Manufacturing and Mechanical Testing of a New Functionally Graded Fiber Reinforced Cement Composite

Bin Shen, Mija Hubler, Glaucio H. Paulino and Leslie J. Struble

Department of Civil and Environmental Engineerin, University of Illinois at Urbana-Champaign
205 N Mathews Ave, Urbana, IL, USA

Abstract. A functionally graded (FG) material system is employed to make fiber use more efficient in a fiber reinforced cement composite (FRCC). This preliminary study demonstrates beam elements that were functionally graded fiber reinforced cement composite (FGFRCC) with four layers, each with a different fiber volume ratio. Fiber volume ratio was graded in accordance with its potential contribution to the mechanical load-bearing capacity so as to reduce the overall fiber volume ratio while preserving the flexural strength and ductility of the beam. Extrusion was used to produce single homogeneous layers of constant fiber volume ratio. The FRCC layers with different fiber volume ratios were stacked according to a desired configuration and then pressed to make an integrated FGFRCC. Flexural tests were carried out to characterize the mechanical behavior, and the results were analyzed to evaluate the effectiveness of the designed fiber distribution. Compared with homogeneous FRCC with the same overall fiber volume fraction, the FGFRCC exhibited about 50% higher strength and comparable ductility.

Keywords: FRCC, FGFRCC, Extrusion, Functionally graded material (FGM)

INTRODUCTION

Many kinds of fiber reinforced cement composites (FRCC) have been developed, studied, and applied in construction in the past few decades [1-4]. A properly designed FRCC may offer enhanced mechanical behavior, higher strength and higher toughness [2]. To greatly improve the mechanical properties, many times fibers at high volumes are needed. Since fibers are costly, using large amount of fibers will substantially increase the material cost. Thus there is a need for new technology to make more effective and efficient use of the costly fibers. We notice that nearly all known FRCC being developed and used in application are homogeneous in a bulk scale, i.e. the fiber volume fraction is constant. The fiber volume fraction is usually determined by the designed maximum tensile strength in a FRCC component. However, when a significant portion of a FRCC component is only under compression or slight tension at most, e.g. beam component under bending, the fibers in that region are not used efficiently because fibers contribute little to compressive strength. Hence an efficient use of the fibers involves distributing them according to the amount of load to be carried. More fibers should be placed where they are mostly needed. One example to use fibers more efficiently is to build sandwich panels from thin fiber reinforced faces and a lightweight core. This is also similar to the case of repairing damaged beams or

CP973, *Multiscale and Functionally Graded Materials 2006*
edited by G. H. Paulino, M.-J. Pindera, R. H. Dodds, Jr., F. A. Rochinha, E. V. Dave, and L. Chen

strengthening in-service beams, where carbon fiber sheets are usually bonded to the bottom of the beam. While this procedure can be effective, significantly different properties between the fiber sheets and the host concrete may cause potential delamination problems.

This problem can be addressed by applying the concept of functionally graded materials [5] - by distributing a fixed amount of fibers according to proportion of load to be carried, the graded composite may provide better performance than the homogeneous composite. In this study, a new processing method is explored for manufacturing such functionally graded fiber reinforced cement (FGFRCC) composites. First, a ram type extruder was fabricated to manufacture thin FRCC beams with different fiber volume fractions. Extrusion has been a very effective way to produce FRCC [6-9]. Essentially, extrusion involves forcing material through a small die. When this technique is applied to manufacture cementitious materials, very low water to cement ratio can be utilized, which contributes to high strength of the matrix and fiber-matrix interfacial bonding [10]. Another major advantage of using extrusion for FRCC is that the high shearing action developed during the forming process forces the short fibers to be aligned in the extrusion direction [8]. Such fiber alignment improves the mechanical performance of FRCC in the extrusion direction, which is beneficial for components that carry tensile load only in one direction. Then, extruded beams with increasing fiber volume fraction were stacked and pressed in a mold to integrate them into an FGFRCC. For comparison, beams with a single global fiber volume fraction were also stacked and pressed. After curing of the composites, three point bending tests were carried out to observe the bending behavior of both graded and homogeneous specimens. The graded composites showed improvement in the bending response as compared to homogeneous composites, when both used a similar net amount of fibers.

MATERIALS

The main components of the FGFRCC are ordinary portland cement (Type I), fly ash, PVA fiber, superplasticizer, and rheological modifier. Class F fly ash is used. The main reason for adding fly ash in the mix was to improve rheological properties of the fresh paste so that it is more extrudable. The PVA fibers used in this study are from the company Kurary, Japan. The fiber type is REC7, with an available cut length of 6 mm and a diameter of 27 μm, and with tensile strength and modulus of 1600 MPa and 37 GPa, respectively. Density of the fibers is 1.3 g/cm^3. A polycarboxylate-based superplasticizer, Grace ADVA, was added to reduce the ratio of water to cementitious materials, and to enhance the plasticity of the fresh paste. A rheological modifier, hydroxypropyl methylcellulose (HPMC), was used to improve cohesion in the fresh paste to make it dough-like. The basic mix proportions of different layers are shown in Table 1. The fiber volume fractions for four layers were: 0% ~ 2%, respectively.

TABLE 1. Basic mix proportions

Cement (wt.)	Fly ash Class F (wt.)	Water (wt.)	Fiber (vol.)	Superplasticizer* (wt.)	MC/water
0.7	0.3	0.23	0% 0.67% 1.33% 2%	0.002	0.04

* Mass of solid admixture

EXPERIMENTS

Mixing procedure: The dry ingredients were first mixed using a planetary-type mixer for at least one minute. Water was then added slowly. The wet mixing continued for 5 to 10 minutes to reach a dough-like state with all fibers being separated completely, then the fresh FRCC was ready for extrusion.

Extrusion: An extruder fabricated for the extrusion of homogeneous FRCC is shown schematically in Fig. 1(a). The ram speed for extrusion was fixed as 20 mm/min, and accordingly, the extrudate speed was 255 mm/min.

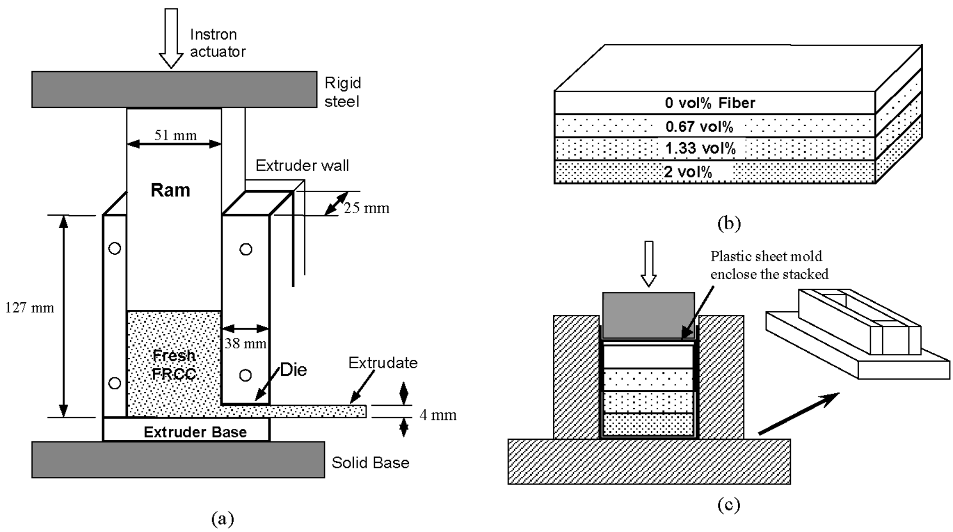

FIGURE 1 Extrusion and pressing: (a) Extruder used to produce a monolithic layer; (b) Stacked extrudate with varying fiber volume fraction; (c) Mold for pressing the stacked layers to produce either FGFRCC or integral layered FRCC

Pressing: After all four layers were extruded, they were stacked as shown in Fig. 1(b), with the fiber volume fraction increased from 0% at the top to 2% at the bottom. The same procedure was carried out to make homogeneous FRCC with uniform fiber volume fraction by stacking four layers with the same fiber volume fraction to make one homogeneous FRCC beam. In order to produce smooth surfaces of the final

FGFRCC, the stacked layers were put in a rigid steel mold lined with plastic sheet (Fig. 1c). Pressing was carried out on an Instron machine using displacement control.

Curing: After pressing, all extrudate with plastic mold were cured under a wet cloth and covered by a plastic sheet for one day. Then the plastic molds were removed and the specimens were cured at 90°C in a water bath for another two days, followed by exposure to ordinary laboratory conditions for another two days. Before flexural testing, the specimens were oven dried at 105°C for one day and kept in laboratory environment for another 24 hours. The curing scheme is the same as described in [10].

Flexural testing: Three-point bending tests were carried out using an Instron testing machine to characterize the deflection behavior. The span was set to 120 mm. Displacement was controlled at 0.3 mm/min.

MECHANICAL TESTING

FRCC Properties

Equivalent elastic flexural stress was computed for all bending tests. The computed flexural stress is plotted versus stroke displacement, as shown in Fig. 2(a). The first cracking stress, f_{fc}, maximum flexural stress, $f_{\max}$, the displacement corresponding to $f_{\max}$, $d_{\max}$, and the ductility were measured or computed, and are summarized in Table 2. In Table 2, each data is an average of test results of 3 specimens. All FRCCs show deflection hardening response [11]. Strength and toughness both increased with fiber volume ratio. The presence of fibers increased the first cracking stress, the point at the end of the stress-displacement linearity, also called bend over point (BOP). The improvement, showing in Fig. 2(b) and Table 2, is almost two fold. It is interesting to see that different fiber volume fractions resulted in a similar BOP.

TABLE 2. Summary of bending tests of homogeneous FRCC and FGFRCC

	0%	0.67%	1%	1.33%	2%	FGFRCC
f_{fc} (MPa)	5.72	11.46	10.56	9.870	12.12	11.14
f_{max} (MPa)	5.72	11.83	12.73	14.65	22.94	18.45
d_{max} (mm)	0.18	0.545	1.01	0.97	2.06	1.19
Ductility (MPa-mm)	0.573	5.719	16.64	15.71	46.15	17.45

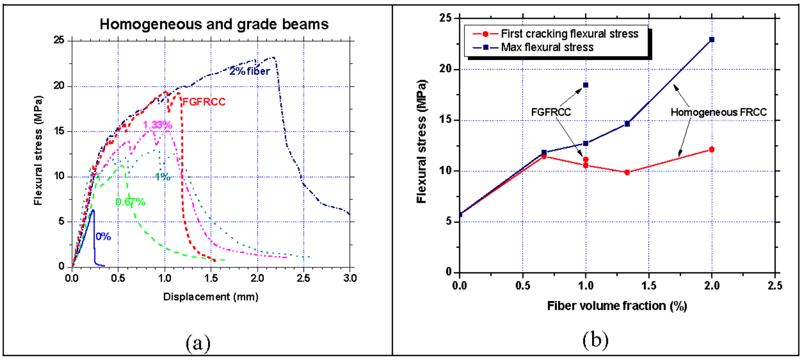

FIGURE. 2 (a) Flexural response of homogenous beams and of FGFRCC; (b) First cracking stress and maximum flexural stress of homogeneous FRCC and FGFRCC

FGFRCC properties

Fig. 2(a) and (b) also show the typical flexural response of the FGFRCC. Compared to homogeneous FRCC, after the BOP, the fast increase of flexural stress with displacement closely resembles that of 2% FRCC. This is because this region of the curve is controlled predominantly by the bottom layer of the FGFRCC, which is the same as 2% FRCC. However, the descending part of the curves drops more sharply than the homogeneous specimens, and is due to the fracture of the upper layers. The softening curves observed in the homogeneous FRCC were not observed for this FGFRCC, which demonstrates that failure of the middle two layers was no later than the bottom layer. Attention therefore will be paid in the future design to adjust the fiber gradation so that the softening behavior is improved, since softening indicates good ductility and is generally desired.

The strength and ductility of the homogeneous 2% FRCC is much superior to FGFRCC. This is apparent since the former has four 2% FRCC "layers" while the latter has only one 2% FRCC layer at the bottom. The FGFRCC has an overall fiber volume fraction of 1%. Compared with homogeneous FRCC, FGFRCC has higher strength and toughness than 1% FRCC (toughness was comparable to 1.33% FRCC). The f_{max} of FGFRCC is about 50% and 30% higher than 1% and 1.33% FRCC, respectively. With 25% less fiber, FGFRCC achieves better mechanical performance than homogeneous 1.33% FRCC. "Better" is interpreted in terms of maximum flexural strength criterion. The FGFRCC beam was able to sustain higher loads than the FRCC beam before failure. A simple gradation allows the fiber to be used more efficiently. This result demonstrates that the idea of FGM for efficient use of fiber in FRCC is promising.

CONCLUSIONS

Processing techniques, extrusion and pressing, were used to produce four-layer FGFRCC. Special issues for manufacturing this new material were presented and discussed, including controlling the processing time through selection of mix proportions, and matching rheological properties between layers. The FGFRCC with 1% overall fiber volume fraction showed higher strength and comparable toughness compared to the homogeneous FRCC with 1.33% fiber volume fraction. This study also indicates the relevance of proper material gradation. The FGFRCC improved properties were obtained when the bottom layer had the highest fiber volume fraction, but not when a reverse gradation profile was used.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support from the Natural Science Foundation under the Partnership for Advancing Technology in Housing program (NSF-PATH). We thank Kuraray Co. Ltd for their free provision of the PVA fibers. The SEM microstructural images were taken in the Center for Microanalysis of Materials, University of Illinois, which is partially supported by the U.S. Department of Energy under grant DEFG02-91-ER45439. We appreciate their invaluable and informative technical support.

REFERENCES

1. H. W. Reinhardt and A. E. Naaman (Ed.), High performance fiber reinforced cement composites: proceedings of the International Workshop "High Performance Fiber Reinforced Cement Composites" held by RILEM and ACI, Stuttgart University and the University of Michigan, and organized by Stuttgart University, Mainz, Germany, June 23-26, 1991, London; New York: E & FN Spon, 1992.
2. A. E. Naaman and H. W. Reinhardt (Ed.), High performance fiber reinforced cement composites 2 (HPFRCC2): Proceedings of the Second International Workshop "High Performance Fiber Reinforced Cement Composites" RILEM, Ann Arbor, USA, June 11-14, 1995, E. & FN Spon, London, 1996.
3. P. N. Balaguru and S. P. Shah, Fiber-reinforced cement composites, McGraw-Hill, New York, 1992.
4. S. Bentur and S. Mindess, Fibre reinforced cementitious composites, Elsevier Applied Science, London, New York, c1990.
5. S. Suresh and A. Mortensen, Fundamentals of functionally graded materials: processing and thermomechanical behavior of graded metals and metal-ceramic composites, London: IOM Communications Ltd, 1998.
6. Y. Shao, S. Marikunte and S. P. Shah, *Concrete International*, **17**, 48-52 (1995).
7. C. Aldea, S. Marikunte, S. P. Shah, *Advanced Cement Based Materials*, **8**, 47-55 (198).
8. H. Stang and V. C. Li, Extrusion of ECC-material, in H.W. Reinhardt, A.E. Naaman (Ed.) Third International Workshop on High Performance Fiber Reinforced Cement Composites (HPFRCC3), Mainz, Germany, May 16-19, 1999, Cachan, France: RILEM Publications, 203-211 (1999).
9. H. Takashima, K. Miyagai, T. Hashida and V. C. Li, *Engineering Fracture Mechanics*, **70**(7-8), 853-870 (2003).
10. S. Peled, S. P. Shah, *Journal of Materials in Civil Engineering*, **15**(2), 192-199 (2003).
11. A. E. Naaman, Strain hardening and deflection hardening fiber reinforced cement composites, in A.E. Naaman, H.W. Reinhardt (Ed.) Fourth International Workshop on High Performance Fiber Reinforced Cement Composites (HPFRCC4), Ann Arbor, USA, June 15-18, 2003, Bagneux, France: RILEM Publications, 95-113 (2003).