EFFECT OF STEEL FIBER SHAPE ON PULLOUT BEHAVIOR OF AUTOCLAVED UHPFRC WITH GRANITE POWDER

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Abstract:

Based on a single fiber pullout test, the bonding strength and the pullout energy between the fibers and ultra-high performance fiber reinforced concrete (UHPFRC) were measured. Five types of steel fibers include straight steel fiber (S), single-linear hooked-end steel fiber (G1), bi-linear hooked-end steel fiber (G2), crimped steel fiber (L1) and small crimped steel fiber (L2). The study results show that, L2 was broken when pulled out from UHPFRC, which is not suitable to be used in UHPFRC. Because of the better mechanical interlocking effect between the fibers of G1, G2, L1 and UHPFRC compared to S. Both the bonding strength and pullout energy are G1 > G2 > L1 > S. G1 with only one hook and a larger angle at its end hook has the best shape in the five types of steel fiber, and its strengthening and toughening effect is the best, which is suitable to be used in the UHPFRC with granite powder.

Résumé

Sur la base d'un essai d'arrachement de fibre unitaire, la contrainte ultime d'adhérence et l'énergie d'arrachement entre les fibres et le béton fibré à ultra-hautes performances (BFUP) ont été mesurées. Cinq types de fibres d'acier ont été étudiés : des fibres d'acier droites (S), des fibres d'acier à crochet simple (G1), des fibres d'acier à doubles crochets d'extrémité (G2), des fibres d'acier ondulées (L1) et des fibres d'acier ondulées courtes (L2). Les résultats de l'étude montrent que la fibre L2 se casse lorsqu'elle est extraite du BFUP, elle n'est donc pas adaptée à l'utilisation dans du BFUP. Les types G1, G2 et L1 sont meilleurs que S à cause d'un meilleur effet de blocage des fibres entre elles et dans le BFUP. Ainsi à la fois pour la contrainte ultime d'adhérence et pour l'énergie d'arrachement on obtient le classement G1>G2>L1>S. Le type G1, avec seulement un crochet et un angle plus large au bout du crochet d'extrémité, a la forme la meilleure parmi les 5 types de fibres d'acier, et son effet sur la résistance et la ténacité est le meilleur, ce qui convient à son emploi dans le BFUP avec de la poudre de granit.

1. INTRODUCTION

Ultra-high performance fiber reinforced concrete (UHPFRC) is a new type of cement-based composites with ultra-high strength, high durability and high toughness [1]. The interfacial transition zone between steel fiber and the UHPFRC is a key to improve the toughness of UHPFRC, which has the important significance in making full use of UHPFRC material performance, reducing the project cost, and popularizing the application of UHPFRC. The steel fiber with high aspect ratio can be effectively used in UHPFRC and can improve the toughness of UHPFRC structures significantly.

In recent years, many investigators studied the pullout behavior of steel fibers with different shape in cement mortar, normal concrete and high-strength concrete, and found that the effect of the appearance characteristics of steel fibers is significant for strengthening and toughening the cement-based material [2-3]. However, the study for pullout behavior was focused on the steel fibers with straight and single-linear end hook type, and the study for steel fiber with bi-linear hooked-end type and crimped type was still not found [4-6]. In addition, there is a large amount of abandoned granite powder in Fujian Province, which cannot be used effectively. Therefore, the granite powder can be used to the preparation of UHPFRC, which achieve a good environmental benefit. However, there is few reports on the preparation of UHPFRC with granite powder. Therefore, the effect of steel fibers with five shapes on strengthening and toughening UHPFRC, in which granite powder is used to replace all quartz powder, will be studied by a single fiber pullout test.

2. RAW MATERIALS, MIX PROPORTION AND TEST METHOD

2.1 Raw materials

Grade 42.5R (Chinese cement grading system) Portland cement with apparent density of 3050 kg/m^3, was adopted. The performances of the cement are shown in Table 1. The silica fume was used as received from the supplier. The SiO_2 content of silica fume is over 90%; its particle size is 0.1-0.2 microns. Its mean particle size is 0.162 microns and its apparent density is 2293 kg/m^3. The chemical composition and physical properties of the quartz sand are shown in Table 2. The type of CX-8 superplasticizer with the water reducing ratio of 25 % was adopted. The tap water in Fuzhou municipal area was used. The specific surface area and density of granite power are 588 m^2/kg and 2293 kg/m^3, respectively. Its chemical composition is shown in Table 3. The five types of copper plated steel fibers, which were used in this study, are straight steel fiber (S), single-linear hooked-end steel fiber (G1), bi-linear hooked-end steel fiber (G2), crimped steel fiber (L1) and small crimped steel fiber (L2).

Table 1: Performance of cement

Specific surface area (m^2/kg)	Loss on ignition (%)	Setting time (min)		Flexural strength (MPa)		Compressive strength (MPa)	
		Initial setting	Final setting	3d	28d	3d	28d
361	1.07	125	185	5.7	8.5	27.5	45

Table 2: Physical and chemical indicators of quartz sand

Size		Chemical compositions (%)	
Mesh number	Particle size (μm)	SiO_2	Fe_2O_3
28-90	600-160	≥99.5	≥0.02

Table 3: Chemical compositions of granite power (%)

Loss on ignition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O
0.72	83.21	2.02	1.76	2.31	0.54	3.39	4.72

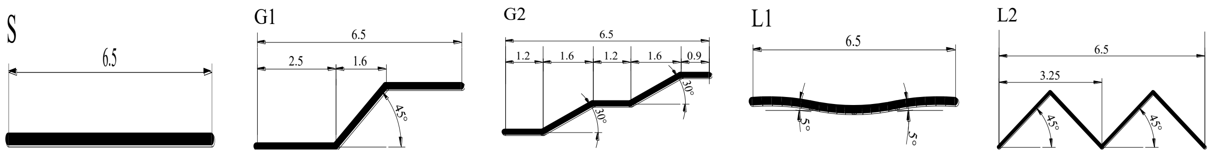
Their physical properties are shown in Fig. 1 and Table 4, where l_f, d_f and w_l represent the length, diameter and wave length of steel fiber, respectively, and f_{ft} represents the tensile strength of steel fiber, and ρ represents aspect ratio. The end dimension and shape of five fibers embedded in UHPFRC are shown in Fig. 2.

Table 4: Physical properties of steel fibers

No.	Form	l_f (mm)	d_f (mm)	ρ	w_l (mm)	f_{ft} (MPa)
S	Straight	13	0.2	65	-	2850
G1	Single-linear Hooked	25	0.3	83.3	-	2850
G2	Bi-linear hooked	25	0.3	83.3	-	2850
L1	Crimped	25	0.25	100	6.5	2500
L2	Small crimped	30	0.3	100	3.25	2900

(a) S (b) G1 (c) G2 (d) L1 (e) L2

Fig. 1 Steel fibers shapes (before pullout)



(a) S (b) G1 (c) G2 (d) L1 (e) L2

Fig. 2 Ends dimension and shape of steel fibers embedded in UHPFRC (unit: mm)

2.2 Mix proportion

The mix proportion of UHPFRC is shown in Table 5. S steel fiber was used in the UHPFRC, whose volume fraction is 2%. Its sand-binder ratio is 0.9 and its water-binder ratio is 0.18.

Table 5: Mix proportion of UHPFRC with granite powder (kg/m^3)

Cement	Silica fume	Granite powder	Quartz sand	Superplasticizer	Water	S Steel fiber
701.5	210.5	259.6	820.8	17.5	164.2	156.0

2.3 Mixing process

According to Table 5, the cement, silica fume, granite powder and quartz sand were put into a mixing pot, and the mixture was pre-stirred for 3 minutes. The superplasticizer was dissolved in water to obtain superplasticizer solution. Then 90% of superplasticizer solution was added into the mixture, which was stirred for 3 minutes. The remained superplasticizer solution was poured into the mixture, which was stirred for another 3 minutes. Finally S steel fiber was added into the mixture, and the mixture was stirred for 3-5 minutes.

2.4 Molding and curing

The mixture was poured into 40mm×40mm×160mm molds, and then the molds with the filled fresh mixture were vibrated for 120 seconds at 1Hz on a vibration table. At the same time, the mixture was poured into half dog bone steel molds. The five types of steel fibers were embedded in the half dog bone UHPFRC mixture, and only one steel fiber was embedded in one half dog bone UHPFRC mixture. Hit the molds 30 times with a hammer. After 24 hours standard curing, the molds was removed. Then the specimens were autoclave cured (namely, vacuumized for half an hour, and increased temperature and pressure in 1 hour, and maintained the temperature of 190-200℃ and pressure of 1.2 MPa for 6 hours, and then reduced pressure in 2 hour). After autoclave curing, the specimens were transferred to the standard curing room until the curing age of 7 days.

2.5 Test methods

Compressive strength and flexural strength were carried out according to the Chinese Code of GB/T 17671-1999. A WDW-30 microcomputer control electronic universal testing machine with the load cell of maximum of 500 N and the displacement resolution of 0.000025 mm was used in pullout test. The pullout rate was set to 0.018 mm/s. The length of steel fiber embedded in UHPFRC is 6.5 mm. The half dog bone steel mould and pullout device can be found in Reference [7]. The pullout test equipment is shown in Fig.3. Though the five types of copper plated steel fibers, namlely S, G1, G2, L1 and L2, were used as single pullout fiber, only S copper plated steel fibers were mixed in half dog bone UHPFRC.

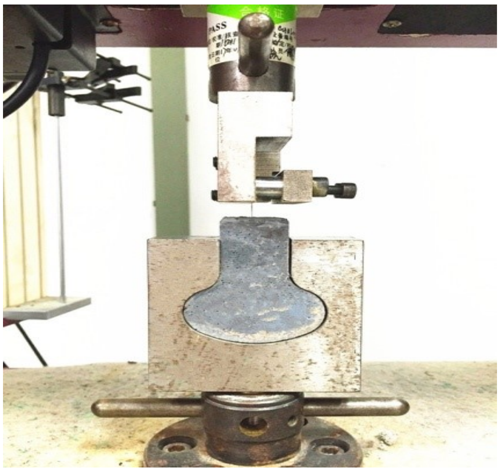


Fig. 3 Pullout test of single steel fiber

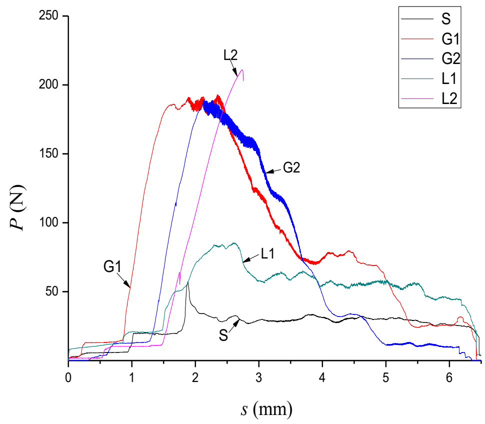


Fig. 4 Pullout average curve of steel fibers

2.6 Evaluation parameters

Each fiber pullout test is described by a pullout load versus-slip relationship in Fig. 4, where P is the pullout load and s is the slip. F_u represents the fiber utilization ratio as shown in Eq.(1); $\sigma_{f,\max}$ indicates the maximum pullout stress (MPa) as shown in Eq.(2); W_p (N·mm) means pullout energy as shown in Eq.(3); τ_{av} (MPa) means the bonding strength value averaged from three parallel specimens as shown in Eq.(4).

$$F_u = \frac{\sigma_{f,\max}}{f_{ft}} \quad (1)$$

$$\sigma_{f,\max} = \frac{P_{\max}}{A_f} = \frac{4 \times P_{\max}}{\pi \times d_f^2} \quad (2)$$

$$W_p = \int_{s=0}^{s=L_E} P ds \quad (3)$$

$$\tau_{\text{av}} = \frac{P_{\max}}{\pi \times d_f \times L_E} \quad (4)$$

where $P_{\max}$ represents the maximum pullout force of steel fiber, A_f represents the steel fiber cross sectional area of steel fiber, and L_E represents steel fiber embedded length.

3. RESULTS AND ANALYSIS

3.1 Influence of steel fiber shape on maximum pullout stress and fiber utilization ratio

The compressive strength and flexural strength of the UHPFRC with granite powder are 173.6 (±12.1) MPa, and 36.0 (±3.6) MPa, respectively. Pullout curves of five steel fibers are shown in Fig. 4. The morphology of these five steel fibers after pullout test is shown in Fig. 5. The maximum pullout stress and fiber utilization ratio of five steel fibers are shown in Fig. 6 and Fig. 7, respectively.

(a) S (b) G1 (c) G2 (d) L1 (e) L2

Fig. 5 Steel fiber shapes (after pullout)

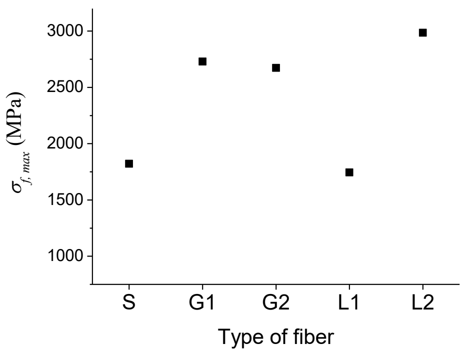


Fig. 6 Maximum pullout stress of steel fibers

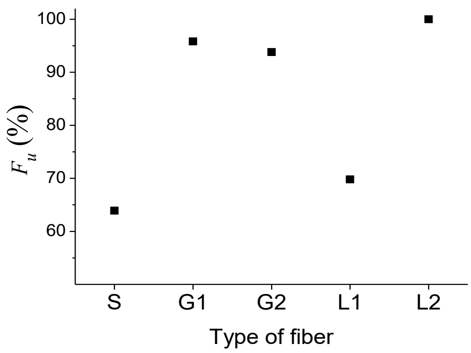


Fig. 7 Fiber utilization ratio of steel fibers

Some research shows that the pullout load of S steel fiber in Ordinary Portland cement concrete (OPC) with compressive strength of 60 MPa suddenly decreased after reaching the maximum loads, and the strengthening and toughening effect of the S steel fiber is not obvious [8]. Because S steel fiber has higher bonding strength in UHPFRC, when pullout displacement of S steel fiber is large, S steel fiber can keep a high pullout load in UHPFRC compared to OPC. Fig. 4 indicates that the pullout curves depend closely on the shape of steel fibers, and the pullout load of S steel fiber is much smaller than that of deformed steel fibers (G1, G2, L1 and L2). The maximum pullout force of S and G1 steel fibers are 57.22 N and 192.99 N, respectively. The maximum pullout force of G1 is the highest, which is 3.4 times compared to S steel fiber.

In Fig. 5, L2 steel fiber broke when pull out from UHPFRC, and S, G1, G2 and L1 steel fiber were pulled out from UHPFRC. However, the shape of G1, G2 and L1 steel fibers embedded in UHPFRC were straight after pullout. Therefore, it indicates that the bonding strength between deformed steel fibers (G1, G2 and L1) and UHPFRC is extremely high.

In Fig. 6 and Fig. 7, the maximum pullout stress and fiber utilization ratio of S steel fiber are 1821 MPa and 63.89 %, respectively. While the maximum pullout stresses and fiber utilization ratios of G1, G2 and L1 steel fibers are 2730 MPa, 2673 MPa, 1745 MPa and 95.8 %, 93.8 %, 69.8 %, respectively. The fiber utilization ratio of G1 steel fiber is the highest.

3.2 Effect of steel fiber shape on average bonding strength and pullout energy

The average bonding strength and pullout energy of five types of steel fiber are shown in Fig. 8 and Fig. 9, respectively.

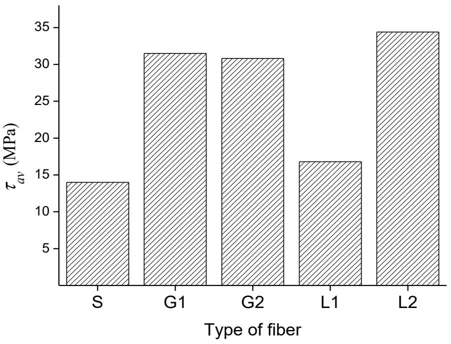


Fig.8 Average bonding strength of five types of steel fibers

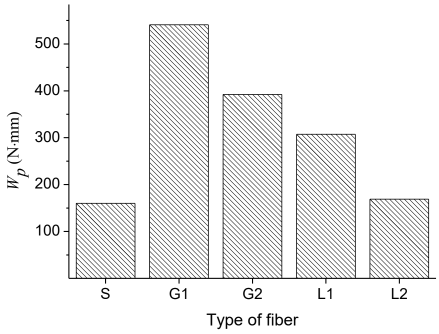


Fig.9 Pullout energy of five types of steel fibers

In Fig. 8, the average bonding strength of S, G1, G2, L1 and L2 steel fibers are 14 MPa, 31.5 MPa, 30.8 MPa, 16.8 MPa and 34.4 MPa, respectively. Though L2 steel fiber broke when pulled out from the UHPFRC, the average bonding strength of L2 steel fiber is higher than that of the other four types of steel fibers, because the maximum pullout force of L2 steel fiber is the largest in the five types of steel fibers. The average bonding strength of G1, G2 and L1 is 2.25 times, 2.2 times and 1.2 times than that of S steel fiber, respectively.

In Fig. 9, the pullout energy of S, G1, G2, L1 and L2 steel fibers are 160 N·mm, 540.9 N·mm, 392.2 N·mm, 307.2 N·mm and 168.8 N·mm, respectively; the pullout energy of G1, G2 and L1 steel fibers is 3.4 times, 2.5 times and 1.9 times than that of S steel fiber, respectively. The average bonding strength and pullout energy of the steel fibers are G1 > G2 > L1 > S, respectively.

4. MECHANISM ANALYSIS

L2 steel fiber was broke when pulled out from UHPFRC, because its pullout stress exceeds the tensile strength of L2 steel fiber, and meanwhile is lower than its allowable interfacial shear strength. The average bonding strength and pullout energy are the important indexes for the toughness of UHPFRC, and the bonding strength between UHPFRC and steel fibers is mainly due to chemical bonding, sliding friction, static friction and mechanical interlocking [9]. Firstly, the chemical bonding strength is due to the sliding effect between steel fibers and UHPFRC [10], which depends on the contact area between UHPFRC and steel fibers. Because the contact areas is G2 > G1 > L1 > S, the chemical bonding strength of steel fibers is G2 > G1 > L1 > S. Secondly, the friction force (including sliding friction and static friction) depends on the roughness and extruding force between UHPFRC and steel fibers, and therefore the friction forces between G2, G1, L1, S and UHPFRC are similar. Finally, the mechanical interlocking force depends on the shape of steel fibers. Compared with G2, G1 has only one hook and larger angle at its end, so the mechanical interlocking force is G1 > G2. However, the angle of L1 is significantly smaller than that of G1 and G2, but larger than that of S. Therefore, mechanical interlocking force is G1 > G2 > L1 > S. Among chemical bonding force, friction force and mechanical interlocking, the mechanical interlocking force is a dominant factor, so the average bonding strength and pullout energy of steel fibers in UHPFRC are G1 ＞ G2 ＞ L1 ＞ S. This conclusion agrees well with the previous study [6] which deemed that the resistance to pullout can be improved by deforming a steel fiber along its length.

5. CONCLUTIONS

- Under autoclave curing, at curing age of 7 days, the average bonding strength between S, G1, G2, L1 and UHPFRC are 14.0 MPa, 31.5 MPa, 30.8 MPa and 16.8 MPa, respectively; the pullout energy of S, G1, G2 and L1 from UHPFRC are 160.0 N·mm, 540.9 N·mm, 392.2 N·mm and 307.2 N·mm, respectively; the fiber utilization ratio of S, G1, G2 and L1 in UHPFRC are 63.9 %, 95.8 %, 93.8 % and 69.8 %, respectively; the average bonding strength and pullout energy are as follows: G1 ＞ G2 ＞ L1 ＞ S.
- Under autoclave curing, at curing age of 7 days, L2 steel fiber was broke when pulled out from UHPFRC because the pullout stress of L2 steel fiber exceeds its tensile strength, and meanwhile is lower than its allowable interfacial shear strength. Therefore, L2 is not suitable to be used in this UHPFRC. G1 has only one hook and larger angle at its end, and is the best shape of steel fibers, and is suitable to be used in UHPFRC with granite powder.

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REFERENCES

[1] Richard, P. and Cheyrezy, M., 'Composition of reactive powder concretes', *Cement and Concrete Research*. **25**(7) (1995) 1501-1511.
[2] Georgiadi, S.K., Mistakidis, E. and Pantousa, D., 'Numerical modelling of the pull-out of hooked steel fibres from high-strength cementitious matrix, supplemented by experimental results', *Construction and Building Materials*. **24**(12) (2010) 2489-2506.
[3] Choi, W.C., Jang, S.J. and Yun, H.D., 'Interface bond characterization between fiber and cementitious matrix', International Journal of Polymer Science. 2015(1) (2015) 1-11.
[4] Wille, K. and Naaman, A.E., 'Effect of ultra-high-performance concrete on pullout behavior of high-strength brass-coated straight steel fibers', *ACI Materials Journal*. **110**(4) (2013) 451-461.
[5] Wille, K. and Naaman, A.E., 'Pullout behavior of high-strength steel fibers embedded in ultra-high-performance concrete', *ACI Materials Journal*. **109**(4) (2012) 479-487.
[6] Banthia, N. 'A study of some factors affecting the fiber-matrix bond in steel fiber reinforced concrete', Canadian Journal of Civil Engineering. 17(4) (1990) 610-620.
[7] Xiaoying Lin., ' Research on single steel fiber pullout behavior in UHPC mixed with granite stone powder ', master's dissertation, Fuzhou: Fuzhou University, (2016).
[8] Naaman, A. E. and Najm, H., 'Bond-slip mechanisms of steel fibers in concrete', *Materials Journal*. **88**(2) (1991) 135-145.
[9] Yang, J., Yudan, J. and Hongbin, L., 'Micro-mechanism of reinforcing and toughening of RPC by steel fiber', *China Science*. **37**(11) (2007) 1403-1416.
[10] Bentur, A., Mindess, S. and Diamond, S., 'Pull-out processes in steel fibre reinforced cement', *International Journal of Cement Composites and Lightweight Concrete*. **7**(1)(1985) 29-37.