Steel fiber has better modifying effects on the properties of concrete, so it is widely used in concrete structures [7]. However, due to its high specific gravity, steel fiber (SF) increases the rebound of shotcrete during tunnel and underground structure construction, which reduces the stability and increases the weight of the structure. Furthermore, in marine environment, corrosion will occur in SFRC through chemistry and electrochemistry reactions, and destroy the performance of the structure [8, 9]. Corrosion spots appear on the concrete surfaces would adverse environments and aesthetic [10]. Glass, synthetic and carbon fibers also have their flaws and shortcomings, i.e. poor durability of glass fiber, high cost of carbon fiber and poor anti-aging ability of synthetic fiber and these led to their application was limited.

In recent years, along with the technology development and new materials comes forth continuously, the use of amorphous alloy is becoming more and more widespread. Amorphous alloy is a long-range disordered structure. The molecules (or atoms and ions) that make up its material do not have regular periodicity in space, and there are no grains and grain boundaries of crystalline alloy [11]. Because of its unique structure, an amorphous alloy has far more corrosion resistivity than that of crystalline alloy and exhibited special mechanical properties [12]. Amorphous alloy fiber (AAF) was applied to ceramic materials, polymer matrix material would...
obtain a preferable effect on the properties [13, 14]. Introducing AAF into the concrete matrix was pioneered by French [15], since then, many researchers studied amorphous alloy reinforced concrete. In Won’s study [16], short amorphous fiber significantly improves the bending strength, corrosion resistance and interfacial adhesion strength of concrete beam. In another study [17] related to type of fiber in reinforced concrete, it was pointed out that flexural strength and toughness increased significantly as compared with SFRC at the same volume fraction. However, the interfacial toughness was greater in hooked-type SF-reinforced concrete than AAF-reinforced counterparts. In addition, previous studies [18, 19] have indicated that AAFRC presented excellent control performance on plastic shrinkage-induced crack. Amorphous alloy fiber with smooth surface counteracts the interfacial property between fiber and matrix interface. Furthermore, research on the durability of AAFRC is far from complete, particularly in the aspects of corrosion resistance. In the present study, the variations in mechanical properties, bonding capacity, corrosion performance of concrete with amorphous alloy fiber was further discussed, and comparison was made with conventional SFRC.

2. Experimental program

2.1. Materials and mix composition

Ordinary Portland cement with Grade 42.5 (ASTM C150–12) was applied in the experiments. Silica fume (SiF) with a specific gravity of 2.20 and surface area of 22500 m² kg⁻¹ was used. Fibers, added to concrete, were in two different types, the properties are listed in Table 1. Crushed gravel (maximum size of 10 mm) was used for the coarse aggregate, and river sand (specific gravity of 2.60) was used for the fine aggregate. A commercially available superplasticiser (SP) based on ether polycarboxylate was used to achieve flowability. The quantity of each constituent of the concrete is given in Table 2. The dry ingredients were mixed at a speed for 2 min. Then, mixed fiber for another 2 min. Water and superplasticizer were then slowly introduced and the materials were mixed for approximately 2 min. The mixture was then casted and cured.

2.2. Mechanical property tests

After mixing, the slump experiment which reflects the workability of concrete was carried out. Then, the well-mixed concrete mixture was poured into molds to form the cubes of size 10 × 10 × 10 cm³ for the compressive and splitting strength testing. The samples were demolded after 24 h and then cured in a curing room (relative humidity in excess of 90%, temperature 20 ± 3 °C) till specified age. The flexural behavior was assessed at 28 days in three rectangular prisms (100 × 100 × 400 mm³). All the tests were assessed according to GB/T 17671–1999 (Standard Test Method for steel fibers reinforced concrete in China).

| Table 1. Properties of amorphous alloy fiber and wave-type steel fiber. |
|---------------------------------------------------------------|
| Type                  | Amorphous alloy fibers | Wave-type steel fibers       |
|-----------------------|------------------------|-------------------------------|
| Elastic modulus (MPa) | 14E4                   | 20E4                         |
| Specific gravity      | 7.2                    | 7.8                          |
| Fiber length (mm)     | 35                     | 35                           |
| Aspect ratio          | 34.3                   | 69.3                         |
| Tensile strength (MPa)| 1400                   | 600                          |
| Ultimate elongation,% | 3.5                    | 3.5                          |
| Acid/alkali resistance| high                   | low                          |
| Electrical conductivity| high                   | high                         |
| Composition           | Fe, Cr, FeSi, P, C, Si | Fe, Cr, FeSi, P, C, Si       |
| Fiber shape           | Corrosion appearance after immersed to 5%NaCl for 30 days |

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2.3. Interface characterization between fiber and matrix

Interfacial microstructure between fiber and matrix was performed with Quanta FEM 250 scanning electron microscope (SEM). The interfacial properties of fiber and matrix were evaluate using the mould of figure 1(a), the detailed test setup was shown in figure 1(b).

The bond strength $f_b$ could be calculated through equation (1):

$$f_b = \frac{F_{max}}{n \mu f L_{em}} \leq 0.4 \sigma_f, \quad L_{em} \leq \frac{f_{ef}}{f_{m,eq}} d_{ef,eq}$$

where $F_{max}$, $n$, $\mu_f$ and $L_{em}$ stand for the maximum pull-out load (N), the number of tested fibers (4), the section circumference of fiber and the length of embedded end of fiber (12 mm). The value $\mu_f$ here is 3.20 mm for steel fiber and 1.59 mm for amorphous fiber. $f_{ef}$ stand for the fiber length and has a value of 35 mm, $f_{eq}$ is the ultimate

| Table 2. Compositions for 1 m$^3$ of concrete kg$^{-1}$. |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Cement          | SiF | Water | Sand | Coarse aggregate | Steel fibre | Amorphous fibres | SP  | W/B |
| CC              | 444.6 | 49.4 | 158 | 647 | 1151 | 0 | 4.94 | 0.32 |
| SFRC-0.5        | 444.6 | 49.4 | 158 | 647 | 1151 | 39 | 4.94 | 0.32 |
| SFRC-1          | 444.6 | 49.4 | 158 | 647 | 1151 | 78 | 4.94 | 0.32 |
| AAFRC-0.2       | 444.6 | 49.4 | 158 | 647 | 1151 | 14.4 | 4.94 | 0.32 |
| AAFRC-0.5       | 444.6 | 49.4 | 158 | 647 | 1151 | 36 | 4.94 | 0.32 |
| AAFRC-1         | 444.6 | 49.4 | 158 | 647 | 1151 | 78 | 4.94 | 0.32 |
| HYFRC-1         | 444.6 | 49.4 | 158 | 647 | 1151 | 39 | 36 | 4.94 | 0.32 |

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where $F_{max}$, $n$, $\mu_f$ and $L_{em}$ stand for the maximum pull-out load (N), the number of tested fibers (4), the section circumference of fiber and the length of embedded end of fiber (12 mm). The value $\mu_f$ here is 3.20 mm for steel fiber and 1.59 mm for amorphous fiber. $f_{ef}$ stand for the fiber length and has a value of 35 mm, $f_{eq}$ is the ultimate
tensile strength of steel fiber (600 MPa) and amorphous fiber (1500 MPa). $f_{c,m}$ stand for concrete strength and $d_{eq}$ stand for the equivalent diameter of steel fiber (1.02 mm) and amorphous fiber (0.50 mm).

2.4. Wetting and drying cycles
The corrosion behavior of SFRC and AAFRC in chloride rich environment was studied by a continuous drying-wetting cycle test [20] in 5% NaCl solution. The specimens were submerged in NaCl for 12 h and then they were exposed to the dry place for another 12 h (one experimental period). After 3 and 30 days of wetting-drying cycles, the flexural strength and interfacial properties were evaluated according to sections 2.2 and 2.3. For obtaining reliable interfacial properties test data after drying-wetting cycle and avoid the fibers at the location of plastic board exposed to NaCl solution directly, epoxy resin was used for protection the non-bonding zone of the fibers.

2.5. Pore structure measurement
Concrete pore structure was measured by means of MIP. To prepare the samples, the concrete (curing for 28 days) were first broken, and then the cement paste fragments selected from the center of specimens and nearby fibers are used. The experimental technique is described in detail elsewhere [21].

3. Results

3.1. Fresh stage properties
The workability of fresh concrete was summarized in table 3. As shown that regardless of fiber type, the slump and spread decreased with the increase of fibers content. However, the addition of steel fiber has a less significantly influence in the fresh properties than amorphous alloy fiber. Compared with the control concrete (CC) sample, the slump and spread of AAFRC sample with 1% fiber decreases from 170 mm to 53 mm and 600 mm to 235 mm (68.8% and 60.8% lower). However, only 47.6% and 45.5% lower for SFRC samples. This could be interpreted by a higher aspect ratio and surface area of amorphous alloy fiber at same volume ratio and length compared to steel fiber, thereby increasing tying force of fiber to aggregate/paste and fluidity of fresh concrete was decreased, even the crimple type of steel fiber provided an anchorage between fiber and the surrounding paste.

3.2. Hardened stage properties
Mechanical properties ($f_c$, $f_s$, and $f_f$) of the mixes at hardened stage were evaluated and present in table 3. Three specimens were tested for each type of experiment, and the average values were reported.

3.2.1. Compressive strength
For all mixes, the compressive strength increased with increasing of curing ages and fiber content. Whereas the increase in compressive strength is not significant with increasing in fibers volume fraction (the maximum increase in the strength is only 10.3% when 1% amorphous fibers was added at curing durations of 28d). It must be noted, however, in contrast to SFRC, the compressive strength after curing for 7 and 28 days of AAFRC increased greater as compared to the control specimens.

3.2.2. Flexural and splitting strength
As commonly known that flexural strength of concrete increases with increase in the fraction of fibers because of the bridging effect of uniformly distributed fibers in the matrix. As shown in table 3, in contrast to the control specimens, when amorphous alloy fibers of 1% was added into the mixes, the increment of the flexural strength
increased 37.5% after curing for 28 days. While, only 27% for steel fiber was added at the same fraction. An interesting aspect is that the flexural strength has a higher value in HFRC specimen as compared to single-fiber-reinforced samples.

Figure 2. Failure modes of the concrete mixes under various loading.

Figure 3. Load-displacement curves of steel (a) and amorphous alloy (b) concrete.
Although the splitting tensile strength can not directly confirm the tensile strength, but it also can reflect the toughness of concrete. As summarized in Table 3, we can see a similar tendency of splitting tensile strength compared to flexural strength.

### 3.2.3. Failure modes

Figure 2 depicts representative samples of each mix after failure under various loading. It can be seen that the CC specimens failed in an explosive manner due to loading, while all FRC specimens show a ductility fracture characterized regardless of fibers type and loading mode because of the fiber’s ability to bridge cracks. As indicated in Figure 2, cracks width decreases in the order of SFRC > AAFRC > HYFRC, Hameed and Turatsinze et al [22] reported that the addition of high elasticity amorphous metallic fiber to steel fiber-reinforced concrete delays the formation of micro-cracks and macro-cracks simultaneously and shows a ‘positive hybrid effect’.
3.3. Interfacial characters between fibers and matrix
The load–displacement plots obtained from the fiber pullout tests are presented in figure 3. It is clear that despite of smooth surfaces for the amorphous alloy fiber, the maximum pull-out load was greater as compared to steel fiber, whereas, with less displacement.

The interfacial properties between fiber and matrix were calculated and summarized in table 4. We can see that amorphous alloy fiber-reinforced concrete had a higher maximum pull-out load and bond strength than steel fiber-reinforced concrete. However, interfacial toughness was lower as compared to steel fiber counterparts. The test results showed the maximum pullout load, bond strength and interfacial toughness of steel fiber concrete are 217.6 N, 1.77 MPa and 294.9 N·mm, respectively. For the amorphous fiber case, the pullout load, bond strength and interfacial toughness are 325.7N, 4.27 MPa and 97.8 N·mm, respectively.

The SEM micrographs of interfacial transition zone (ITZ) between fiber and matrix in SFRC and AAFRC specimens are presented in figure 4. It is clear that the porous structures at ITZ in SFRC sample are more obvious (figure 4(a)) than in AAFRC sample figure 4(b). Therefore, it is expected that the mechanical and durable properties of AAFRC samples could be improved.

The micro-hardness at the ITZ was determined by micro-hardness tester, as seen in figure 5. The interfacial micro-hardness developed in concrete containing amorphous fiber was higher than that of the steel fiber sample, while the thickness of ITZ was lower, which is consistent with the SEM results.

3.4. Mechanical properties and interfacial characters after wetting/drying cycles
Figure 6 presents the mechanical properties and interfacial properties of concrete before and after wetting/drying cycles. Compared with the specimens before corrosion, the compressive and flexural strength of SFRC specimens increased by 5% and 7% after 3 days of experimental period, decreased by 13% and 18% after 30 days of experimental period. However, hardly had any influences for AAFRC specimens (figure 6(a)) because of superior corrosion resistivity of amorphous materials (table 1).

As shown in figure 6(b), compared with un-corroded SFRC specimens, the bond strength increased 8% after 3 days of wetting/drying cycles, when decreased 10% after 30 days of wetting/drying cycles. The interfacial toughness also changes with the experimental period prolonging. However, there are no obvious differences for AAFRC specimens before and after corroded.

4. Discussion

4.1. Mechanical properties
As commonly known, adding fiber is one of the most important means to improve the mechanical performance of concrete. The addition of fibers changed the compressive strength is attributed to the two contradictory aspects:

(1) Fibers added to the cement matrix materials delay crack propagation (figure 2) and led to an increase in the rupture stress;
Fibers added to the cement matrix materials led to an increase in porosity compared to the control concrete, thus the strength is decreased. Considering the two opposite processes, there is an optimal value of fiber volume fraction at which the highest compressive strength of fiber-reinforced concrete can be obtained.

Figure 7 shows the pore size distribution of concrete nearby fiber. The total specific pore volumes, the most probable pore diameters and the porosity of various fiber contents and types are given in Table 5.

From Table 5, we can see a trend that the total specific pore volume and porosity increases with increase in the fraction of fibers, when the most probable pore diameter decreases. However, compared with crimple steel fiber-reinforced concrete, amorphous alloy fiber show thin shape which help particle packing at fiber and matrix interface, increased compactness of concrete (figure 4(b)) and led to a higher compressive strength (table 3).

The flexural and splitting strength reflect the ductility of concrete and related to the distribution of fibers. The toughness of concrete will be enhanced if fibers are parallel orientated to the load direction due to the bridging effect of fibers reach their full potential. To assess the fiber distribution, orientation-factor $\alpha$ ($0 < \alpha < 1$) was used in this paper [21]. It is expressed as:

| Sample     | Total specific pore volume (ml g$^{-1}$) | Most probable pore diameter (nm) | Porosity (%) |
|------------|----------------------------------------|---------------------------------|--------------|
| CC         | 0.051                                  | 17.63                           | 8.3          |
| AAFRC-0.5  | 0.061                                  | 14.41                           | 10.9         |
| AAFRC-1    | 0.064                                  | 21.60                           | 11.6         |
| SF-0.5     | 0.072                                  | 33.75                           | 12.3         |
| SF-1       | 0.075                                  | 36.35                           | 14.6         |

(2) Fibers added to the cement matrix materials led to an increase in porosity compared to the control concrete, thus the strength is decreased.

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where, \( N \) is the actual number of fibers in a given sectional area; \( N_{th} \) stand for the theoretical number of the fibers parallel orientated to the load direction; \( A_f \) and \( V_f \) is the section of fiber and the volume fraction of fiber; \( A_c \) is the cross-section area of concrete specimen. \( \alpha = 0 \) stand for the concrete without fiber. For \( \alpha = 1 \), all the fibers are oriented parallelly to the transverse-section.

Figure 8 shows the distribution of fibers after flexural test. The orientation coefficient \( \alpha (0.33 \sim 0.40) \) of all the mixes is represents in table 6. With increment of fiber volume fraction, orientation coefficient \( \alpha \) has no apparent varies regardless of fiber type, whereas \( \alpha \) has a greater value in the AAFRC specimen than in the SFRC specimen at the same fraction. It is concluded that because of high aspect ratio, amorphous alloy fiber is generally more effective in controlling the prefer distribution of fiber and would create a well oriented in the direction of the tensile stresses.

A perverse aspect is that the flexural strength reached maximum in HYFRC specimen despite a slight decreases of \( \alpha \) as compared to AAFRC specimen at the same fraction, which is attributed to the ‘positive hybrid effects’. Additionally, previous studies [21] presented that amorphous alloy fibers were added into the steel fiber-reinforced concrete can substantially prevent the micro-cracking growth and improve the mechanical properties of concrete. This can be used to illustrate the phenomenon that hairline crack in HYFRC sample is no apparent after flexural tested (figure 2).

4.2. Interfacial characters

Robins and Austin [23] studied the pullout response of hooked steel fiber and suggested several distinct regions of load-displacement curve, i.e. elastic stage, fiber debonding stage, fiber straightening stage, frictional sliding stage and fiber remove from the matrix.

In this study, the crimped steel fiber was added into the mixes and obtained a similar pullout mechanism compared to hooked-steel fiber used in Robins’s study, except for a tiny straightening degree (figure 9(a)). The load decreases slowly after maximum pull-out load (figure 3(a)). However, the bond strength was greater in AAFRC specimens as compared to SFRC specimens and different from the results of Won and Hong [16], which is likely attributed to the lower water to binder ratio (0.32 in the current study and 0.5 in the study of reference [14]) and the interface more homogeneous and compact (figure 4).

An obvious aspect is that the load-displacement plots of SFRC have a debonding stage before the maximum pull-out load (figure 3(a)). However, the transition point is located behind the maximum pull-out load (figure 3(b)) which causing by the different pull-out mechanism of wave steel fiber and amorphous fiber. The transition point for steel fiber is attributed to fiber debonding, however, for amorphous fiber, the transition point is attributed to partial fiber fracture (figure 9(b)).

### Table 6. The orientation coefficient \( \alpha \) of all the mixes.

| Specimens     | CC   | SFRC-0.5 | SFRC-1 | AAFRC-0.2 | AAFRC-0.5 | AAFRC-1 | HSAFRC-1 |
|---------------|------|----------|--------|-----------|-----------|---------|----------|
| \( \alpha \)  | 0    | 0.33     | 0.34   | 0.39      | 0.38      | 0.40    | 0.35     |

\[
\alpha = \frac{N}{N_{th}} = \frac{A_f}{V_f A_c}
\] (2)
4.3. Mechanical properties and interfacial characters after wetting/drying cycles

Figure 6 shows the mechanical properties, bond strength and interface toughness obtained from the compressive, flexural and fiber pullout tests of SFRC and AAFRC under different corrosion period. The results evidence that compared with un-corroded specimens of SFRC samples, the occurrence of an increase in the compressive, flexural and pullout properties when 3 days experimental period, while the values decrease after 30 days experimental period. However, in the case of AAFRC specimens, the strengths are nearly unchanged, even 30 days wetting/drying cycles due to the excellent corrosion resistance of amorphous alloy.

Figure 10 shows the appearance of steel fiber after wetting/drying cycle tests. It is clear that rust layer thickness was increased with experimental period from 3 days to 30 days. The rust layers may cause the increase of friction resistance of the fiber due to the increase of surface roughness. While with the experimental period prolonging, the cross section was decreased, which causing the bridge ability of fiber was weakened. Furthermore, with the rust layers accumulated to a certain thickness, corrosion expansion force inside the concrete would increase and led to cracks forming. Previous studies [24, 25] also revealed that the thickness of steel fiber increases by 2–3 times, and produce large expansion pressure on the surrounding concrete.

5. Conclusions

Amorphous alloy fiber increases the tying force of fiber to aggregate in AAFRC and led to a decreasing of workability as compared to SFRC in the fresh stage.

Fibers have a positive effect on the strength, especially on flexural strength and splitting strength. However, the effect of amorphous fiber is even more visible as compared to steel fiber in the same fiber volume fraction.

After 30 days dry-wet cycles in 5%NaCl solution, amorphous fiber-reinforced concrete showed no reduction in performance. By contrast, SFRC exhibited a reduction of mechanical properties.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.
Declaration of competing interest

The authors declare no conflict of interest.

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