Cement & Concrete Composites 30 (2008) 917–928

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Comparative flexural behavior of four fiber reinforced cementitious composites

Dong joo Kim *, Antoine E. Naaman, Sherif El-Tawil

CEE Department, University of Michigan, 2350 Hayward, 2365 G.G. Brown Building, Ann Arbor, MI 48109-2125, United States

ARTICLE INFO

Article history:
Received 7 July 2008
Received in revised form 12 August 2008
Accepted 14 August 2008
Available online 29 August 2008

Keywords:
Deflection-hardening
Load capacity
Energy absorption capacity
Multiple cracking behavior
Fiber type
Fiber volume ratio
Toughness
Equivalent bond strength

ABSTRACT

This research investigates the flexural behavior of fiber reinforced cementitious composites (FRCC) with four different types of fibers and two volume fraction contents (0.4% and 1.2%) within a nominally identical mortar matrix (56 MPa compressive strength). The four fibers are high strength steel twisted (T-), high strength steel hooked (H-), high molecular weight polyethylene spectra (SP-), and PVA-fibers. The tests were carried out according to ASTM standards. The T-fiber specimens showed best performance in almost all aspects of behavior including load carrying capacity, energy absorption capacity and multiple cracking behavior, while the PVA-fiber specimens exhibited comparatively the worst performance in all aspects of response. The only category in which SP-fiber specimens outperformed T-fiber specimens was deflection capacity, where SP-specimens exhibited the highest deflection at maximum load. By comparing the test results to data from an additional test program involving the use of a higher strength mortar (84 MPa) with both H- and T-fibers, it is shown that, again, T-fibers perform significantly better than H-fibers in a higher strength matrix. The test results from both experimental programs were used to critique the new ASTM standard [C 1609/C 1609M-05], and a few suggestions were made for improving the applicability of the standard to deflection-hardening FRCCs.

1. Introduction

The addition of a relatively small quantity of short random fibers to a cementitious matrix is known to improve the mechanical response of the resulting product, commonly known as a fiber reinforced cementitious composite (FRCC). FRCCs have the potential of exhibiting higher strength and ductility in comparison to unreinforced mortar or concrete, which fail in tension immediately after the formation of a single crack. The performance of FRCC can be improved to the point where it exhibits a deflection-hardening response in bending accompanied by multiple cracks after initial cracking. In such a case, FRCC is known as deflection-hardening FRCC, or DHFRCC. The relationship between DHFRCC and strain-hardening FRCC in direct tension was discussed by Naaman [1]. He showed that, in order for the bending response to exhibit deflection-hardening, the average post-cracking strength in tension needs to be only about a third of the cracking strength. Thus a much smaller amount of fibers is required to obtain deflection-hardening response than to obtain strain-hardening behavior. Furthermore, Naaman [1] formulated an equation for the critical volume fraction of fibers to achieve deflection-hardening behavior. Recently, Soranakom and Mobasher [2] also discussed the correlation of tensile and flexural responses of FRCC and provided closed form equations to predict flexural behavior of FRCC based on its uniaxial tension and compression response. They also suggested that the tensile behavior of FRCC can be back-calculated from convenient flexural tests.

The performance of FRCC depends on many factors, such as fiber material properties (e.g., fiber strength, stiffness, and Poisson's ratio), fiber geometry (smooth, end hooked, crimped, twisted), fiber volume content, matrix properties (e.g., matrix strength, stiffness, Poisson's ratio), and interface properties (adhesion, frictional, and mechanical bond). Clearly, for a given matrix, the type and quantity of fibers are key parameters influencing the performance of FRCC and their cost. Everything else being equal, using a low fiber volume fraction, while still attaining strain-hardening or deflection-hardening response, is attractive from the cost point of view.

Although many researchers have conducted bending tests and reported the flexural response of FRCC, most used different sizes of specimen, matrix composition, and fiber and volume content in their experiments. Often, only one fiber type or material was considered and no attempt was made to compare performance with other fibers types or materials. Also, some researchers did not follow standard test procedures, e.g. as specified by ASTM. In addition, most of experimental studies that investigated the effect of fiber types were performed approximately a decade ago. Therefore, the types of fiber investigated in prior research are quite different from the high performance fibers used in this study. This situation, and the need to isolate the effect of fiber type on the flexural performance of FRCC, has motivated the experimental study reported in this paper, which focuses on the flexural performance

* Corresponding author. Tel.: +1 734 936 2405; fax: +1 734 764 4292.
E-mail address: kdjoo@umich.edu (D.j. Kim).

0958-9465/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2008.08.002

of FRCC involving four high performance fibers within a nominally identical mortar matrix (56 MPa compressive strength).

The main objective of this research is to investigate the influence of fiber type and fiber volume content on the bending response of four FRCCs. Testing and analysis of results were carried out according to ASTM standard C 1609/C 1609M-05 [3]. The research is geared towards mixtures showing deflection-hardening behavior with low to moderate fiber contents, here, 0.4% and 1.2% by volume. To gain further insight into the effect of matrix strength, the results of this research are compared to test results from a related program involving the use of a higher strength matrix (84 MPa compressive strength). The test results lead to some suggestions to improve current standard ASTM C 1609.

2. Bending behavior of FRCC beams

Much research on the bending behavior of FRCC has been carried out over the past four decades in US and elsewhere. Soroushian and Bayasi [4] investigated the effect of fiber type on the general performance of fiber reinforced concrete. They used different types of steel fibers, including straight-round, crimped-round, crimped-rectangular, hooked-single, and hooked-collated fibers with 2% fiber volume content. They reported that the overall workability was independent of fiber type except for crimped fiber. They also noted that hooked fibers showed better performance than straight and crimped fibers.

Gopalaratnam et al. [5] pointed out the importance of accurate deflection measurement in estimating toughness and other parameters describing flexural behavior of FRCC. They also noted that the effect of fiber type, fiber volume fraction and specimen size could be discerned from toughness measures. Balaguru et al. [6] investigated the flexural toughness of FRCC with deformed steel fibers using the procedure for deflection measurement suggested by Gopalaratnam et al. [5]. They investigated three types of fibers: hooked-end, corrugated, and end deformed steel fibers. In computing toughness, they used the I5 and I10 indices defined according to the ASTM C 1018 [7] procedure. Their results indicated that the toughness indices did not reflect the variations observed in the load–deflection curves. They also noted that, of the three types of fibers investigated, hooked-end fibers were the most effective in improving toughness.

Banthia and Trottier [8] pointed out several difficulties in both ASTM C 1018 and JSCE SF-4 methods for FRCC toughness characterization and suggested an alternative technique. For the former method (ASTM C 1018), they discussed the difficulty of measuring deflection correctly, and accurately identifying the first cracking point. For the latter (JSCE SF-4), they showed that the flexural toughness (FT) factor depends upon the geometry of the specimen and noted that the end-point used in the computation, at span-over-150, is arbitrary and actually much greater than the deflection at serviceability.

Several points necessary to estimate the performance of deflection-hardening FRCC were discussed by Naaman [1]. In addition to the toughness index for describing the toughness of FRCC, he recommended using the average post-cracking strength or surface energy as additional parameters. He also defined ductility as the ratio of total energy consumed up to a certain point to the elastic energy and mentioned that the scale effect and testing procedure could influence multiple cracking in strain-hardening or deflection-hardening FRCC.

Chandrangsu and Naaman [9] compared the performance of three different fibers, twisted (Torex), spectra, and PVA-fiber, in both tensile and bending response using two different specimen sizes. The length of the fibers was 30 mm for Torex fibers, 38 mm for spectra fibers, and 12 mm for PVA-fiber. The smaller bending specimens had a 75 mm × 12.5 mm thin rectangular section with 225 mm span length, while the larger size bending specimens had a 100 mm × 100 mm square section with 300 mm span length. The twisted (Torex) fibers generated best performance in both tensile and bending test among the three fibers considered. In addition, a strong size effect was noticed especially in the bending test, in terms of strength and deflection. The smaller bending specimens showed 80% higher modulus of rupture, and 500% higher deflection (actual displacement not normalized) at maximum load compared with the larger specimens.

3. Parameters describing flexural behavior of FRCC

The bending behavior of FRCC can generally be classified as either deflection-softening or deflection-hardening, as shown by curves (a) and (b), respectively, in Fig. 1 [10]. FRCC showing deflection-hardening behavior generates a higher load carrying capacity after first cracking compared with normal concrete or deflection-softening FRCC. In this research, the first cracking point is defined as the point where nonlinearity in the load–deflection curve becomes evident. This point is termed limit of proportionality (LOP) according to the previous ASTM standard C 1018-97 [7]. The new ASTM standard C 1609/C 1609M-05 [3] uses the first peak point, defined as a point where the slope is zero, which is inappropriate for use with materials exhibiting deflection-hardening with multiple micro cracks. In other words, it is hard to pinpoint the first peak strength as required by ASTM standard C 1609/C 1609M-05 [3] if the bending behavior of the material shows stable deflection-hardening as shown in the upper curves of Fig. 1. Therefore, LOP is used in this work instead of first peak strength. The load value at LOP is termed P_{LOP} and the corresponding deflection value is δ_{LOP} in Fig. 1. The stress obtained when the first cracking load is inserted into Eq. (1) is defined as the first-crack strength, f_{LOP}. The energy equivalent to the area under the load–deflection curve up to LOP is defined as first-crack toughness $\mathrm{Tough}_{\mathrm{LOP}}$. This definition is consistent with the ASTM standard definition for toughness at various points of the load–deflection curve, as explained farther below. From ASTM C 1609/C 1609M-05 [3], the stress at LOP is obtained from

$$f_{\mathrm{LOP}} = P_{\mathrm{LOP}} \cdot \frac{L}{bh^2}, \tag{1}$$

where L is the span length, b is the width of specimen, and h is the height of specimen.

The modulus of rupture (MOR) is defined as the point where softening starts to occur after point LOP as shown in Fig. 1. Besides the LOP and MOR points, six other points are defined as follows:

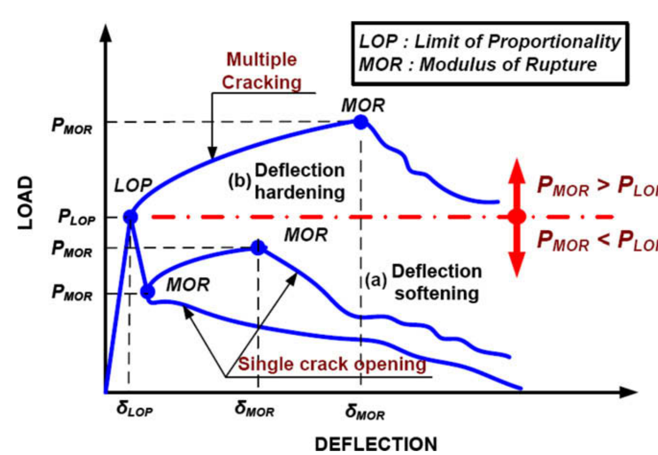

Fig. 1. Typical load–deflection response curves of FRCC.