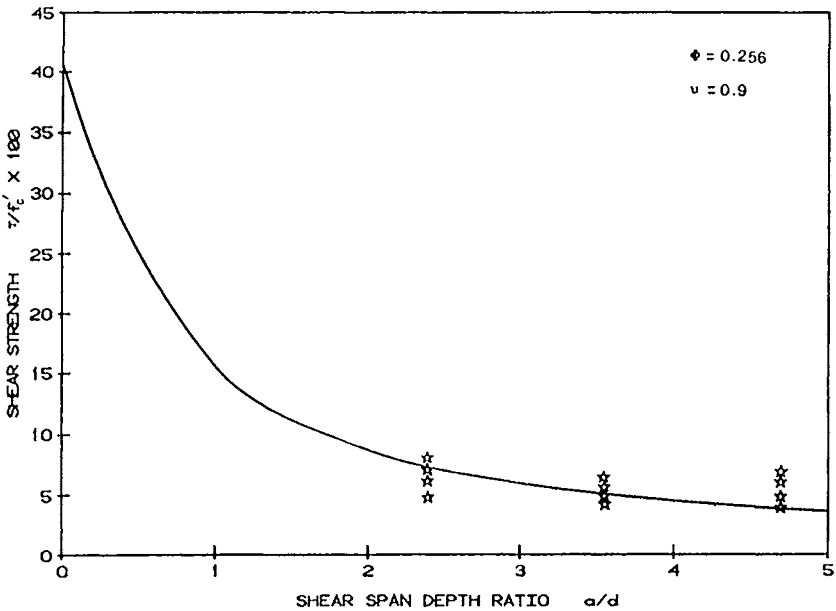

Fig. 13—Shear strength data Youssef plotted on Nielsen and Braestrup solution (Youssef 1989)

SP 142-9

Influence of Test Control on the Load-Deflection Behavior of FRC

by A. Khajuria, Z. El-Shakra, S. Gopalaratnam, and P. Balaguru

Synopsis: Load-deflection responses obtained using deflection control and crack-mouth opening displacement (CMOD) control are compared. CMOD control provides a more stable response in the immediate post-peak regime of the load-deflection response than deflection control. The differences in the responses recorded using these two types of test control are more pronounced for the more brittle mixes. Results reported and discussed in the paper were obtained using third-point loading in flexure. Deflection controlled tests were performed using manual control on a stiff million pound capacity machine. This is similar to the manner in which most commercial laboratories perform deflection controlled tests on concrete specimens. CMOD controlled tests were conducted using a servo-controlled machine. Normal and light-weight aggregate concrete mixes were evaluated with polymeric fiber loadings of 1, 2, 3 and 4 lb/yd^3 [0.6, 1.2, 1.8, 2.4 kg/m^3]. Overall load-deflection reponse and material toughness values are compared and discussed. Beams reinforced with low volume contents of polymeric fibers typically exhibit a sharp drop in load carrying capacity after first-crack. The shape of the load-deflection response in the initial portion of the softening regime is important for toughness computations, particularly for the smaller ASTM indices such as I_5 and I_{10}. Since the type of test control and the level of post-peak stability provided by the test set-up influence the shape of the load-deflection response in this regime of interest, there are questions regarding the objectivity of toughness indices computed at small limiting deflections.

Keywords: Beams (supports); concretes; crack-mouth opening displacement; deflection; fiber reinforced concretes; fibers; flexure; lightweight concretes; strength; tests; toughness

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INTRODUCTION

The ability to absorb relatively large amounts of energy before complete failure, superior resistance to crack propagation, significant post-cracking residual strength, and the ability to withstand large deformations are characteristics that distinguish fiber reinforced concrete from plain concrete. In recent years, substantial amount of research has been conducted in the development of standardized test procedures to evaluate the improvement in the mechanical performance resulting from the addition of fibers to plain concrete [1-4]. One of the important properties of the resulting composite, generically termed as fiber reinforced concrete (FRC), is its energy absorption capacity or toughness. In general, the area under the static load-deformation curve is used as a measure of toughness. Flexural toughness is often measured and reported although other test configurations have also been used [4,5].

Toughness can be defined in terms of the energy absorbed by a specimen and is typically computed using the area under the load-deflection (P-δ) curve. The P-δ curve is influenced by; (a) the specimen size (depth, span, and width, with depth and span significantly influencing the response recorded); (b) the loading configuration (midpoint versus third-point); (c) the type of control (load, load-point or midpoint deflection, crosshead displacement, and CMOD; (d) the machine stiffness; and (e) the loading rate (static, dynamic, and impact). Also governing the levels of these influences are composition parameters such as the type of fiber (steel-smooth, indented, hooked, and polypropylene-single filament, fibrillated, etc.), volume content and aspect ratio of the fibrous reinforcement, the matrix quality, and the fiber-matrix interface characteristics. To minimize some of these effects, normalization of the energy absorption capacity has been suggested resulting in a nondimensional toughness index [1], or indices that can be related to different levels of serviceability and/or performance [2,3].

Previous investigations have demonstrated the influence of specimen size, loading configuration (notched versus unnotched third-point flexural specimens), and rate of loading on the load-deflection characteristics of FRC [6-8]. Results obtained for the load-deflection response using deflection and CMOD control are compared and discussed in this paper.

EXPERIMENTAL PROGRAM

The primary variables for this investigation are matrix type and fiber content. The two types of matrix were made using normal weight and light-weight aggregates. The fiber content ranged from 1 lb/yd^3 to 4 lb/yd^3 (0.6 kg/m^3 to 2.4 kg/m^3). Seven mixtures were cast for this investigation (four mixtures of normal weight concrete and three mixtures of lightweight concrete). Three specimens each were tested under deflection control and under CMOD control, for each of the seven mixtures. Specimen size used was 4x4x14 in. tested over a 12 in. outer span (102x102x356 mm, 305 mm). Single filament polymeric fibers nominally 23 microns in diameter and 0.75 in. long (19 mm, Nylon 6) were used in this investigation. The low fiber content is typical of commercially used polymeric fiber reinforced concrete mixtures in applications such as slabs. Such mixtures are quite brittle and as a result are relatively more sensitive to the type of test control used. Hence, the mixtures discussed above were studied in the present investigation.

MATERIALS, MIXTURE PROPORTIONS AND SPECIMEN PREPARATION

Materials

The constituent materials used consisted of ASTM Type I cement, natural sand, crushed stone (normal weight), or expanded shale (lightweight), water, water-reducing and air-entraining admixtures, and polymeric fibers. Sieve analysis was performed on the fine aggregate, and normal and lightweight coarse aggregates in accordance with the ASTM specification. Aggregate gradation met ASTM C-33 requirements. The Nylon 6 single filament polymeric fibers were 23 microns (nominal) in diameter and 0.75 in. (19 mm) long. The mechanical and physical properties of the fibers are presented in Table 1.

Mixture Proportions

Concrete was proportioned to obtain approximate 28-day compressive strengths of 3,000 psi (21 MPa) for normal and lightweight mixtures. The matrix composition for both mixtures are presented in Table 2.

The fiber contents used in this investigation were 1, 2, 3, and 4 lb/yd^3 (0.6, 1.2, 1.8, and 2.4 kg/m^3) for the normal weight concrete and 1, 2, 3 lb/yd^3 (0.6, 1.2, and 1.8 kg/m^3) for the lightweight concrete. As mentioned earlier, the fiber contents were intentionally chosen to be low. This ensured that the specimens were brittle. In addition these fiber contents reflect the fiber volume fractions used in most practical application such as slab on grade.

Specimen Preparation

All of the specimens were fabricated at Rutgers University. The coarse and fine aggregates were first thoroughly mixed with 2/3 of the water required, for one minute, in a three cubic foot (0.9 m^3) conventional laboratory mixer. ASTM Type I cement, water-reducing and air-entraining admixtures, and the remainder of the water were added later. The ingredients were mixed for another three minutes. Following this, the fibers were hand dispersed into the mixer while the mixer was operating at the normal mixing speed. Mixing was continued for another ten minutes. The lightweight aggregates were soaked in water for at least twenty-four hours prior to mixing. They were added to the mixture in a saturated surface dry condition. The beams were cast using 4x4x14 in. (102x102x356 mm) plexiglas molds. The molds were vibrated to reduce air voids using a conventional laboratory table vibrator. The specimens were then kept in the molds and were covered with polyethylene sheets for approximately twenty-four hours to prevent loss of moisture. The specimens were later stripped out of the molds and were placed in a humidity room (98% relative humidity) for 27 days. Companion 6x12 in. (152x305 mm) cylinders were tested to confirm average 28-day compressive strengths of 3,000 psi (21 MPa).

DETAILS OF THE TEST SET-UP AND TESTING PROGRAM

Normal, and lightweight concrete, flexural beams were tested in a third-point loading configuration using both deflection and crack mouth opening displacement (CMOD) for controlling the tests. The beams tested under deflection control were unnotched. The beams tested under CMOD control were notched, with a notch-depth to beam-depth ratio of 1:8.

The tests conducted using deflection control were carried out at Rutgers University using a stiff million pound capacity machine. A dial gage with a resolution of 0.0001 in. (0.0025 mm) was used to measure net-deflection of the beam at midspan. The rate of deflection was manually maintained in the range of 0.0025 to 0.003 in/min. (0.063 to 0.075 mm/min). Such manual control is typically used in most commercial laboratories and is allowed in the test procedure described by ASTM C 1018-89 (Note 6, Section 9.3). The dial gage was mounted between the beam and the supporting frame, Fig. 1. Deflections were recorded at regular load increments until the first-crack. After first-crack, loads were recorded for chosen midspan deflections.

A special deflection measuring system was used in order to exclude extraneous deformations at the beam supports, Fig. 1 [9]. Net-deflection at beam midspan was measured using a dial gage mounted between the tension face of the beam and the bottom plate of the supporting frame and attached to the middepth of the specimen (to minimize the effect of twisting). The frame was mounted on the specimen using four screws, two on each side, located exactly over the supports. A schematic of the flexural test set-up used at Rutgers University is shown in Fig. 1.

The tests conducted using CMOD control were carried out at the University of Missouri-Columbia. A servo-controlled MTS testing machine and associated electronics permitted closed-loop flexural testing of notched beams under CMOD control. A standard full-bridge strain-gage-based clip-on gage was used to measure crack-mouth opening displacement. The signal from the clip-on gage was used to control the test. The compressed gage length of the clip-on gage was 0.2 in. (5 mm). Clip-on gage had a maximum displacement range of +0.1 in. (+3 mm). The clip-on gage was mounted between two aluminum lips, 0.2 in. (5 mm) apart, glued across the notch to hold the clip-on gage in place. Three specimens were tested for each series using beam midpoint net-deflection rate of approximately 0.004 in/min. (6 mm/s). The tests were stopped at a crack-mouth opening displacement of 0.08 in. (2 mm).

Net-deflection at the beam midspan was measured in relation to the beam supports using a simple yoke design [6]. The yoke consists of a frame made from aluminum. Two rigid rectangular aluminum bars and a raised aluminum channel section permit the mounting of the displacement transducer (LVDT or other similar devices) at the midpoint (span-wise as well as width-wise) on the compression face of the beam. This mounting scheme also provides for easy zeroing of the displacement transducer. The frame is supported on the compression face of the beam using two cylindrical pins located directly over the beam supports. Since the yoke rests on the beam, it poses no practical difficulty in setting up the net-deflection measurement device. The self weight of the yoke is adequate for lending stability to the set-up and providing necessary precompression for the spring-loaded LVDT or other similar displacement measuring devices. A schematic of the flexural test set-up used at the University of Missouri-Columbia is shown in Fig. 2.

TEST RESULTS AND DISCUSSIONS

Typical load-deflection response obtained using deflection control and CMOD control are plotted in Fig. 3. The smaller load-carrying capacity of the beam tested under CMOD control is due primarily to the smaller net-depth of the specimens tested using CMOD control (3.5 in. versus 4 in. depth for the beams tested using deflection control - 89 mm and 102 mm respectively). However, when the stress levels are compared based on elastic behavior assuming notch insensitive behavior, specimens tested using CMOD control exhibited slightly smaller strengths than those tested under deflection control

It can be observed in Fig. 3 that the precrack load-deflection response is approximately the same for deflection and CMOD control. At the initiation of the crack (at peak-load), the load capacity of the beam reduces substantially because of low fiber contents. In the deflection control test, the midspan deflection rapidly increases until the load drops back to the reserve capacity of the beam. Since the load-deflection response between the peak-load and the reserve capacity could not be measured, these two points are connected by dotted lines. The actual response lies between the shown dotted line and a vertical drop from the peak-load to the reserve capacity of the beam. The CMOD control provides a smooth transition from the peak to post-peak reserve capacity. Since the rate of crack mouth opening displacement (CMOD) is controlled, the machine does not allow a rapid increase in CMOD and hence, the corresponding displacement. At large displacements, both systems provide a continuous line.

Fig. 4 shows the influence of the mixture composition and type of test on the ultimate strength of the specimen. Each point on this and subsequent figures (Figs. 5-6) represents the average result from three tests. The lines plotted in Figs. 4 to 6 represent the averages and show the general trends of the variations. As mentioned earlier, strengths obtained using notched specimens under CMOD control are somewhat lower than those obtained using unnotched specimens under displacement control. Further testing of notched specimens under deflection control in a continuing study, is expected to provide information that will help isolate the influences of test control and probable notch sensitivity of brittle FRC mixtures. FRC specimens made with lightweight matrix were weaker than similarly reinforced specimens made with normal weight matrix in all instances. Although, in the present investigation, only three specimens were tested for each mixture in each test configuration, observations of the scatter in the test results for the CMOD controlled and deflection controlled tests follow trends reported by Gopalaratnam et al [8].

Fig. 5 shows plots of ASTM indices (a) I_5 and (b) I_{100} (computed at a limiting deflection of $50.5\delta_f$, where δ_f is the deflection at first-crack) versus mixture composition parameters. As observed in earlier studies [8,9] toughnesses computed at small limiting deflections, are insensitive to the fiber content (Fig. 5a). In addition it can be seen that I_5 for FRC composites made with normal and lightweight matrices are comparable in all instances. Even at very large limiting deflections such as the one used to compute I_{100}, the ASTM type index can only marginally distinguish between FRC composites made with normal and lightweight matrices. Influence of the type of test control on the ASTM toughness index on the other hand is more readily apparent even at the small limiting deflections (Fig. 5a). This difference is more pronounced for toughness computed at the larger limiting deflections (Fig. 5b).

Energy absorbed by the specimen per unit net cross-sectional area, computed up to a prescribed limiting deflection or until failure (using application specific criteria to define failure) can be used as an alternate method to characterize toughness of

FRC composites [10]. This measure can, with some analytical effort, be related to the more fundamental definitions of fracture energy used in the fracture of concrete. Fig. 6 presents energy absorbed by the different composites using a limiting deflection of 0.06 in. (1.5 mm) as an example. This measure, like the ASTM toughness indices, is sensitive to the type of test control. In addition, this measure is better in distinguishing differences in energy absorption capacity of specimens made with different fiber contents, and different matrix types.

CONCLUSIONS

- Post-peak response of the flexural test depends upon the type of test control. This is particularly true for the more brittle FRC compositions.

- ASTM indices computed at small limiting deflections are insensitive to the fiber or matrix parameters. Indices computed at large limiting deflections are, however, more sensitive to these parameters.

- Energy absorbed per unit cross-sectional area appears to be reasonably sensitive to the fiber and matrix parameters.

- The type of test control significantly influences the load-deflection response recorded for FRC composites. This issue needs to be addressed if we need to obtain reproducible toughness measures on machines with vastly different stiffness characteristics and mechanisms of control.

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