Effect of Fiber Length in Extruded and Cast Cement Composites

by A. Peled, Y. Akkaya, and S. P. Shah

Synopsis:

The influence of fiber length on tension and flexural behavior of extruded and cast cement composites was examined for PVA (hydrophilic) fibers and polypropylene (hydrophobic) fibers. The fiber-matrix interface, fiber surface, and microstructure of the composite cross-section were characterized by SEM. Opposite trends were obtained for the cast and extruded composites with increasing fiber length. For the extruded composites, decreasing fiber length increased flexural and tensile response, whereas for the cast composites increasing the fiber length increased the flexural and tensile response. These differences were found to be a result of differences in fiber-matrix bond properties and fiber distribution. The extruded composites showed a stronger fiber-matrix bond compared to the cast composites. This led to differences in the fiber failure mechanism: fiber rupture of the 6mm fibers in the extruded composite, and fiber pullout of both fiber lengths in the cast composites and for the 2mm fibers in the extruded composites.

Keywords: reinforcement; cement composite; extrusion; fiber length; PVA fibers; polypropylene fibers; bond; fiber-matrix interface

Alva Peled is a post-doctoral fellow at the NSF Center for Advanced Cement-Based Materials at Northwestern University. She received her D.Sc. degree from the Technion, Israel Technology Institute in Civil Engineering, her M.Sc. is from The Hebrew University Israel in Chemistry of Polymers and Textile. Her B.Tech. is in Textile Technology. Her research interests include fibers and fabrics as reinforcement for composites, processing and fiber-matrix interfaces.

Yilmaz Akkaya is a graduate student in the Civil Engineering Department at Northwestern University. He obtained his M.Sc. degree from the Istanbul Technical University in Department of Civil Engineering Materials. His research interests include fiber reinforced concrete, durability and microstructure of concrete, statistical analysis, extrusion processing, laser interferometry techniques and repair of structures.

Surendra P. Shah, FACI, is a Walter P. Murphy Professor of Civil Engineering at Northwestern University and a director of the NSF Center for Science and Technology of Advanced Cement-Based Materials. He has been involved extensively with research on constitutive relationships, failure and fracture of concrete, nondestructive testing, and impact and impulsive loading. He has published more than 300 technical articles and has edited and co-authored numerous books.

INTRODUCTION

In general, fibers are incorporated in the brittle cement matrix to control cracking, to provide high ductility and improved impact resistance, to increase tensile and flexural strengths and to provide a strain-hardening type of response (1). Fiber reinforced concretes (FRC) can be categorized into two classes by their tensile responses: low-performance FRC and high performance FRC (HPFRC). Conventional FRC mainly exhibits an increase in ductility of the composite compared to the plain matrix; whereas HPFRC exhibits a substantial strain-hardening type of response, leading to a large improvement in both strength and toughness of the composite compared with the plain matrix. Fibers can improve the matrix tensile strength, if they can effectively bridge matrix microcracks. The effectiveness of the fiber-bridging action depends on the length, diameter, and distribution of fibers, as well as matrix properties. Fibers that bridge microcracks create closing pressures that suppress crack growth (2,3).

Fiber length affects the contribution of the fiber to the strength and toughness of the composite (1,4). A minimum (critical) length should be considered when discussing fiber length effects. This critical length is the minimum length required developing the full strength capacity of the fiber. Composites with fiber lengths lower than the critical length fail without fiber fracture during fiber pullout, since the fiber is not long enough to generate sufficient bond to fracture. In this case the failure is governed by debonding or matrix fracture. In composites with fiber length greater than the critical length, fiber strength can be attained and the failure is governed by fiber fracture. In general, a continuous increase in fiber length is advantageous for generating high strength. However, when toughness is considered, an increase in length over the critical length can be detrimental. The critical length of the fiber is controlled by the fiber-matrix bond (4). When the fiber-matrix bond increases the critical length decreases.

The present work was conducted to study the effects of fiber length on the flexural and tension behavior of extruded cement composites. Extrusion is a technique that has been shown to impart high performance characteristics to fiber reinforced cementitious materials (5). In the extrusion process a highly viscous plastic-like mixture is forced through a rigid opening (a die) having geometry of a desired cross-section. The advantage of using extrusion in cement product processing is that fibers can be aligned in the load-bearing direction, the matrix and fiber packing can be optimized to achieve low porosity, and the bond between fiber and matrix can be improved. During the extrusion processing the viscosity (rheology) of the material is a controlling factor. The mixture must be sufficiently plastic (soft) to flow under pressure and pass easily through the die, but on the other hand, it must be rigid enough to resist deformation and retain the extruded cross section after it exit from the die. If the rheology of the material is not close to ideal, it can reduce composite performance. Fiber length can change the viscosity of the fresh mixture and influence the performance of the composite.

The influence of fiber length on flexural and tensile behavior of extruded cement composites was examined for PVA (hydrophilic) fibers and polypropylene (hydrophobic) fibers. For comparison the effect of fiber length was also examined for composites produced with the conventional casting process, using the same PVA fibers as for the extrusion composites.

EXPERIMENTAL

Materials and Processing

The effect of fiber length was examined on two different production processes, extrusion and cast, and two fiber types, PVA and polypropylene. The fiber lengths examined were 2, 4, and 6mm for the PVA fibers and 13, and 19mm for the polypropylene fibers. Both fiber types and all fiber lengths were examined in the extrusion process. For the cast process only PVA fibers having lengths of 2 and 6 mm were examined. The properties of the PVA fibers are: 1900 MPa tensile strength, 41 GPa modulus of elasticity, and 14 microns diameter. The tensile strength of the polypropylene fibers is 700 MPa.

The basic extruded material composition by volume was: 3% fibers, 12% silica fume, 1% superplasticizer and 1% methylcellulose for helping the extrusion process, with a water/cement ratio of 0.3. In the case of the cast composites in order to increase the fluidity of the fresh mixture, the 1% by volume methylcellulose was replaced with superplasticizer, keeping the same water/cement ratio of 0.3 as for the extruded composites.

The preparation of the mixtures for both cast and extruded composites was as follows for both fiber types: first the liquid phase was mixed together with the fibers to get a proper dispersion of the fibers in the composite, and then the solid materials were incorporated in the mixture. All the components were mixed together for about 10-15 minutes. Sheet specimens were produced for both the cast and extrusion peocesses; the specimens were 4mm thick and 25mm wide.

After production, the specimens were cured under a plastic sheet. After one day the specimens were demolded (in the case of the cast specimens) and cured at 100% RH at 90ºC for 2 days. After storing for another 24 hours in 50% RH at room temperature the specimens were dried at 105ºC for 24 hours and tested in flexure.

Extrusion and Test Methods

Extrusion--A small-scale extrusion rheometer was used at a rate of 0.5 mm/sec to evaluate the rheology of the different batches. A ram type extruder was used for this purpose; in a ram extruder a piston is used to apply pressure to the material in the barrel in order to force it through a die.

Flexural test--A three-point flexural test was carried out to characterize the flexural behavior of the composites. The span was 101.6mm (4inch). The three point bending test was conducted using stroke control at a rate of about 0.7 mm/min. The test results presented are for an average of 6 specimens. Typical stress-deflection curves representing the composites flexural behavior were chosen for comparison.

Tension test--For the PVA fiber composites (cast and extruded) without sand, in addition to the flexural tests, tension tests were performed for un-notched specimens at a rate of 0.02mm/min. A gage length of 12.7 mm (0.5inch) was used for controlling the test by using the average measerment from two CMOD gages. The specimens were 152.4 mm long and tested in the longitudinal direction of the specimen (the extrusion direction). The tensile strength and the area under the stress-strain curves (toughness) up to 1.2×10^{-4} strain were calculated. The test results presented are an average of 5 specimens. Typical representative stress-strain curves were chosen for comparison.

Microstructure characterization--Fragments of specimens of the PVA fiber composites obtained after tension and flexural tests were dried at 60°C prior to being gold-coated for observation in a scanning electron microscope (SEM), in an attempt to characterize the fiber-matrix interface, the fiber surface, and the microstructure of the composite cross-section. The tensile zone was mainly observed with the flexure specimens. The observations were conducted on the composite fracture surface and on the polished surface of tensile composites. Examination of the top views and side views of the fracture surface were obtained. The side view was mainly used to observe the protruded length of the fiber, which remained on top of the fracture surface after the tension test. This was used to characterize the fiber failure mechanism. In the case of the polished specimens, the polishing was done along the specimen length, exposing the wide side of the composite, in order to observe the orientation of the fibers. Also another set was polished across the width of the specimen in order to observe the distribution of fibers at a cross section near the fracture zone.

MECHANICAL BEHAVIOR

Effect of fiber Length

The effect of fiber length on tension and flexural behavior of extruded composites can be seen in Figure 1 for PVA fiber composites and for polypropylene fiber composites. Table 1 presents the average tensile and flexural strengths and composite toughness for the PVA fibers. It can be clearly seen that for both fiber types decreasing the fiber length significantly enhances the tensile and flexural response of the extruded composites. The improvement is in both strength (tensile and flexural) and toughness. About a four-fold enhancement was obtained in the ductility of composite with 2mm PVA fibers compared to composites with 6mm fibers (flexural composites). A strain hardening response can be seen for the PVA fiber composites. The figure also shows the substantial improvement achieved with the PVA fibers on composite flexural behavior compared with the plain matrix.

This is in contrast to the extruded composites in the cast systems, where increasing the fiber length improves the composite flexural and tensile response (Figure 2 and Table 1). Here about a two-fold improvement in the ductility of the flexural composite and 60% increase in the flexural strength values were obtained for composites with 6mm long fibers compared to those with 2mm long fibers. This influence of fiber length was obtained when fibers fail by pullout for both fiber lengths. Longer fibers lead to a high energy, requirement to pull out the fiber, and this results in a high tensile and flexural response.

This contradictory trend in the cast and extruded composites indicates that short fibers are advantageous when using the extrusion technique, whereas long fibers are advantageous when using the cast technique. In general, short fibers are easier to handle during mixing; result in less broken fibers (mainly when brittle fibers were used), and are more easily dispersed in the composite (fewer fiber bundles).

Effect of Processing

Figure 3 compares the tensile response of cast and extruded composites with PVA fibers for 2mm fiber length and for 6mm fiber length. The extrusion process significantly improves the tensile response of composites containing 2mm fibers (Figure 3a). For composites containing 6mm fibers, the cast composite exhibits higher ductility and toughness, whereas the extruded composite shows more brittle behavior with higher composite tensile strength (Figure 3b). The high ductility of the cast composite with 6mm fibers suggests that the fiber failure mechanism is governed mainly by fiber pullout, whereas the brittle behavior and the high strength of the extruded composite suggests fiber rupture (4).

Comparison between the tensile behavior of the extruded composite containing 2mm fibers and the cast composite containing 6mm fibers shows a substantial strain hardening response of the extruded composites (Figure 4). This means that the extrusion technique enables reduction of the fiber length to as low as 2mm and at the same time achievement of a significant strain hardening response of the composite, which cannot be obtained when the conventional cast technique is used, even with a 6mm fiber length.

MICROSTRUCTURE

Fiber Failure Mechanism

Figure 5 shows a side view of a fracture surface after a tensile test for extruded and cast composites with 2 and 6mm fiber lengths. This view shows the length of fibers protruding from the matrix surface after the test. Assuming similar fiber-matrix bond for both fiber lengths (i.e. the same critical fiber length), one would expect to obtain a longer protruded length for the long fibers (6mm), if both fiber lengths (2 and 6mm) were completely pulled out during testing.

In the extruded system, the protruded length of the 6mm fibers is less than that of the 2mm fibers (Figures 5a and c). Thus fiber fracture rather than fiber pullout is indicated as the failure mechanism for the 6mm fibers. The long protruded length exhibited with the 2mm fibers is a result of fiber pullout.

For the cast composites a longer protruded length is obtained with the 6mm fibers compared to the 2mm fibers (Figures 5b and c). This indicates a failure mechanism controlled by the fiber pullout process for both fiber lengths in the cast composites.

It can be concluded that for the extruded system, the fiber pullout process is the failure mechanism for the 2mm fibers and fiber fracture is the dominant failure mechanism for the 6mm fibers. In the cast system, a fiber pullout process is the failure mechanism for both fiber lengths. The pullout mechanism can lead to an enhanced ductile behavior of the extruded composite with the 2mm fibers and the cast composites with 6mm fibers (Figures 1 and 2).

Fiber-Matrix Bond

Observations of the fiber-matrix interface and the surface of the fiber itself were conducted, in an attempt to characterize the fiber-matrix bond of cast and extruded composites:

a) Fiber-matrix interface--Figure 6 shows SEM micrographs of PVA fiber embedded in the cement matrix for extruded and cast composites. A large gap between the fiber and the matrix and a porous matrix around the fiber can be seen in the cast composite (Figure 6b). A much more compacted matrix around the fiber can be seen in the extruded composite (Figure 6a), i.e. stronger fiber-matrix bond.
b) Fiber surface--Figure 7 shows SEM micrographs of the PVA fiber surface after a flexure test. These observations were made for the 2mm fibers, since in both processing methods (extruded and cast) these fibers exhibited fiber pullout failure. Significant long fibrils and a rough fiber surface can be seen in the extruded composite (Figure 7a). Very fine fibrils and a much smoother fiber surface can be seen in the cast composite (Figure 7b). The long fibrils and the roughness of the extruded fiber surface indicate an aggressive pullout process with high friction between the fiber and the relatively dense matrix of the extruded composite.

Figure 8 shows a top view of a fracture surface after testing. The figure shows a large amount of long fibrils lying on top of the fracture surface of the extruded composite made with 2mm fibers (Figure 8a). Such fibrils were not observed in the case of the extruded composite with 6mm fibers (Figure 8b) and with the cast composite (Figure 8c). This indicates once again the higher pullout resistance of the 2mm fibers in the extruded system. This figure also shows a longer protruded length of the 2mm fibers, compared with the 6mm fiber in the extruded composites. Note that the protruded length of the cast specimen with 2mm long fiber is quite long.

Based on the entire set of observations it is concluded that the extrusion process improved fiber-matrix bond compared with cast composites. This strong bond can be obtained, since in the extrusion process the materials are formed under high shear and high compressive forces during production. A strong fiber-matrix bond leads to a shorter critical fiber length. Fibers with a greater length than the critical length are long enough so that the failure is governed by fiber fracture. The embedded length of the 6mm fibers in the extruded composites exceeded the critical length, thus fiber fracture rather than fiber pullout is the failure mechanism for composites made with those fibers. This can explain the contradictory influence of fiber length on mechanical behavior obtained with the cast and the extruded composites when increasing fiber length (Figure 1 and 2).

<u>Fiber Dispersion</u>

Figure 9 shows the distribution of the fibers in the extruded composite cross-section for the different fiber lengths. It can be seen that the 2mm fiber dispersed more homogeneously in the composite than the 6mm fibers. More fiber clumps can be seen in the case of the 6mm fibers. The better dispersion of the 2mm fibers in the extruded composite contributes to the high tensile and flexural response of this composite (Figure 1).

Higher tensile strength was obtained with the extruded composite with 2mm fibers, compared to the extruded composite with 6mm fibers (Figure 1 and Table 1). This was so even though the failure of the 6mm fiber was governed by fiber fracture, which should lead to brittle composite behavior but with high strength. The more uniform dispersion of the 2mm fibers in the extruded composite appears to contribute to this behavior.

CONCLUSIONS

1) In the extruded composites decreasing fiber length improves the mechanical behavior (tensile and flexural) of the composite. This trend was obtained for different fiber types: PVA and polypropylene.

2) In the case of the cast composites increasing fiber length increases the mechanical behavior (tensile and flexural) of the composite. Based on microstructure characterization, the fiber pullout process is the fiber failure mechanism for both fiber lengths. A longer fiber length (6mm) required more energy to pull out, leading to the higher strength (flexural and tensile) and toughness of the composite.

3) The extrusion process improves the fiber-matrix bond compared with cast composites. Extruded composites made with a 2mm long fiber showed a superior strain hardening response compared to cast composites made with 6mm fibers.

4) The difference in the fiber-matrix bond between extruded and cast composites resulted in different fiber failure mechanisms:

a) Fiber pullout occurred in the case of the extruded composites with 2mm fibers and in case of cast composites with both fiber lengths, and
b) Fiber fracture in the case of extruded composite with 6mm fiber.

5) With the extrusion technique it is possible to reduce the fiber length to as low as 2mm and at the same time achieve a significant high strain hardening response of the composite, which cannot be achieved when the conventional casting technique is used, even with a 6mm fiber length.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the Illinois Clean Coal Institute and the project manager Dr. Daniel D. Banerjee,

REFERENCES

1) Balaguru, P.N. and Shah, S.P., "Fiber Reinforced Cement Composites", McGraw Hills Inc. Publishers, New York, 1992.

2) Shah, S. "Do fibers increase the tensile strength of cement based matrixes?", ACI Material Journal, Nov-Dec. 1991, pp. 595-602.

3) Lang, C. Ouyangg and S.P. Shah, " Behavior of Cement Based Matrices Reinforced by Randomly Dispersed Microfibers", Advanced Cement Based Materials, 1996, Vol. 3, pp. 20-30.

4) Bentur, A. 1989. "Fiber Reinforced Cementitious Materials". Material Science of Concrete. Ed. J. P. Skalny, The American Ceramic Society: 223-279.

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

Table 1: Flexural and tensile strengths and toughness of the extruded and cast composites containing PVA fibers.

Processing	Fiber Length (mm	Flexural Strength (MPa)	Tensile Strength (MPa)	Toughness (Area under the curve up to 1.2 x10^{-4} strain)
	Plain Matrix	13.8	---	---
Extrusion	2	33.8	9.1	96
	4	29.7	8.3	77
	6	25.0	7.3	49
Cast	2	20.1	2.8	29
	6	29.2	5.3	59