TAILORING OF PVA FIBER/MATRIX INTERFACE FOR ENGINEERED CEMENTITIOUS COMPOSITES (ECC)

Shuxin Wang and Victor C. Li

The University of Michigan, Department of Civil and Environmental Engineering,
2350 Hayward St., Ann Arbor, MI 48109, USA. email: vcli@engin.umich.edu

1. Introduction

ECC represents a unique group of randomly oriented short fiber-reinforced cementitious composites designed on micromechanical principles (Li 1998). While conventional fiber-reinforced concrete (FRC) exhibits tension-softening after cracking, ECC strain-hardens under tension with multiple-cracking and features a strain-stress curve with a shape similar to that of a ductile metal with yielding point. The high ductility (typically exceeding 3%) associated with strain-hardening is of great significance in improving infrastructure durability against corrosion, fatigue, and resistance to structural overload. Unlike other types of high performance FRC, where the performance is boosted by using high volume fraction of fiber, the unique properties of ECC is achieved by carefully tailoring the fiber, matrix, and interface microstructures and micromechanical properties such that a minimum amount of fiber (typically less than 2% by volume) is needed. Because of the moderately low fiber content, ECC delivers best workability and lowest cost at the same performance base.

Among various polymeric fibers being used in developing ECC materials, polyvinyl-alcohol (PVA) fiber is of great interest due to its small diameter, high strength, high modulus of elasticity, and relatively low cost. However, directly applying commercially available PVA fibers has resulted in composites with significantly low tensile strain capacities on the order of 0.5-1.0% even if as much as 4% fiber volume fraction is used (Shao & Shah 1997; Kanda & Li 1998). The reason behind the poor ductility is that PVA fiber tends to rupture instead of being pulled out in a cementitious matrix due to the strong chemical bonding to cement hydrates and the slip-hardening response during pullout that leads to shear-delamination failure of the PVA fiber (Redon *et al* 2001). In this paper, focus is placed on the tailoring of the fiber/matrix interface under the guidance of micromechanics models to create an extremely ductile PVA-ECC composite. Specifically, the excessive interface bond and the slip-hardening behavior are controlled by fiber surface treatment in the form of oil coating.

2. Interface Tailoring Guideline

The micromechanics of tensile strain-hardening for cementitious composites reinforced with randomly oriented short fibers is comprised of two aspects: the requirement of steady state crack propagation necessary for composite strain-hardening behavior (Marshall & Cox 1988), and the influence of interface and fiber properties on the stress-crack opening relationship (Li & Leung 1992). When combined, these analyses provide guidelines for the tailoring of fiber, matrix and interface in order to attain strain-hardening with the minimum amount of fibers. A complete analytic model can be found in Lin, Kanda and Li (1999), where the interface is characterized by frictional bond τ_0, chemical bond G_d, and slip-hardening coefficient β. For the specific PVA fiber used in the study (its geometric and mechanical properties have already optimized by using this model) at a fixed fiber volume fraction of $V_f = 2\%$, numerical analysis indicates that the optimal values of τ_0, G_d and β should fall into the ranges of 1.0 - 2.1 MPa, 0 - 2.2 J/m^2, and 0 - 1.5 respectively (Wu 2001), for a typical matrix toughness of $J_m = 5$ J/m^2.

3. Experimental Program and Results

Two sets of experiments were conducted to investigate the effectiveness of interface tailoring: single fiber pullout test at interface level and uniaxial tension test at composite level. The major parameter investigated here was the effect of the oiling agent amount on the interfacial bond properties. From the single fiber pullout test, the bond properties including τ_0, G_d and β can be quantified. The amount of oiling agent can then be adjusted to tailor the bond properties to the optimal ranges described above. Uniaxial tension test, which characterizes the strain-hardening behavior, was conducted to verify the micromechanics model prediction.

The interface values were found to be successively reduced by increasing the amount of oiling agent on the fiber. When τ_0, G_d and β approached or dropped below the target values, the ductility of the composite was greatly enhanced. Figure 1 shows the decreasing values of τ_0, G_d and β as a function of oiling agent measured in single fiber pullout tests, as well as the target values determined theoretically. This set of data suggests that oiling agent in excess of 0.6-0.8% is needed to achieve strain-hardening. Microscopic analysis further revealed that the delamination phenomenon of PVA fiber was alleviated with the increase of oiling content. Reflected on the composite performance, the tensile strain capacity increased from less than 1% to about 5% accompanied by decreases of cracking spacing, when the oiling agent increased from 0 to 1.2% (Figure 2). It is clear that the composite reaches multiple crack saturation when the oiling content reaches about 0.6-0.8% as expected.

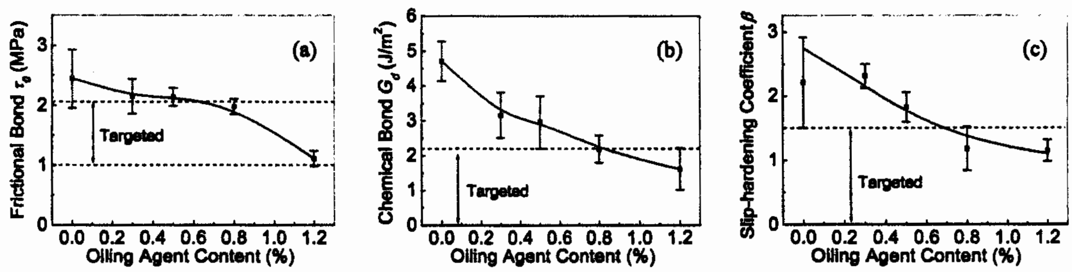

Figure 1 Effects of oiling content on interface properties. Also shown is the targeted range determined by theoretical model.

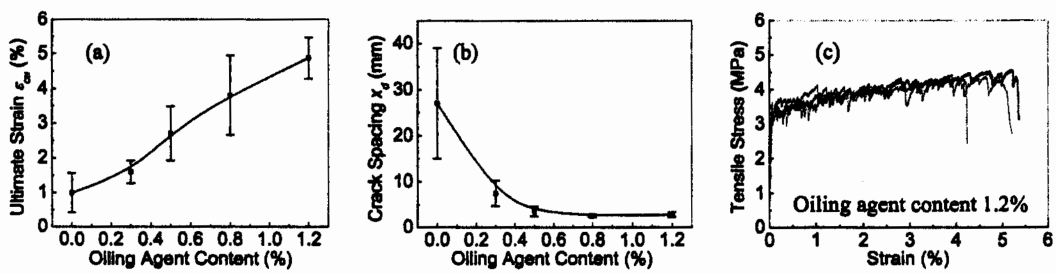

Figure 2 Influences of oiling content on tensile strain capacity (a) and crack spacing (b), as well as tensile stress-strain curve of the composite with 1.2% oiling agent content (c).

4. Conclusion

Unlike many common fiber/matrix composite systems, the bonding between PVA fiber and a cementitious matrix is too high and needs to be lowered. The oiling agent is demonstrated via single fiber pullout test to be effective in counteracting the excessive chemical bond and slip-hardening effect for PVA fibers in cementitious composites. Tensile strain-hardening with strain-capacity in excess of 4% can be achieved with PVA fiber reinforced ECC composites provided that the interface is properly tailored to control the magnitudes of G_d, τ_0 and β. The oiling content of 1.2% gives the best result in this series of tests. Micromechanical model of tensile strain-hardening in cementitious composites provides useful guidance for microstructure tailoring. This research demonstrates that surface treatment of synthetic fibers can be very effective in significantly modifying composite behavior. A high performance to cost ratio is critical in successfully introducing a fiber into the high volume cost-sensitive civil engineering market.

References

Kanda, T. & Li, V.C. (1998), Interface Property and Apparent Strength of a High Strength Hydrophilic Fiber in Cement Matrix, *ASCE J. Materials in Civil Engineering*, **10**(1): 5-13.

Li, V.C. & Leung, C.K.Y. (1992), Steady State and Multiple Cracking of Short Random Fiber Composites, *ASCE J. of Engineering Mechanics*, **188**: 2246-2264.

Li, V.C. (1998), Engineered Cementitious Composites - Tailored Composites Through Micromechanical Modeling, in *Fiber Reinforced Concrete: Present and the Future* edited by N. Banthia, A. Bentur, A. and A. Mufti, Canadian Society for Civil Engineering, Montreal, 64-97.

Lin, Z., Kanda, T. & Li, V.C. (1999), On Interface Property Characterization and Performance of Fiber Reinforced Cementitious Composites, *J. Concrete Science and Engineering, RILEM*, **1**: 173-184.

Marshall, D. & Cox, B.N. (188), A J-integral Method For Calculating Steady-State Matrix Cracking Stress In Composites, *Mechanics of Materials*, **7**(8): 127-133.

Redon, C., Li, V.C., Wu, C., Hoshiro, H., Saito, T. & Ogawa, A. (2001), Measuring and Modifying Interface Properties of PVA Fibers in ECC Matrix, *ASCE J. Materials in Civil Engineering*, **13**(6): 399-406.

Shao, Y. & Shah, S. P. (1997), Mechanical Properties of PVA Fiber Reinforced Cement Composites Fabricated by Extrusion Processing, *ACI Material Journal*, **94**(6): 555-564.

Wu, C. (2001), *Micromechanical Tailoring of PVA-ECC for Structural Applications*, PhD Thesis, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, USA.