Tailoring SHCC made of two kinds of PVA fibers

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ABSTRACT: Some Fiber-Reinforced Concrete (FRC), commonly called Strain-Hardening Cement-based Composite (SHCC), can show a very ductile behavior under tensile actions. Specifically, in the post cracking stage, several cracks develop before complete failure, which occurs when tensile strains localize in one of the formed cracks. As is well known, multiple cracking and strain hardening can be achieved in cement-based specimens subjected to uniaxial tension by increasing the volume fraction of steel fibers with hooked ends, or by using plastic fibers with and without steel fibers, or by means of high bond steel fibers (e.g., twisted fibers or cords). To better understand why, in such situations, high mechanical performances are obtained, an analytical micro-mechanical model has been proposed. The model, capable of predicting the average distance between cracks as measured in some experimental campaigns, is here used to achieve a strain-hardening behavior in a more cost-effective FRC. Specifically, a new Hybrid Fiber Reinforced Concrete, made with two different types of PVA fibers, has been developed at Tohoku University of Sendai (Japan). By means of the shorter and thinner PVA fibers (diameter = 0.04 mm; length = 6 mm), it is possible to enhance the toughness of the cement-based matrix, whereas longer fibers (diameter = 0.1 mm; length = 12 mm) bridge the macro-cracks. By combining direct uniaxial tensile tests, performed on the so-called dumbbell-shaped specimens, and the results of the micro-mechanical model, the critical value of the fiber volume fraction can be evaluated. It should be considered as the minimum amount of longer fibers which can lead to the formation of multiple cracking and strain hardening under tensile actions. The aim of the present paper is to reduce such volume as much as possible, in order to improve the workability and reduce the final cost of SHCC.

1 INTRODUCTION

According to Banthia and Sappakittyaporn (2007), in hybrid Fiber Reinforced Concrete (FRC) <<...there is positive interaction between the fibers and the resulting hybrid performance exceeds the sum of individual fiber performances. This phenomenon is often termed “Synergy”>> Combining fibers of different geometry is a possible manner to create this synergy. Indeed, short fibers, generally called microfibers, enhance the fracture toughness of cementitious matrix in tension. Thus, after the first elastic behavior, the mechanical response of FRC can show a delayed microcracking stage, because of the bridging action performed by the short thin fibers (Stahli and van Mier, 2007). Conversely, the beneficial effects of long fibers are particularly evident in the third stage, and consist of arresting and delaying the growth of macrocracks.

If the amount of long and short fibers is appropriately evaluated, it is possible to obtain a strain hardening cementitious composite (SHCC), capable of developing more than one crack prior to
the localization of tensile strains (Kawamata et al., 2003). To achieve such ductile behavior, hybrid fiber reinforced composites should be tailored on the basis of experimental analyses (Banthia and Sappakittipakorn, 2007), and/or through theoretical approaches, which often enable investigations on the parameters not covered by tests (Bolander et al., 2007).

In what follows, a particular class of hybrid SHCC, made of short and long plastic fibers is taken into consideration. In such tailor-made concretes, crack pattern is experimentally investigated by means of uniaxial tensile tests on “dumbbell type” specimens. The observed crack spacing is also predicted by a cohesive interface model, already introduced to calculate the critical fiber volume fraction (Fantilli et al., 2009). It should be considered as the minimum amount of fibers (in a mono-fiber composite) which can lead to the formation of multiple cracking and strain hardening under tensile actions. The aim of the present paper is to extend the application of this model to hybrid SHCC, in order to reduce the volume of long fibers and improve the workability.

2 MODELING THE STRAIN HARDENING AND MULTIPLE CRACKING OF SHCC

Fiber can be considered as the reinforcing bar \((A_f = \text{area of the fiber})\) of an element in tension (Fig. 1a) having a single crack in the concrete area \(A_c = A_f / V_f\) (in this way the fiber volume fraction \(V_f\) is equal to the geometrical reinforcement percentage \(\rho = A_f / A_c\)).

By increasing the crack width \(w\), the mechanical response of this structure, in terms of \(N-w\) (Fig. 1c), depends on slips between fiber and matrix, whose distribution \(s(z)\) is qualitatively drawn in Fig. 1b. In the case of fibers symmetrically situated with respect to the crack, the maximum slip is located in the cracked cross-section (where \(s = w/2\)), from which it progressively vanishes with the increase of the distance \(z\) from the crack. In particular, \(s(z) = 0\) if \(z \geq l_{tr}\) (where \(l_{tr}\) = transmission length). As \(z\) increases, the tensile stresses of fiber, \(\sigma_s(z)\), continuously transfer to the cementitious matrix, because of bond stresses \(\tau(z)\) acting on the interface between materials. As a consequence, within the domain \(0 \leq z \leq l_{tr}\), tensile stresses in the matrix, \(\sigma_c(z)\), are higher far from the crack surfaces (Fig. 1b). Beyond the transmission length, neither slips nor bond stresses exist, and, therefore, the condition of perfect bond is verified when \(z > l_{tr}\) (i.e., \(\sigma_c = \text{const. and } \sigma_s = \text{const.}\)). In this zone, the stress \(\sigma_c\) reaches the maximum value \(\sigma_{c,max}\).

At onset of cracking, when \(w \rightarrow 0\), \(\sigma_{c,max}\) is generally lower than the strength \(f_c\) and the \(N-w\) diagram shows a softening branch. If these conditions persist for higher crack width, the failure of the structural element depicted in Fig. 1a occurs in the presence of a single tensile crack.

Conversely, when \(\sigma_{c,max} = f_c\), which corresponds to the point B of Fig. 1c, new cracks appear and, with the increase of \(w\), strain hardening characterizes the \(N-w\) diagram. According to Fantilli et al. (2009), during this stage, the average crack spacing ranges between \(l_{tr}\) and \(2 l_{tr}\) (Fig. 1c).

Under the condition of symmetry depicted in Figs. 1a-b, the multiple cracking regime is possible if the semi-length of the fiber is higher than the maximum crack spacing (i.e., \(2 l_{tr} < L_f / 2\)). Thus the definition of \(l_{tr}\) at cracking load (i.e., at point B of in Fig. 1c) is of primary importance in evaluating the presence of multiple cracking and strain hardening response in FRC composites.

The following value of the transmission length is obtained by adapting the tension-stiffening equations of RC structures to the fiber-matrix tie illustrated in Fig. 1a (Fantilli et al., 2009):

\[
l_{tr} = -\frac{\ln\left(\left(p_f k_g V_f - 2 A_f k_c \sqrt{\alpha}\right)\left(p_f k_g V_f + 2 A_f k_c \sqrt{\alpha}\right)\right)}{\sqrt{\alpha}}
\]

where,
Figure 1 – The model for fiber-matrix interaction (Fantilli et al., 2009): a) an element with a single crack; b) slip $s(z)$, bond stress $\tau(z)$, concrete stress $\sigma_c(z)$, and fiber stress $\sigma_s(z)$ distributions around the crack; c) mechanical response in terms of normal force vs. crack spacing vs. crack width.

\[
\alpha = \frac{p_f k_B}{A_f} \left( 1 + \frac{V_f}{E_c} \right)
\]

(2)

In both the equations $p_f = \text{perimeter of fiber cross-section}$; $E_c, E_f = \text{Young's moduli of cement-based matrix and fiber, respectively}$; $k_C = \text{cohesive parameter}$; and $k_B = \text{bond parameter}$.

Since Eq. (1) is obtained in the situation in which the first crack is growing (i.e., $w \to 0$) and other cracks are going to develop (point B in Fig. 1c), $k_C$ is used to approximate the fictitious crack model of the cementitious matrix. As depicted in Fig. 2a, this coefficient can be associated to the so-called Fracture Energy $G_f$, which differs from the work of fracture $G_F$ (Bazant and Becq-Giraudon, 2002). Similarly, the tension stiffening equations are here applied when $s \to 0$, thus bond stresses can be assumed to be in direct proportion (through the coefficient $k_B$ - Fig. 2b) with slips (Fantilli et al., 2009).

The condition of multiple cracking and strain hardening do not occur in FRC if:

\[
V_f \leq V_{\text{fc}} = \frac{A_f}{E_f p_f k_B} \left( 1 + \frac{1 + \left( \frac{E_c}{E_f} \right)^2 p_f k_B}{A_f E_s (k_c)^2} \right)
\]

(3)

where $V_{\text{fc}} = \text{fiber volume fraction that produces the condition } l_w \to \infty \text{ (see Eq. (1))}$. 

In order to obtain a length from Eq. (1) and a number from Eq. (3), the parameter $\alpha$ should be the square of a length. This is possible when the bond parameter $k_B$ (and $k_C$ as well) is assumed to be a stress over a length (see Fig. 2).
3 EXPERIMENTAL STUDY

In order to verify the applicability of the Eqs.(1)-(3) to hybrid SHCC, an experimental campaign has been performed on a new composite. In particular, specimens reinforced with short Polyvinyl Alcohol (PVA) fibers (0.75% in volume) and different amounts of long PVA fibers have been tested in uniaxial tension. The main geometrical and mechanical properties of the two fibers, called respectively REC15 and RECS100, are summarized in Table 1.

In each specimen, the fiber volume fraction \( V_f \) is only referred to the amount of RECS100, whereas short REC15 fibers are assumed to be a part of the cement-based matrix, whose constituents and mix proportion are reported in Table 2, and Table 3, respectively. Young’s modulus \( E_c = 23.3 \) GPa, cohesive parameter \( k_c = 27.5 \) MPa/mm, and tensile strength \( f_{ct} = 2.5 \) MPa define the uncracked and cracked stages of this matrix.

Table 1. Geometrical and mechanical properties of the fibers.

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Diameter (mm)</th>
<th>Length (mm)</th>
<th>Density (g/cm³)</th>
<th>Tensile Strength (MPa)</th>
<th>Failure Elongation (%)</th>
<th>Modulus of Elasticity (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RECS100</td>
<td>0.10</td>
<td>12</td>
<td>1.3</td>
<td>1100</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>REC15</td>
<td>0.04</td>
<td>6</td>
<td>1.3</td>
<td>1600</td>
<td>6.0</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 2. Composition of the cementitious matrix.

<table>
<thead>
<tr>
<th>Material</th>
<th>Symbol</th>
<th>Density (g/cm³)</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>C</td>
<td>3.14</td>
<td>Early strength Portland Cement</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>FA</td>
<td>2.39</td>
<td>-</td>
</tr>
<tr>
<td>Sand</td>
<td>S</td>
<td>2.61</td>
<td>Mean particle diameter: 180μm</td>
</tr>
<tr>
<td>Super plasticizer</td>
<td>SP</td>
<td>1.05</td>
<td>Polycarboxylic acid ether system</td>
</tr>
</tbody>
</table>
Table 3. Mix proportion of the cementitious matrix (B = binder).

<table>
<thead>
<tr>
<th>W/B (weight %)</th>
<th>FA/B (weight %)</th>
<th>S/B (weight %)</th>
<th>SP/B (weight %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>30</td>
<td>40</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Figure 3 – Uniaxial tests on hybrid SHCC: a) geometrical properties of dumbbell specimens (Japan Society of Civil Engineers, 2007); b) the Instron testing machine.

The geometrical dimensions of the “dumbbell type” specimens tested in the present work, and depicted in Fig. 3a, are in accordance with the Recommendations of the Japan Society of Civil Engineers (2007) for HPFRCC composites. The four specimens analyzed in the present paper are reported in Table 4. Two of them contain 2.0% in volume of RECS100 fibers (specimens 2PVA_200_1 and 2PVA_200_2), whereas the other specimens (2PVA_280_1 and 2PVA_280_2) have 2.8% in volume of long fibers.

Loads were vertically applied with a 30 kN capacity Instron testing machine, using “fix-fix” support conditions (Fig. 3b). Each test was controlled by vertical displacement at a velocity of 0.5 mm/min. Average extension was measured over the central gauge length (80 mm) by means of two LVDTs, placed on the opposite side of the member and attached to mounting frames, firmly clamped on to the specimens. In this zone, before strain localization, average crack spacing was also measured and compared with the theoretical prediction of the cohesive interface model introduced by Fantilli et al. (2009).

Table 4. Average crack spacing measured in the central part of dumbbell specimens

<table>
<thead>
<tr>
<th>Name</th>
<th>$V_f$ RECS100</th>
<th>Crack distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2PVA_200_1</td>
<td>2</td>
<td>4.6</td>
</tr>
<tr>
<td>2PVA_200_2</td>
<td>2</td>
<td>4.5</td>
</tr>
<tr>
<td>2PVA_280_1</td>
<td>2.8</td>
<td>2.1</td>
</tr>
<tr>
<td>2PVA_280_2</td>
<td>2.8</td>
<td>2.0</td>
</tr>
</tbody>
</table>
EXPERIMENTAL RESULTS AND THEORETICAL PREDICTION

The stress-strain curves of the four specimens are depicted in Fig. 4. Strain hardening is clearly evident in all the diagrams, and the maximum tensile stress (whose average value is 2.72 MPa) is about 10% higher than the strength of the matrix ($f_c = 2.5$ MPa). In the same way, it is possible to observe the multiple cracking in the photographs reported in Fig. 5, which were taken just after the failure.

They can be used to evaluate experimentally the crack spacing, here considered as the ratio between the central gauge length and the number of cracks. The values of crack distances are reported in Table 4. For the two types of fiber-reinforcement, the higher the amount of long PVA fibers (i.e., RECS100), the higher the number of cracks which affect the central part (80 mm in length) of the dumbbell specimen depicted in Fig. 3a.

As shown in Fig. 6, the measured crack spacing is compared with the values of transmission length (Eq. (1)). However, to make this comparison possible for all the mixtures, the parameter $k_B$ (related to bond and snubbing phenomena of RECS100 fibers) has to be defined from the best-fitting of the experimental results.

Figure 4 – Stress-strain relationships of the four specimens tested in the present project.
If $k_B = 60$ MPa/mm is assumed for the four specimens, all the measured crack spacings fall within the range bordered by the curves $l_{tr}V_f$ and $2l_{tr}V_f$ (Eq. (1)). Moreover, Eq. (3) gives $V_{f_{cr}} = 0.7\%$ for the specimens of this SHCC. Nevertheless, when $V_f = V_{f_{cr}}$, only PVA fibers with $L_f > 12 \text{ mm}$ can generate multiple cracking and an average crack spacing ranged by the minimum and the maximum theoretical distance ($l_{tr}$ and $2l_{tr}$, respectively). Conversely, Fig. 6 seems to suggest $V_f = 1.7\%$ as the minimum volume fraction of long PVA fibers. Since in the present experimental campaign the lowest volume is 2\%, the minimum amount of RECS100 can be further reduced of about 20\%.

Figure 6 – Comparison between the average crack spacing predicted with the cohesive interface model proposed by Fantilli et al. (2009) and those experimentally measured.
CONCLUSIONS

Eqs.(1)-(3), obtained from a cohesive interface model, can be effectively used to analyze different types of very ductile composites. In the case of the hybrid SHCC investigated in the present paper, the minimum amount of long PVA fibers can be effectively defined by these equations. Specifically, strain hardening and multiple cracking occurs in cement-based composites reinforced with short PVA fibers (0.75% in volume) and with no less than 1.6% of long PVA fibers.

REFERENCES

Japan Society of Civil Engineers (2007) Recommendations for Design and Construction of HPFRCC with Multiple Fine Cracks. (in Japanese)