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PREPARATION AND FRACTURE PROPERTIES OF DIFFERENT TYPES OF ALIGNED STEEL FIBER REINFORCED CONCRETE

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Abstract: The orientation of steel fibers influences the fracture properties of steel fiber reinforced concrete (SFRC) structures. In order to enhance the fracture properties of SFRC structures, the magnetic field method was used to adjust the fiber orientation to maximize the reinforcing efficiency of steel fibers. By this method, the unidirectionally aligned steel fiber reinforced concrete (1D-ASFRC) was manufactured. Furthermore, the two-dimensionally aligned steel fiber reinforced concrete (2D-ASFRC), annularly aligned steel fiber reinforced concrete (AASFRC) and full-field aligned steel fiber reinforced concrete (FASFRC) were prepared based on this fiber orientation adjustment technique, with the aim of promoting the application of ASFRC in various structural forms such as pipe segments, slabs, pavements, bridge decks, and open-hole structures. Subsequently, the advantages of ASFRC in enhancing fracture properties were examined by comparing its performance against that of conventional SFRC specimens. The results indicated that compared to SFRC, both fracture toughness and fracture energy were significantly improved in ASFRC. This implies that using less fibers in ASFRC structures can ensure the fracture properties equivalent to that of SFRC structures. Finally, an investigation into the reinforcement mechanism of ASFRC was conducted from the perspective of fiber distribution characteristics and numerical simulation.

1 INTRODUCTION

As a kind of commonly used fiber reinforced composite material in civil engineering, the steel fiber reinforced concrete (SFRC) considerably improves the service performance of concrete due to its reinforcing, toughening and crack resistance on the matrix. Therefore, SFRC has been extensively utilized in municipal, transportation, bridge decks, tunnel and military [1-5].

Throughout the operational lifespan of structural elements, the orientation of fibers critically influences their mechanical properties [6]. Typically, steel fibers are dispersed randomly within the matrix. Consequently, only those fibers aligned parallel or nearly parallel to the direction of tensile stress contribute to reinforcement. In contrast, steel fibers aligned perpendicularly or at an oblique angle to the tensile stress exhibit minimal reinforcing efficiency [7]. To enhance the reinforcing efficiency of steel fibers, the orientation of steel fibers was manipulated to prepare aligned steel fiber reinforced concrete (ASFRC) [8,9]. In ASFRC, all fibers are aligned with the direction of principal stress, thereby increasing the number of fibers bridging the cracks and significantly enhancing the mechanical performance SFRC [10-14]. Nonetheless, in structural elements such as pipe segments, floor panels, pavements, bridge decks, and open-hole structures, the stress directions vary across different parts of the structure. Therefore, there is an urgent need to develop innovative fiber alignment technologies to adapt ASFRC for diverse structural configurations.

The unidirectionally aligned steel fiber reinforced concrete (1D-ASFRC), two-dimensionally aligned steel fiber reinforced concrete (2D-ASFRC), annularly aligned steel fiber reinforced concrete (AASFRC) and full-field aligned steel fiber reinforced concrete (FASFRC) were manufactured based on the magnetic field treatment method, so as to enhance their suitability for specific structural applications, such as pipe segments, pavements, bridge decks, and open-hole structures. Subsequently, the fracture and mechanical properties of 1D-ASFRC, 2D-ASFRC, AASFRC and FASFRC were introduced. Ultimately, the reinforcement and toughening mechanism of aligned steel fibers was elucidated through an analysis of the distribution characteristics of cross-sectional fibers and numerical simulation.

2 RAW MATERIALS AND THE ADJUSTMENT OF STEEL FIBERS

2.1 Raw materials and mix proportion

The P·O 42.5 cement was added as cementitious, and the river sand (2.5 of fineness modulus) was utilized as fine aggregates. No coarse aggregate was added to obtain the ideal alignment effect of steel fibers. The superplasticizer was added into the mixture to adjust the workability. The steel fibers, with 30 mm in length and 0.5 mm in diameter, were used. Table 1 shows the detailed mix proportion. SFRC specimens were prepared by conventional method as control group. Specimens of ASFRC with varying fiber distribution characteristics were prepared, and the preparation method was introduced in Section 2.2.

Table 1: Mix proportion of SFRC and ASFRC specimens.

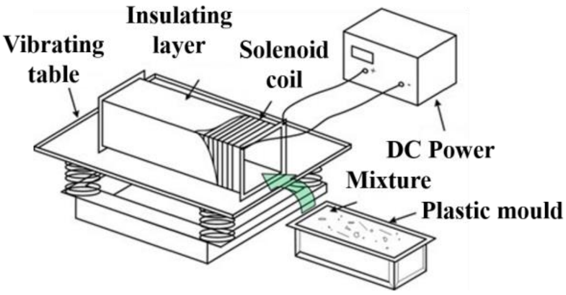
w/c	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Steel fibers (%, by volume)
0.42	266	634	1268	0.8
	265	632	1264	1.2
	263	627	1254	2.0

2.2 Raw materials and mix proportion

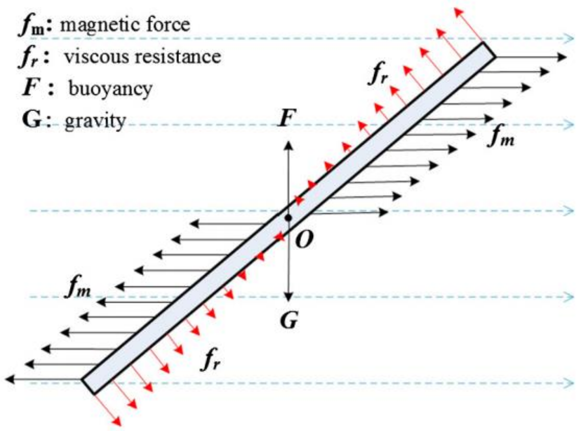
2.2.1 Unidirectionally aligned steel fiber reinforced concrete (1D-ASFRC)

The orientation of fibers can be manipulated and regulated through the application of an external electromagnetic field, leveraging the principles of magnetism. Ferromagnetic steel fibers inherently align with the magnetic field's direction under a uniform magnetic field because of the magnetic forces. Consequently, aligning the magnetic field with the tensile stress in SFRC, enables the steel fibers to align accordingly, thereby optimizing reinforcing efficiency. In the process of alignment, the two ends of fiber become magnetized into south and north poles under the magnetic field. At the same time, a pair of forces, which are equal in magnitude but opposite in direction, act on the two poles. Driven by the force, the fiber rotates, until aligns with the direction of the magnetic field.

Based on these principles, a device capable of generating a uniform magnetic field was developed. In the process of preparing unidirectionally aligned steel fiber reinforced concrete (1D-ASFRC), a plastic mould containing the mixture was initially placed on a vibrating table for 30 seconds to compact the mixture. Subsequently, the plastic mould was positioned within the inner space of the solenoid (Figure 1(a)), which was connected to a power source. The vibrating table and power source were turned on simultaneously and operated for approximately 60 seconds, resulting in the unidirectional alignment of the steel fibers (Figure 1(b)).



(a) Device for preparing 1D-ASFRC



(b) Force analysis of single fiber under magnetic field

Figure 1: Preparation of 1D-ASFRC [15].

2.2.2 Two-dimensionally aligned steel fiber reinforced concrete (2D-ASFRC)

For components or projects such as floor slabs, pavements, bridge decks and airport runways, the slab is subjected to horizontal tension, but the stress direction is uncertain. In this case, the steel fiber reinforced concrete (SFRC) with randomly aligned steel fibers may prove ineffective, as vertically distributed fibers do not contribute to reinforcement and may pose potential hazards by protruding from the surface. To address this issue, the two-dimensionally aligned steel fiber reinforced concrete (2D-ASFRC), with the fibers randomly distributed in horizontal plane, was prepared based on a rotating electromagnetic field (Figure 2).

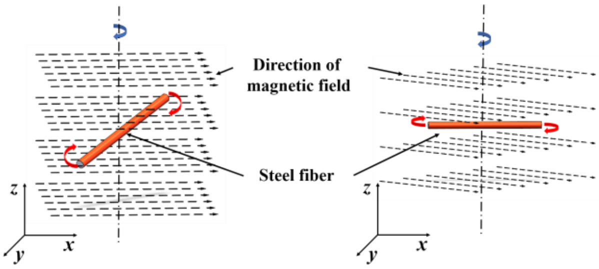
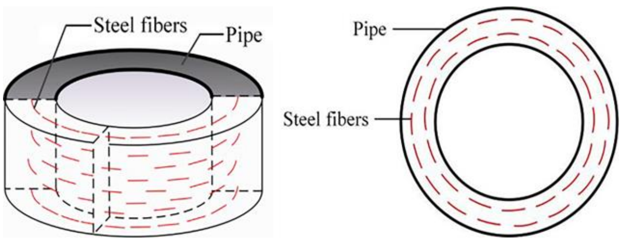


Figure 2: Preparation of 2D-ASFRC [16].

2.2.3 Annularly aligned steel fiber reinforced concrete (AASFRC)

In order to promote AASFRC to be widely used in pipe segment, the annularly aligned steel fiber reinforced concrete (AASFRC) was manufactured. The steel fiber concrete mixture was placed into a circular plastic mould wrapped with copper wire, which was connected to a power supply. The power supply and vibration table were turned on to work for about 300 seconds to complete the preparation of AASFRC (Figure 3).

(a) The plastic mould wrapped with copper wire

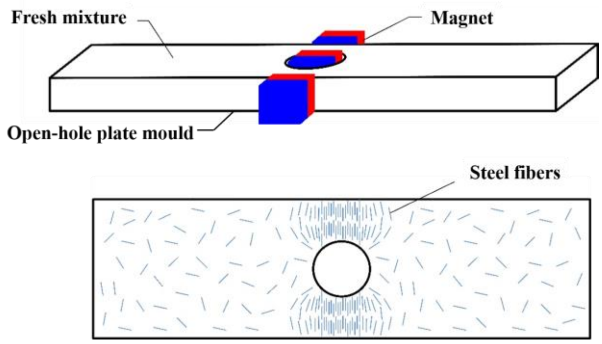


(b) Fiber distribution in AASFRC pipe

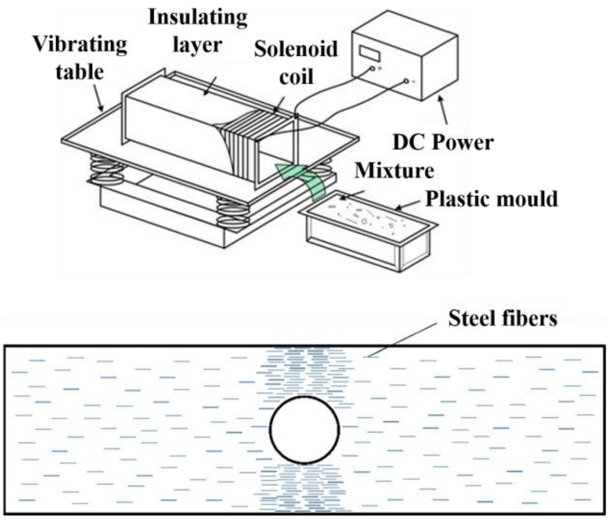
Figure 3: Preparation of AASFRC [17].

2.2.4 Full-field aligned steel fiber reinforced concrete (FASFRC)

The preparation of full-field aligned steel fiber reinforced concrete (FASFRC) aims to mitigate stress concentration issues in open-hole structures. This preparation process primarily involved two stages: the aggregation of steel fibers and their subsequent alignment (Figure 4). Initially, three magnets were placed around the hole. The magnets attracted the fibers within the mixture towards the hole, thereby facilitating their aggregation. The alignment of fibers was accomplished through exposure to a magnetic field, as shown in Figure 1(a).



(a) The aggregation of fibers.



(b) The alignment of fibers.

Figure 4: Preparation of FASFRC [18].

3 RESULTS AND DISCUSSION

3.1 The fracture and mechanical properties of 1D-ASFRC

The results of the fracture test indicate that, in comparison to SFRC, the fracture energy GF of 1D-ASFRC with V_f = 0.8%, 1.2%, and 2.0% was increased by approximately 110%-170%. Correspondingly, the K_{Ic} values increased by 162.43%, 139.01%, and 30.67%, respectively [19]. The uniaxial tensile test reveals that the tensile performance of 1D-ASFRC for V_f = 1.2% was comparable to that of SFRC specimens with a V_f of 2.0%, resulting in at least a 40% reduction in fiber content for 1D-ASFRC while maintaining similar tensile performance. Furthermore, the 1D-ASFRC specimens demonstrated strain-hardening behavior, while SFRC exhibited strain-softing behavior even if higher fiber content [14]. Additionally, improvements in other mechanical properties of 1D-ASFRC were observed (see Figure 5).

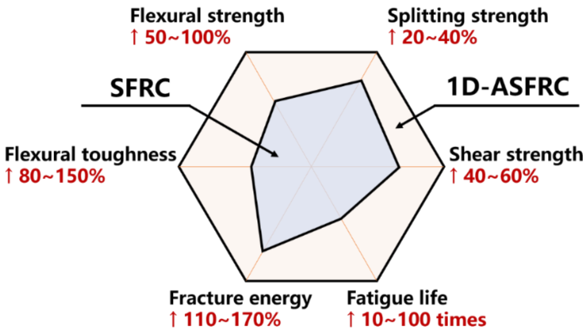


Figure 5: Comparison of mechanical properties between 1D-ASFRC and SFRC.

3.2 Flexural performance of 2D-ASFRC

The findings from the round panel flexural test indicate that the round panel flexural strength of 2D-ASFRC was enhanced by 13%, 22%, and 23% with V_f = 0.8%, 1.2%, and 2.0%, respectively. Additionally, at equivalent deflection levels and same fiber addition, the flexural toughness of 2D-ASFRC specimens exhibited enhancements of 30%, 40%, and 26%, respectively, in comparison to SFRC specimens [16].

3.3 Internal water pressure of AASFRC

The findings from internal water pressure test show that in terms of ultimate internal water pressure (UIWP), AASFRC pipe exhibited an increase of 20%-32% compared with SFRC specimen. Notably, the UIWP of SFRC pipe with V_f = 1.2% was approximately even lower than that of AASFRC pipe for V_f =

0.8%. This suggests that the utilization of AASFRC pipes can potentially reduce 33% of fiber consumption while remaining UIWP unchanged [17].

3.4 Uniaxial tensile performance of FASFRC

The uniaxial tensile test indicates that, in comparison to SFRC, FASFRC specimens was observed an enhancement up to 49% in uniaxial tensile strength. Additionally, the tensile work was increased by 52%, 35%, and 36% for the same fiber volume fractions. Meanwhile, similar increasing trend was observed in the uniaxial tensile toughness ratio, which was increased by 7%-21% [18].

4 REINFORCING MECHANISM

4.1 Fiber distribution characteristics of cross section

In SFRC, the distribution of steel fibers is typically random, resulting in some fibers aligning parallel to potential crack planes, thereby limiting their ability to effectively bridge cracks. However, through the alignment of steel fibers, their capacity to bridge cracks is maximized. Consequently, the fracture and mechanical properties of ASFRC are markedly enhanced when the fiber content remains unchanged [7].

4.2 Fiber resultant stress

The extended finite element method was used to develop a microscopic numerical model for ASFRC and SFRC, which was then verified through experimental comparison. The fiber resultant force of ASFRC and SFRC specimens throughout the whole loading process was calculated. It was found that the fiber resultant force in ASFRC specimen was higher, indicating that the aligned steel fibers can withstand more stress from the matrix [19].

5 CONCLUSION

Based on the magnetic field treatment technique, various configurations of ASFRC were prepared, including unidirectionally aligned (1D-ASFRC), two-dimensionally aligned (2D-ASFRC), annularly aligned (AASFRC), and fully-field aligned (FASFRC), each tailored to specific structural forms and stress characteristics. The fracture and mechanical properties of ASFRC, and the reinforcing mechanism of aligned steel fibers were elucidated. The following conclusions can be drawn:

(1) Steel fibers subjected to a uniform magnetic field with a constant orientation can undergo magnetization and alignment, resulting in the fiber axis aligning with the magnetic field direction. This technique was employed in the fabrication of 1D-ASFRC, 2D-ASFRC, AASFRC, and FASFRC, thereby enhancing the adaptability of ASFRC for various structural applications, including tunnel segments, open-hole structures, bridge decks, and pavements.

(2) The fracture energy of ASFRC at varying fiber contents can be enhanced by up to 170% in comparison to SFRC, while the fracture toughness can be improved by up to 160%. The internal water pressure performance of AASFRC indicates that its ultimate internal water pressure can be augmented by 20% to 32% relative to SFRC. As for FASFRC, the uniaxial tensile strength, tensile work, and uniaxial tensile toughness are increased by 45%, 41%, and 18%, respectively. Furthermore, the round panel flexural test of 2D-SFRC demonstrates that its flexural strength can be elevated by an average of 19% compared to SFRC.

(3) The reinforcing mechanism of aligned steel fibers was explained through the fiber distribution characteristics on cross-sectional and fiber resultant stress. Aligning steel fibers increases the number of fibers that bridge cracks in the matrix, thereby increasing the fracture and mechanical properties. Through numerical simulation, it was found that the fiber resultant stress of aligned steel fibers was higher than that of randomly distributed steel fibers, indicating that the alignment of steel fibers can improve the stress transfer efficiency from the matrix to the steel fibers, thereby reducing the risk of matrix cracking.

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