PULL-OUT RESPONSE OF SINGLE STEEL FIBER EMBEDDED IN PVA FIBER REINFORCED CEMENTITIOUS MATRIX

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Abstract: Comparing to Strain Hardening Cementitious Composites (SHCC) with polyvinyl alcohol (PVA) fibers alone, recent test results show that the hybridization of PVA and steel fibers can improve the crack control ability and shear performance of SHCC, indicating a possible synergistic effect between the two kinds of fibers. The objective of this paper is to investigate the physical basis behind the synergy between PVA and steel fibers. As steel fibers are much larger in diameter than the PVA fibers, one can consider them to be embedded inside a PVA fiber reinforced matrix. With a specially designed testing set-up, fiber pull-out test is performed on a single steel fiber embedded inside a cementitious block with different contents of PVA fibers. In the test, the load verses displacement relationship during fiber debonding and pull-out is measured. The parameters investigated include the geometry of steel fibers, the fiber inclination angle (0°, 30° and 60°), as well as the PVA fiber volume fraction (0% as control, 1.0% and 2.0%). With the test results, it is possible to quantify the synergistic effect between PVA and steel fibers, which can be used for the optimal design of hybrid PVA/steel fiber SHCC in the future.

1 INTRODUCTION

Conventional cementitious materials are highly brittle. Research on fracture of composites has led to the development of Strain-Hardening Cementitious Composites (SHCC) exhibiting tensile strain hardening and multiple cracking [1-3]. With tremendous ductility, excellent crack control ability, high toughness, as well as good energy absorption,

SHCC is an attractive material for many structural applications [4]. In common SHCC, only polymeric fibers such as polyethylene (PE) or polyvinyl alcohol (PVA) have been employed, as high ductility can be achieved with a relative low fiber volume fraction (about 2%). To further enhance the performance of SHCC, the use of hybrid fibers has been investigated [5-9]. Comparing to SHCC with PVA fibers alone, recent test results show that the hybridization of PVA and steel fibers can

improve the crack control ability and shear performance of SHCC [10], indicating a possible synergistic effect between the two kinds of fibers.

The pull-out of a single fiber embedded in cementitious matrix is widely recognized as one of the basic tests to be performed to provide information on the expected behavior of a given fiber reinforced cementitious composites, for straight fibers [11-14] as well as deformed fibers [15-19]. Fiber/matrix debonding and frictional sliding are the two main mechanisms controlling the pull-out response of straight fibers, while additional anchor mechanism should be considered for deformed fibers. Thus, it is of great importance that the pull-out test be interpreted in a way that yields the true material parameters governing the physical process.

In most short fiber reinforced cementitious composites, fibers are randomly distributed. Generally speaking, the bridging force provided by an inclined fiber (i.e., a fiber which is not perpendicular to the crack) can be considered as the vector sum of two components (**Fig. 1**): a debonding/pull-out component along the axis of the fiber and a bending component perpendicular to the fiber direction. For an inclined flexible fiber (such as PVA fibers in the present study), it was considered as a flexible string passing over a frictional pulley, and a snubbing friction model was derived to relate the peak pull-out load to the fiber inclination angle by Li et al. [20]. The model was further evaluated and modified by Maalej et al. [21] and Leung and Ybanez [12]. On the other hand, for an inclined stiff fiber (such as steel fibers in the present study), Leung and Chi [22] developed a micromechanical model focusing on the component of crack-bridging force due to fiber bending, which is obtained by analyzing the bending of an elastoplastic beam on an elastic foundation with variable stiffness along the fiber. The model was further improved by Fantilli and Vallini [23]. In addition, some new models for inclined deformed fibers have also been developed [24, 25].

Pull-out tests with inclined steel fibers have been reported by various investigators [26-29].

However, the available results are somewhat inconsistent. In some cases there exists an optimum inclination angle with respect to the maximum fiber pull-out load, but other tests shows the maximum pull-out load decreases with increasing inclination angle.

Figure 1: (a) Bending and shearing of fiber across a crack, (b) Components of a crack-bridging force ([30]).

2 RESEARCH OBJECTIVE

The objective of this paper is to investigate the physical basis behind the synergy between PVA and steel fibers in SHCC. As steel fibers are much larger in diameter than the PVA fibers, one can consider them to be embedded inside a PVA fiber reinforced matrix. It is speculated that the PVA fibers can reinforce the matrix, hence decreasing the matrix spalling caused by steel fibers and increasing the pull-out resistance. Both aligned and inclined single steel fiber pulling-out from PVA fiber reinforced matrix are experimentally studied, based on a specially designed single-steel-fiber pullout test set-up developed by Leung and co-workers [12, 31]. The parameters investigated include the geometry of steel fibers, the fiber inclination angle (0° , 30° and 60°), as well as the PVA fiber volume fraction (0% as control, 1.0% and 2.0%). With the test results, it is possible to quantify the synergistic effect

between PVA and steel fibers, which will be used for the optimal design of hybrid PVA/steel fiber SHCC in the future.

3 EXPERIMENTAL PROGRAM

3.1 Materials

A matrix with ultra-high volume fly ash (fly ash-to-binder ratio of 80% by weight) designed by the authors [32], with mix proportions shown in **Table 1**, was employed. The matrix can achieve a compressive strength of more than 40 MPa in 7-day age and more than 55 MPa in 28-day age. The Type I 52.5N Portland cement was produced by Green Island Cement Co., Ltd. and the Class F fly ash was provided by China Power and Light Co., Ltd. The silica fume was marketed as Elkem Microsilica 920U, with the bulk density of 200 to 350

kg/m³. Silica sand with a specific gravity of 2.61 and particle sizes ranging from 120 to 212 μm was used. A very small amount of AVDA 105 super-plasticizer (SP), with solid content of 30%, produced by Grace Construction Products Co., Ltd. was added to adjust the rheological properties of the fresh mix for better fiber distribution and workability. The nominal physical properties of the fibers are given in **Table 2**, for Kuraray K-II REC15 PVA fiber, Dramix ZP305 steel fiber and Dramix RC-80/60-BM steel fiber. Both Dramix fibers are made with hooks at the fiber end. In the pull-out tests on straight fiber, the hooks are cut.

Table 1: Mix proportion of the matrix (by weight)

Cement	Fly Ash	Silica Fume	Sand	Water
0.18	0.8	0.02	0.2	0.2

Table 2: Properties of fibers

Fiber Types	Length (mm)	Diameter (mm)	Length of One Hook (mm)	Modulus of Elasticity (Gpa)	Strength (Mpa)	Surface Coating
PVA	8	0.039	-	40	1600	Oil (1.2% by weight)
ZP305	30	0.55	4	210	1345	None
RC-80/60-BM	60	0.75	5	210	1550	None

Figure 2: (a) Casting of specimen; (b) Details of the fiber grip; (c) Set-up for pull-out test.

3.2 Sample preparation

For each group listed in **Table 3**, at least 6 samples with one inclined angle have been prepared, and at least 3 useful curves have been recorded.

The steel fiber was first inserted into a small plexiglass block with a hole drilled at the

appropriate angle in the middle (**Fig. 2(a)**). A fiber length of 8 mm was left outside the block. The hole in the block was made slightly larger than the fiber size, and molding clay was placed in the hole to secure the fiber. After the fibers are secured in the blocks, the blocks were placed in a matching steel mold. With each mold, one specimen at each designated inclination angle

(0°, 30° and 60°) could be prepared. The pull-out specimen would have the size of 25.4 mm (length) $\times$ 25.4 mm (width) $\times$ 9.5 mm (height). Demolding oil was applied to all surfaces that would be in contact with mortar. Extra care was taken to avoid contaminating the fiber surface.

0%, 1.0% and 2.0% of PVA fibers by volume were introduced into the matrix by wet mixing. To cast specimens, materials was mixed by hand with an eggbeater and added slowly into the mold in two layers, to achieve a 2D PVA fiber distribution in the samples. Compaction is achieved by tapping the matrix with a small steel stick. After finishing the surface, the specimens were covered with a polyethylene sheet to prevent loss of moisture and stored for 24 hours at room temperature prior to demolding. The demolded specimens were cured in the fog room at the temperature of $23^\circ\text{C} \pm 2^\circ\text{C}$ and the relative humidity of $95\% \pm 5\%$ until they reached 7-day age [33].

Table 3: Experimental Program

Group ID	Steel Fiber Geometry	Steel Fiber Incline Angle	PVA Volume Fraction
O6	0.55mm w/o hook	0°, 30°, 60°	0.0%
O8	0.55mm w/o hook	0°, 30°, 60°	1.0%
O10	0.55mm w/o hook	0°, 30°, 60°	2.0%
O11	0.55mm w/ hook	0°, 30°, 60°	0.0%
O13	0.55mm w/ hook	0°, 30°, 60°	1.0%
O15	0.55mm w/ hook	0°, 30°, 60°	2.0%
O16	0.75mm w/ hook	0°	0.0%
O18	0.75mm w/ hook	0°	1.0%
O20	0.75mm w/ hook	0°	2.0%

3.3 Test setup and testing procedure

To carry out fiber pull-out tests, special grips are designed to hold the fiber (**Fig. 2(b)**). The grip consists of two separate parts connected by screws. At the middle of the grip there is a hole

drilled at the required angle. The hole size is made as close to the fiber size as possible. After inserting the fiber, a screw on top of the hole is tightened to secure the fiber. By using the appropriate grip for a given angle of inclination, it can be ensured that the fibers are straight at the beginning of the test (**Fig. 2(c)**). After inserting and tightening the steel fiber into the grip, the other side of the pull-out specimen is then glued to a specimen holder. The details of the pull-out apparatus can be found in Leung and Geng [31]. After the specimen is properly placed in the apparatus, a LVDT is placed between the grip and the specimen holder for displacement measurement. The loading rate was fixed at 0.25 mm/min under displacement control. The load verses displacement relationship during fiber debonding and pull-out was recorded.

4 RESULTS AND DISCUSSIONS

All the fiber pull-out load verses pull-out displacement curves are summarized and shown in **Fig. 3** to **Fig. 9**, while the peak pull-out load and pull-out work verses inclined angle for various PVA fiber content are exhibited in **Fig. 10** to **Fig. 12**. The pull-out work represents energy absorption during the pull-out process.

4.1 Steel fiber geometry

Based on the results shown in **Fig. 10(a)** and **Fig. 11(a)**, the peak pull-out load can be significantly improved by the introduction of a hook at the end of a fiber, but the samples fail with a more brittle manner as shown in the pull-out curves.

Comparing **Fig. 11(a)** and **Fig. 12(a)**, the peak load value is not proportional to the diameter of steel fibers. In addition, as shown in **Fig. 6(a)** and **Fig. 9(a)**, without PVA fibers, samples with larger steel fibers are more ductile than that with smaller fibers. The possible reason is that in the case with a larger steel fiber, the matrix between the front of the hook and the specimen surface (the shaded region in **Fig. 13**) fails first due to the larger local force introduced by the fiber, before the fiber is totally pulled out from the matrix. The pull-out displacement is hence larger.

Figure 3: Pull-out response of Group O6: (a) Degree = 0°; (b) Degree = 30°; (c) Degree = 60°.

Figure 4: Pull-out response of Group O8: (a) Degree = 0°; (b) Degree = 30°; (c) Degree = 60°.

Figure 5: Pull-out response of Group O10: (a) Degree = 0°; (b) Degree = 30°; (c) Degree = 60°.

Figure 6: Pull-out response of Group O11: (a) Degree = 0°; (b) Degree = 30°; (c) Degree = 60°.

Figure 7: Pull-out response of Group O13: (a) Degree = 0°; (b) Degree = 30°; (c) Degree = 60°.

Figure 8: Pull-out response of Group O15: (a) Degree = 0°; (b) Degree = 30°; (c) Degree = 60°.

Figure 9: Pull-out response of: (a) Group O16; (b) Group O18; (c) Group O20.

Figure 10: Straight steel fibers ($d_f = 0.55$ mm): (a) Peak pull-out load; (b) Pull-out work.

Figure 11: Hooked-end steel fibers ($d_f = 0.55$ mm): (a) Peak pull-out load; (b) Pull-out work.

Figure 12: Hooked-end steel fibers ($d_f = 0.75$ mm): (a) Peak pull-out load; (b) Pull-out work.

Figure 13: Large local force caused by the hook.

4.2 Steel fiber inclined angle

From the results in **Fig. 10** for straight fibers, it can be found that the influence of the fiber inclined angle on the peak pull-out load is not significant, especially for those with PVA fibers in the matrix. The inclination of the steel fibers changes the failure mode from a brittle to a more ductile manner, and the samples with 30° inclined fibers consume more energy than the other cases. Typical failure modes around the pulled out fiber for samples with no PVA fibers and 2.0 vol.% of PVA fibers are shown in **Fig. 14**. With PVA fibers in the matrix, the spalling around the steel fiber is significantly reduced.

After complete pull-out, the residual deformations of straight steel fibers embedded in the matrix with 1.0 vol.% PVA fibers, are shown in **Fig. 15**. For inclined fibers, the pull-out force includes both the debonding component (given by the pull-out curve of the aligned fiber) and the bending component (**Fig. 1**). Larger residual deformation, which is caused by larger fiber bending component of crack-bridging force, can be observed in the case with higher inclined angle.

Figure 14: Typical failure modes of (a) O6; (b) O10.

Figure 15: Aligned and inclined straight steel fibers after totally been pulled out (with 1.0 vol.% PVA).

As indicated in **Fig. 11**, for the peak pull-out load of hooked-end fibers, the aligned-fiber cases exhibit the highest value, while the samples with 30° and 60° inclined fibers shows similar and lower values. It can be observed that the samples fail in a more brittle manner when the fiber angle increases. Typical failure modes of samples around the pulled out fiber without PVA fibers and 1.0 vol.% PVA fibers are shown in **Fig. 16**.

Figure 16: Typical failure modes of (a) O11; (b) O13.

4.3 PVA fiber content

For the straight steel fiber, the influence of the PVA fiber content is found to vary with different steel fiber inclination angles (**Fig. 10**). For the cases with aligned fibers, the peak pull-out load and the pull-out work are almost the same, which is reasonable since the introduction of PVA fibers may not have significant influence of the fiber/matrix interface for steel fibers.

As shown in **Fig. 14**, the introduction of fibers into the matrix can reduce matrix spalling around the inclined steel fiber. As a result, the bending component of the pull-out force is increased. For the samples with 30° inclined fibers, the increase in bending component can compensates for the reduced debonding component. For the specimens with 60° inclined fibers, the reduced spalling with fiber addition over-compensates for the smaller debonding component, so the pull-out behavior, in terms of the peak pull-out load and the pull-out work, are both improved.

Close examination of the present test method reveals one shortcoming. Due to the wall effect [34] introduced by the plexiglass block around

the steel fiber pull-out region (**Fig. 2(a)**), the distribution of PVA fibers are restricted, which vary from the real situation in a crack. Modification of the test method has been developed and new tests will be performed.

For the hooked-end steel fibers (**Fig. 11** and **Fig. 12**), the existence of PVA fibers can effectively prevent the matrix spalling and make the samples fail in a more ductile manner, while slightly increasing the peak pull-out load. Typical failure modes at the pull-out point of samples with large hooked-end steel fibers (Group O16, O18 and O20) are shown in **Fig. 17**. In all cases, spalling is very severe. The control of matrix spalling by PVA fibers can effectively enhance the post-peak behavior in the pull-out curves. The pull-out work is hence significantly increased.

Figure 17: Typical failure modes of (a) O16; (b) O18; (c) O20

5 CONCLUSIONS

With a specially designed testing set-up, fiber pull-out test is performed on a single steel fiber embedded inside a cementitious block with different contents of PVA fibers. The parameters investigated include the geometry of steel fibers, the fiber inclination angle (0° , 30° and 60°), as well as the PVA fiber volume fraction (0% as control, 1.0% and 2.0%). From the test results, the following conclusions can be made:

- 1) The peak pull-out load can be significantly improved by the introduction of a hook at the end of a fiber, but the samples fail in a more brittle manner.
- 2) For the samples with straight steel fibers, the influence of the fiber inclined angle

on the peak pull-out load is not significant, especially for those with PVA fibers in the matrix. The inclination of the steel fiber changes the failure mode from a brittle to a more ductile manner, and the samples with 30° inclined fibers consume more energy than the other cases.

- 3) The samples with hooked-end steel fibers fail in a more brittle manner with a lower peak pull-out load when the fiber inclined angle increases.
- 4) The introduction of PVA fibers can effectively prevent the matrix spalling around hooked-end fibers or inclined steel fibers. The samples then fail in a more ductile way. The peak pull-out load may stay similar, but the pull-out work can be significantly increased.

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