Influence of Loading Type, Specimen Size, and Fiber Content on Flexural Toughness of Fiber-Reinforced Concrete

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Results of an experimental investigation to determine the influence of specimen size, fiber type, and fiber content on the flexural behavior of steel fiber-reinforced concrete are presented. Two fiber types and four mixes are investigated. With four series in each mix, there are sixteen series. The effect of the two cross-sectional sizes of 150 × 150 mm and 100 × 100 mm (6 in. × 6 in. and 4 in. × 4 in.) on flexural strength is also studied. Hardened concrete is tested for pulse velocity and flexure. For each series, two specimens are tested for monotonic, and one specimen for cyclic, loading. Loading and unloading rates were the same for both monotonic and cyclic loading. In addition to the load deflection measurements, the crack mouth opening displacements versus load are recorded in the case of notched specimens. Load deformation behavior, post crack load drop phenomenon, and toughness for two types of fibers are evaluated and compared. There is evidence of scatter of results related to the difficulty in achieving a uniform distribution of randomly oriented fibers. The flexural toughness factor, recommended by the Japan Society of Civil Engineers is calculated. A comparison of load deflection curves under monotonic and cyclic loading indicates that the fibers primarily influence the envelope curve and that cyclic loading does not have any appreciable influence on the energy absorption characteristics. The load versus crack mouth opening displacement behavior is similar to the load deflection curve for notched specimens.

Research (*1–16*) has established that the addition of fibers considerably improves the static flexural strength, impact strength, direct tensile strength, fatigue strength, ductility, and flexural toughness of concrete. However, the degree of improvement in such parameters depends on many factors, including size, type, and aspect ratio of fibers. Because fiber-reinforced concrete (FRC), in many applications, is subjected primarily to bending instead of axial loading, performance in flexure is most important. However, lack of sufficient information on fracture toughness and flexural behavior of concretes subjected to static and cyclic loadings with different types and quantities of fibers underscores the need for more research. Such information is essential to design engineers who use FRC in airfield and highway pavements, industrial floors, tunnel linings, and earthquake- and impact-resisting structures.

RESEARCH SIGNIFICANCE

Toughness, a measure of the energy absorption capacity, is used to characterize the FRC's ability to resist fracture when subjected to static, dynamic, and impact loads. Energy absorbed by a specimen is computed using the area under the complete load deflection curve. However, the load deflection curve is observed to be dependent upon the specimen size, the loading configuration, the type of control, and the loading type. The load deflection curve also can be used for determining the modulus of elasticity, first crack strength, and the flexural strength of the composite. Governing the level of these influences are composition parameters, such as the type of fiber, volume content, and aspect ratio of fibrous reinforcement. Currently available test standards for the evaluation of fracture toughness indices, ASTM C1018, Japanese Concrete Institute (JCI) SF4 (17), Japan Society of Civil Engineers (JSCE) SF5 (18), and American Concrete Institute (ACI) 544 (*19,20*), recognize these influences. The research reported in this paper deals with the systematic study of the effects of commonly used fibers on the flexural properties of composites, the volume content, aspect ratio, specimen size, loading system, and test configuration (for notched and unnotched specimens).

EXPERIMENTAL PROGRAM

Two fiber types were selected for the study, the 50.8-mm (2-in.) long hooked-end steel and 50.8-mm (2-in.) long crimped steel fibers. Two volume percentages, 0.5 and 1.0 percent, were investigated for both types of fibers. Two specimen configurations were selected, notched and unnotched. Table 1 provides the mix designations and fresh concrete properties used for different specimens. Four specimens for each series were made. Specimens were cast as large slabs and sawed to size (for flexure tests) to minimize the edge effect. In the case of notched specimens, notch depths for large and small specimens were approximately 18.7 mm (0.75 in.) and 12.5 mm (0.50 in.), respectively. After casting, the slabs were covered with plastic sheets for 24 hr at room temperature. Specimens were then cured in a curing room before being sawed to size and wrapped. Each specimen was wrapped individually in a plastic sheet and was labeled. The specimens remained covered until 1 hr before testing. All mixes were designed for an approximate compressive strength of 34.45 MPa (5000 psi) to 41.34 MPa (6000 psi). All beams were tested for pulse velocity (ASTM C597) at the age of 2 to 3 months.

Beams were tested at the age of 2 to 3 months, as per ASTM C1018, for static flexural strength under third-point loading. For static tests, a dial gauge with an accuracy of 0.0025 mm (0.0001 in.) was used to measure the midspan deflection. The gauge was located at the mid-width point of the specimen to minimize the effect of twisting on the deflection measurements. The rate of loading was maintained in the range .05 mm/min to .1 mm/min (0.002 in./min to 0.004 in./min), as per ASTM C1018. The loads were recorded for every increment of .005-mm (0.0002-in.) deflection until the first crack appeared, and at different intervals thereafter. Specimens

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TABLE 1 Mix Designations and Fresh Concrete Properties

Mix #	Unnotched/ Notched	Specimen Size (mm)	Fiber Type	Fiber Content	Slump (mm)	Unit Weight (kg/m³)	Air Content (%)
A1LU	Unnotched	150x150x525	Hooked-end	0.5	14	2198.7	7.0
A2LU	Unnotched	150x150x525	Hooked-end	1.0	9	2205.1	7.0
A1SU	Unnotched	100x100x350	Hooked-end	0.5	14	2198.7	7.0
A2SU	Unnotched	100x100x350	Hooked-end	1.0	9	2205.1	7.0
B1LU	Unnotched	150x150x525	Crimped	0.5	9	2243.5	5.0
B2LU	Unnotched	150x150x525	Crimped	1.0	8	2240.3	6.5
B1SU	Unnotched	100x100x350	Crimped	0.5	9	2243.5	5.0
B2SU	Unnotched	100x100x350	Crimped	1.0	8	2240.3	6.5
A1LN	Notched	150x150x525	Hooked-end	0.5	14	2198.7	7.0
A2LN	Notched	150x150x525	Hooked-end	1.0	9	2205.7	7.0
A1SN	Notched	100x100x350	Hooked-end	0.5	14	2198.7	7.0
A2SN	Notched	100x100x350	Hooked-end	1.0	9	2205.7	7.0
B1LN	Notched	150x150x525	Crimped	0.5	9	2243.5	5.0
B2LN	Notched	150x150x525	Crimped	1.0	8	2240.3	6.5
B1SN	Notched	100x100x350	Crimped	0.5	9	2243.5	5.0
B2SN	Notched	100x100x350	Crimped	1.0	8	2240.3	6.5

were loaded up to a minimum midpoint deflection of 1/150 of the span, which allowed for computation of ACI, ASTM, and JCI and JSCE fracture toughness indices. In addition to load deflection measurements, the load versus crack-mouth opening displacement readings were measured for notched specimens (ASTM E399). Notched and unnotched specimens were also tested under cyclic loading. Loading and unloading was done at 2, 3, 5.5 and 15.5 times the first crack deflection, using the same unloading/reloading rate as was used for monotonic loading.

TEST RESULTS AND DISCUSSION

Static Flexural Strength

Results of a comparison of the static flexural strengths for unnotched and notched beams are shown in Figure 1. There was a significant fracture strength increase as the fiber content increased from 0.5 to 1.0 percent, in the case of the hooked end fibers, and a much lower increase for the concrete with crimped fibers. The

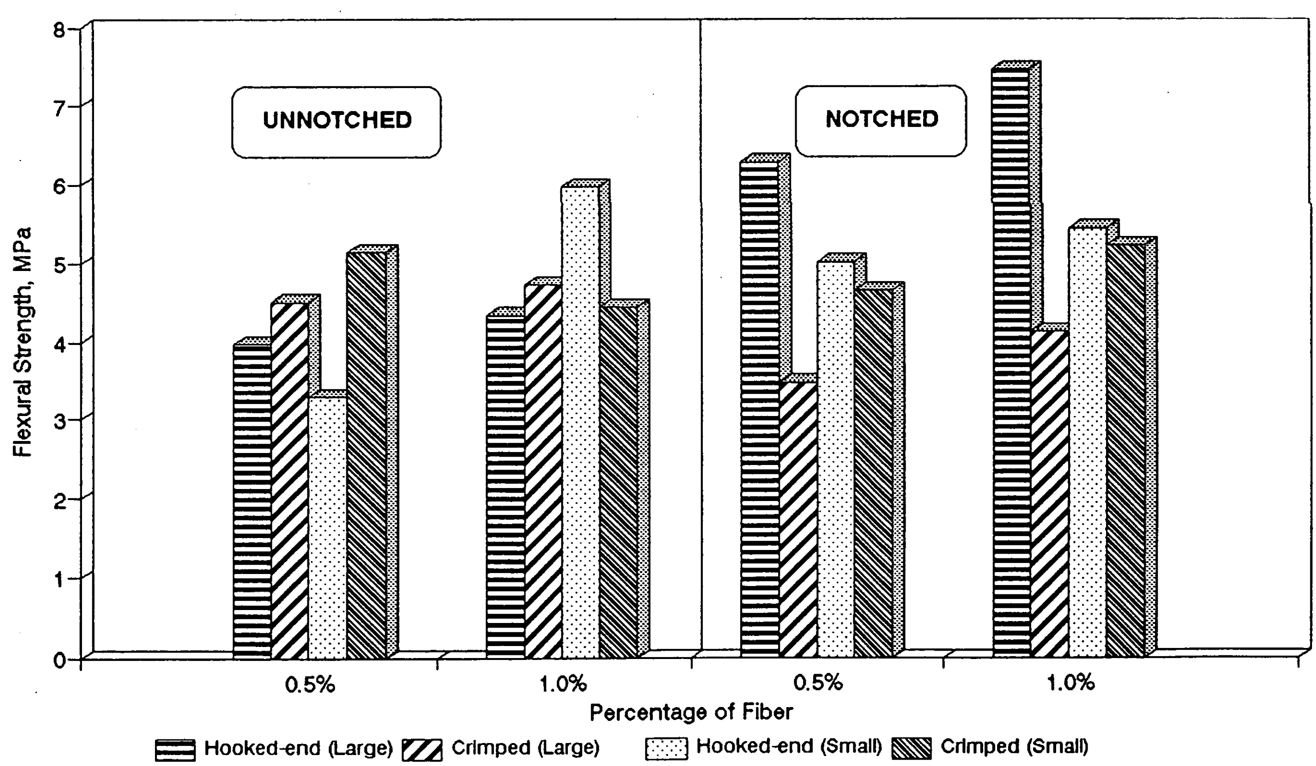

FIGURE 1 Flexural strength versus percentage of fiber.

percentage increases were 74 and 38 percent, respectively, for small and large specimens for hooked fibers. There was no particular trend observed with respect to the size of the beams for both types of fibers, because the distribution of the fibers in the critical tension zone of the beams varied greatly. Flexural strength was more significantly dependent on the actual number of fibers found in the tension block than on the size of the cross section. However, when fiber distribution was fairly uniform, the larger sized specimens had lower flexural strengths.

Flexural Load Deflection Curves

Total area under the load deflection curve is indicative of the energy absorbed by the beam. Load deflection curves were drawn using data from the static flexure test. Load deflection curves for both types of fibers were compared by volume, for 0.5 and 1.0 percent of fiber contents, for both specimen sizes (*21*). Comparison of the static load-deflection curves for FRC with 0.5 and 1.0 percent fiber volumes indicated that the initial elastic part of the curves did not change appreciably. However, the post-crack plastic behavior improved significantly with an increase in fiber content from 0.5 to 1.0 percent. Ultimate loads also increased with an increase in fiber content. An increase in the fracture energy resulted from a greater number of fibers bridging the cracks in FRC with higher fiber content. However, the increase in fracture energy depended greatly on the type of fiber, particularly on the bond and anchorage developed by the geometry of the fiber. Hooked-end fibers had better anchorage and bond than the crimped fibers. Hence, the ultimate loads and the total fracture energy were considerably higher for FRC with hooked-end fibers.

Post-Crack Load Drop Phenomenon

Post-crack load drop is defined as the difference between maximum load and load recorded at a deflection equal to three times the deflection measured at first crack (*2*). Post-crack load drop was less with an increase in fiber content. Typical load drops expressed as a percentage of maximum loads are 20, 10, and 18 and 15 percent for small specimens with 0.5 and 1.0 percent crimped and hooked-end fibers, respectively. Similarly, the load drops were 15, 9, and 21 percent and 3 percent for large specimens with 0.5 and 1.0 percent hooked-end and crimped fibers.

Fracture Toughness and Toughness Indexes

One major objective for adding fibers to concrete is to increase fracture toughness. Various fiber efficiencies can be evaluated by comparing their ability to increase the fracture toughness of concretes. Fracture toughness is a measure of the energy absorption capacity to resist failure when subjected to a flexural load. Tests for the measurement of fracture toughness and toughness indices are recommended by ASTM, JCI (*17*), and ACI (*19,20*). The tests are included in the specifications for FRC to ensure a minimum performance standard when used in construction.

Toughness index, as proposed by ASTM C1018, is a dimensionless parameter that defines or fingerprints the shape of the load-deflection curve. Indexes have been defined on the basis of three service loads, identified as multiples of the first-crack deflection. The index is computed by dividing the total area under the load-deflection curve up to the given service level deflection, by the area under the same curve up to the first-crack deflection. Toughness index I_5 is calculated for a defection of three times the first crack deflection. Likewise I_{10} and I_{30} are the indices up to 5.5 and 15.5 times the first-crack deflection, respectively. First-crack toughness is expressed as the energy absorbed by the standard beam, and it is given by the area of the load-deflection curve up to the first-crack load. Calculated toughness indexes I_5, I_{10}, and I_{30} and first-crack toughness values are presented in Table 2. Results of a comparison of the first-crack toughness values for unnotched and notched beams are provided in Figure 2. Results of a comparison of the toughness indexes I_5, I_{10}, and I_{30} are presented in Figure 3 for unnotched and in Figure 4 for notched beams.

Compared with plain concrete, for which the toughness index is one, FRC had significantly greater toughness, and slightly higher first-crack strength. The increase depended on the type and quantity of fibers added. Toughness increased with the number of fibers, both hooked-end and crimped. Hooked-end fiber–reinforced concrete had higher toughness indexes when it was compared to con-

TABLE 2 Fracture Toughness (ASTM C1018 and JCI SF4)

Mix #	Flexural Strength, MPa	First Crack Toughness, MPa	ASTM C1018					JCI SF4 Fe MPa
			I5	I10	I30	I10/I5	I30/I10	
A1LU	3.97	0.59	6.18	11.87	33.21	1.91	2.85	3.32
A2LU	4.34	1.00	4.48	8.96	27.06	1.74	3.01	3.11
A1SU	3.29	0.28	4.18	8.82	24.89	2.09	2.83	2.69
A2SU	5.96	0.28	5.07	10.51	33.75	2.06	3.24	5.51
B1LU	4.50	1.57	4.33	7.84	20.54	1.81	2.61	1.97
B2LU	4.72	0.71	5.12	10.39	30.79	2.01	2.96	3.05
B1SU	5.13	0.28	4.78	10.00	24.14	2.10	2.41	2.42
B2SU	4.43	0.23	4.80	9.61	26.95	2.00	2.79	3.10
A1LN	6.29	0.85	5.06	10.62	33.19	2.09	3.12	3.76
A2LN	4.47	0.77	5.58	11.08	34.99	2.07	3.00	3.43
A1SN	5.02	0.16	5.76	12.29	39.09	2.13	3.17	3.22
A2SN	5.44	0.20	4.65	9.19	30.02	1.97	3.27	2.57
B1LN	3.48	0.41	4.18	7.72	20.93	1.84	2.69	1.67
B2LN	4.12	0.63	4.61	8.86	30.18	1.95	3.38	2.32
B1SN	4.66	0.15	4.68	9.36	28.22	1.98	2.95	2.64
B2SN	5.22	0.20	4.58	9.40	28.74	2.04	3.05	3.02

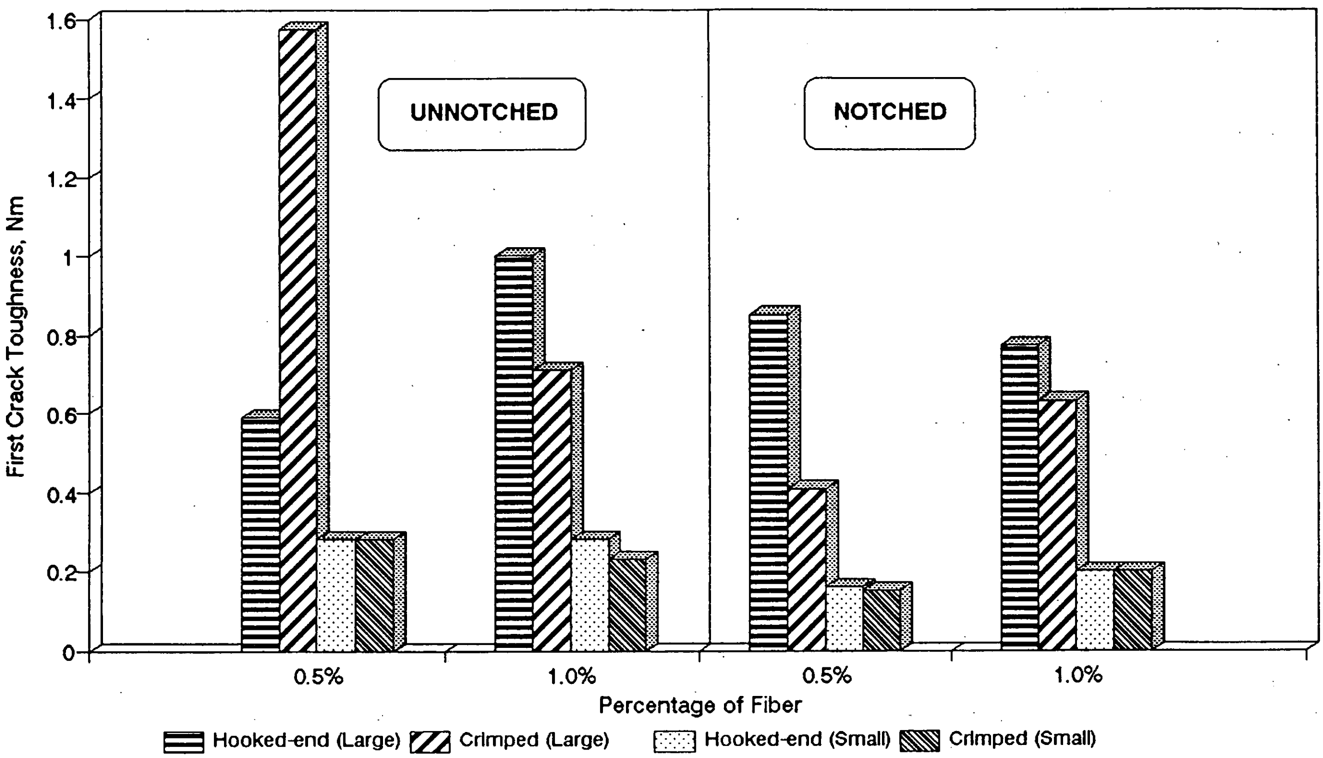

FIGURE 2 **First-crack toughness versus percentage of fiber.**

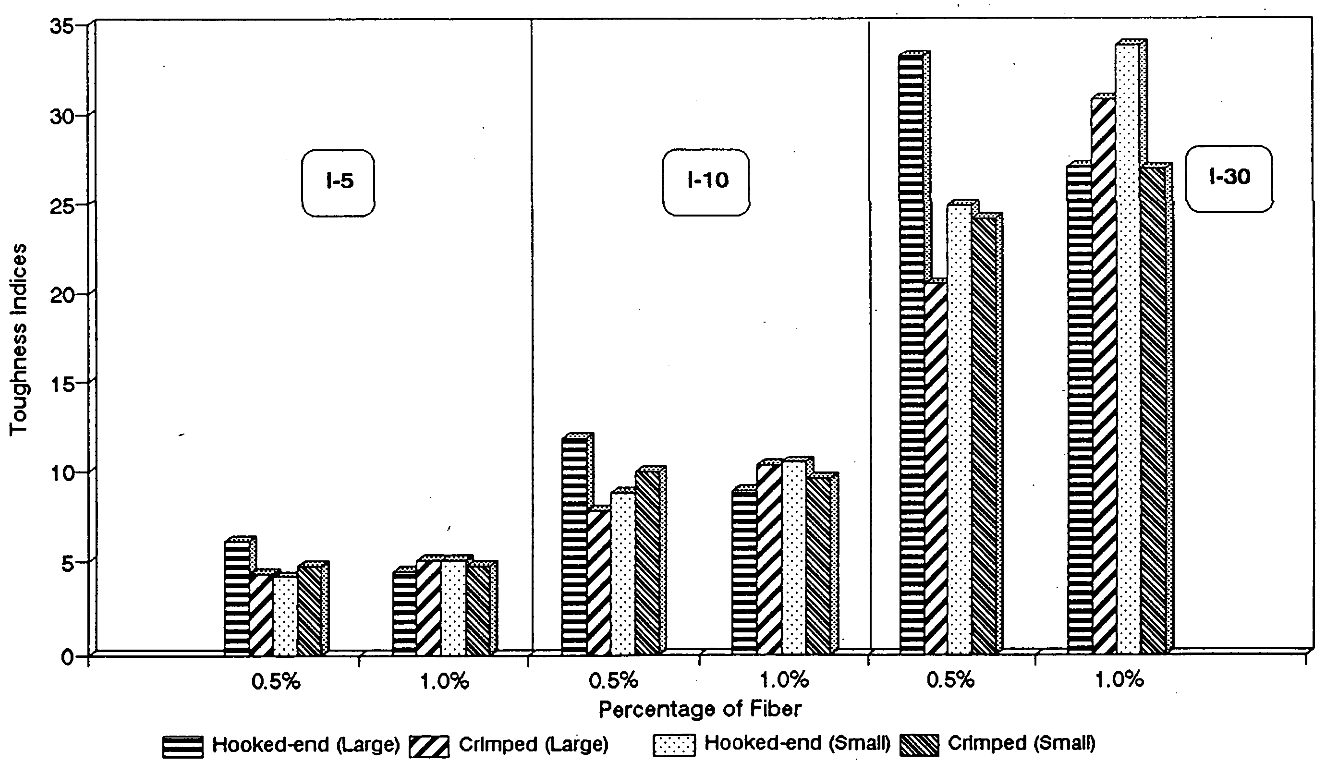

FIGURE 3 **Toughness indexes versus percentage of fiber for unnotched specimens.**

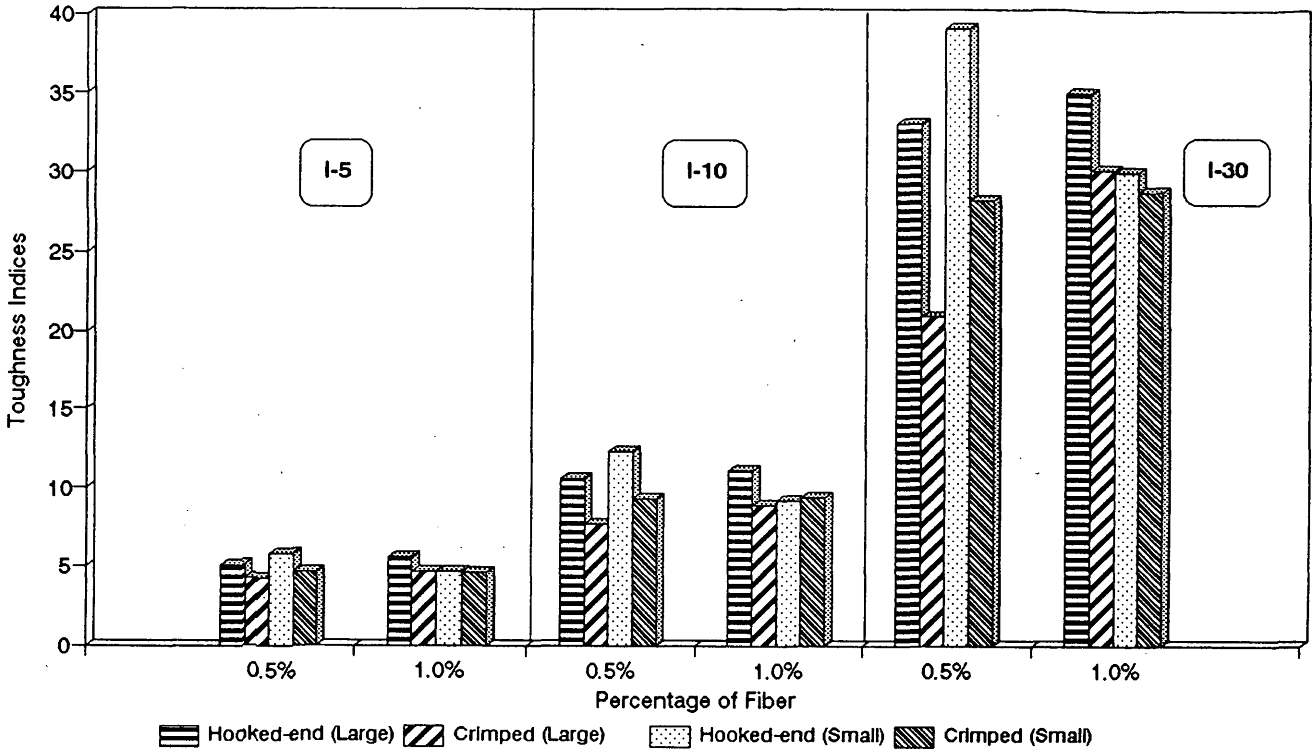

FIGURE 4 Toughness indexes versus percentage of fiber for notched specimens.

crete with an equal quantity of crimped fibers. Better anchorage and bond provided by the hooked-end fibers contributed to the increase in toughness. The influence of the size of the specimens was not clearly indicated because of the inevitable variability in the fiber distribution.

The ratios, I_{10}/I_5 and I_{30}/I_{10} were calculated and are presented in Table 2. The ratios, good indicators of post-crack plastic behavior of the specimens, have values equal to 2 and 3 for I_{10}/I_5 and I_{30}/I_{10}, respectively, and show perfect plastic behavior. Hooked-end fiber reinforced concrete demonstrated almost perfect plastic behavior after the first crack and up to 15.5 times the first crack deflection, because the ratios I_{10}/I_5 and I_{30}/I_{10} are close to two and three.

FRC with crimped fibers showed a decline in the load carrying capacity after a deflection of 5.5 times the first crack deflection. The I_{30}/I_{10} were less than three. The difference in behavior may be attributed to the fiber efficiency.

The most important variable governing the toughness index of steel fiber–reinforced concrete SFRC is the fiber efficiency. Other factors that influence the toughness index are the position of crack, fiber content, and distribution of the fibers. Fiber efficiency is controlled by the resistance of fibers to pull out from the matrix that is developed as a result of bond strength at the fiber-matrix interface. Because the pull out resistance increases with increased fiber length, the longer the fiber the more it improves the properties of composites. Also, because the pull out resistance is proportional to interfacial surface area, nonround fiber cross sections and small diameter round fibers offer more pull out resistance per unit volume than do larger diameter round fibers, because they have more surface area per unit volume.

Hence, a high ratio of length to diameter is associated with fiber efficiency. On that basis, it would appear that fibers should have an aspect ratio high enough to ensure that their tensile strength is approached as a composite fails. Unfortunately, that is not practical. Many investigations indicate that use of fibers with an aspect ratio higher than 100 causes inadequate workability, FRC with nonuniform distribution of fiber, or both (*9*).

In this investigation, the aspect ratio used was 100, and 40 to 65 for type A and B fibers, respectively. Failure of the composites usually was governed by the fiber pull out. The advantage of the pull out type of failure is that it is gradual and ductile compared with a more rapid and possibly catastrophic failure, which can occur if fibers are brittle and break under tension, with little or no elongation. Fiber pull out or fiber fracture depends on the yield strength of the fibers, and the bond and the anchorage between the matrix and the fiber.

Flexural Toughness Factor

The JCI (*17*) and JSCE (*18*) methods for calculating fracture toughness are identical. Toughness is defined in absolute terms as the energy required to deflect the FRC beam at a midspan of 1/150 of the span, δtb. The flexural toughness factor Fe, which is taken as the average flexural strength, is given by the following equation:

$$Fe = Tb \times l/\delta tb \times b \times h^2$$

where

Fe = flexural toughness factor,
Tb = flexural toughness,
δtb = deflection of 1/150 of the span,
l = span,
b = width of failed cross section, and
h = height of failed cross section.

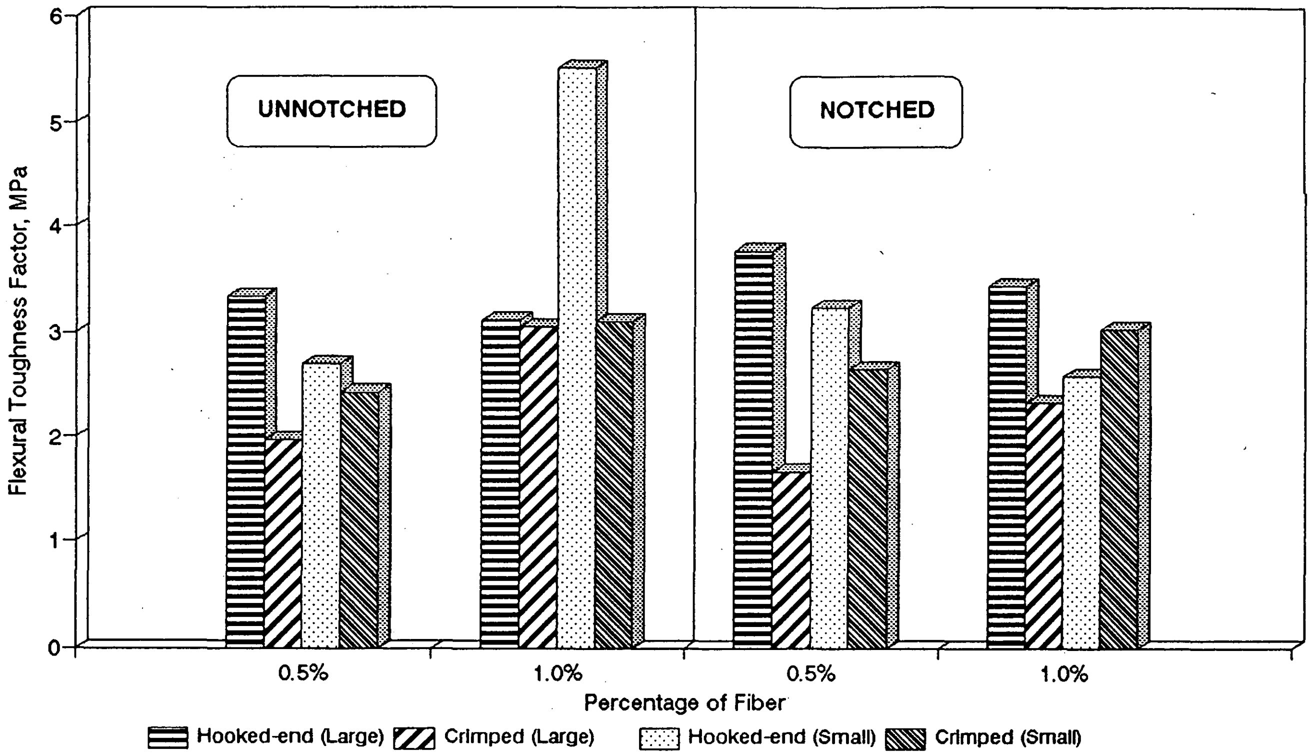

FIGURE 5 Flexural toughness factor versus percentage of fiber.

The flexural toughness factor values are provided in Table 2, and Figure 5 presents comparative results for unnotched and notched beams. The flexural toughness factor had increased as the percentage of the fibers increased, in both types of fibers, except for the large specimens with Type A fiber. Flexural toughness values increased 50 percent for small specimens with Type A fiber, as the percentage of fiber increased from 0.5 to 1.0 percent Similarly, the percentage increases were 20 and 35 percent for small and large specimens with Type B fiber. A detailed analysis presented elsewhere (*21*) indicated that notches in the beams do not influence toughness indexes (ASTM) and flexural toughness factors (JCI).

Cyclic Loading

The ability of structures to resist dynamic loading, such as earthquake loading, depends on the fracture toughness of the material. SFRC with higher fracture toughness and a very high post-crack energy absorption capacity before collapse is a suitable material for the construction of earthquake-resisting structures. The behavior of SFRC and its fracture toughness when subjected to cyclic loading were determined.

Load-deflection curves and complete analysis of results are presented elsewhere (*21*). A typical load-deflection curve obtained in cyclic loading test superimposed by a load-deflection curve obtained under monotonic load for the same SFRC with unnotched beams is shown in Figure 6; the same comparison for notched specimens is shown in Figure 7.

Curves under cyclic loading followed closely the curves for monotonic loading, indicating that the behavior of FRC under cyclic loading can be predicted from the monotonic load curve. Total energy absorbed for collapse appeared to be nearly the same for both loading cases. However, growth of permanent strain and decay in elastic modulus were observed after every cycle, when the loading was higher than the first-crack load. There was not any discernible difference in the behavior of beams with and without notches when subjected to either cyclic loading or monotonic loading.

Crack Mouth Opening Displacement

In addition to the load deformation characteristics, crack mouth opening displacement (CMOD) versus load was recorded under monotonic and as well cyclic loading for notched specimens. A typical load versus CMOD curve is shown in Figure 8. A similar type of behavior was observed for the load versus CMOD curves under both monotonic and cyclic loading. The CMOD was linear, until a crack appeared, then it became nonlinear. The load-CMOD curves and the load-deflection curves were similar for monotonic and cyclic loading.

CONCLUSIONS

- Fracture toughness, as measured by ASTM- and JCI-recommended test procedures, increases significantly with the addition of steel fibers in concrete. With an increase in fiber content, the fracture toughness increases. The degree of increase depends on the type and quantity of fibers added. The hooked-end SFRC had greater toughness than the SFRC with crimped fiber, with an equal quantity of fibers in both. The higher the FRC's fiber content, the lower its corresponding post-crack load drop.

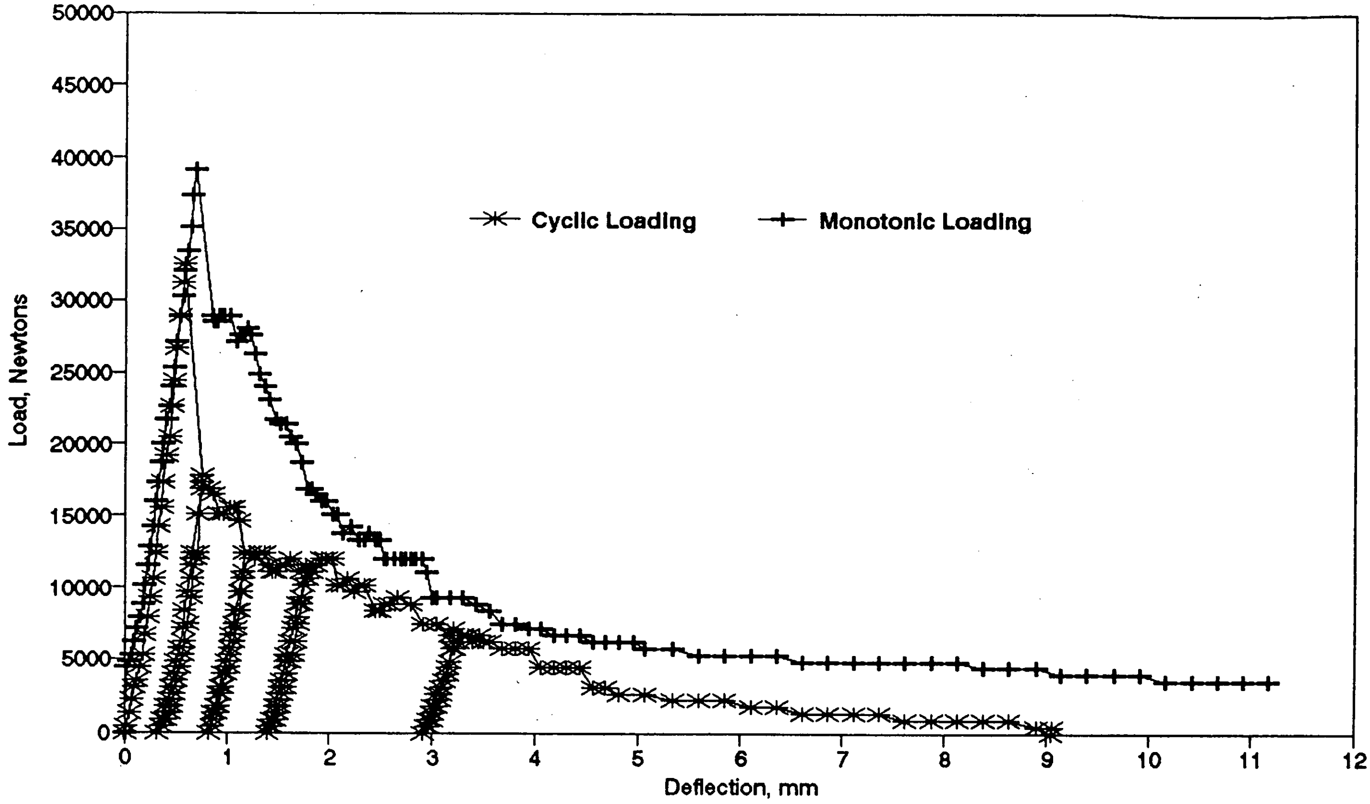

FIGURE 6 Load deflection curves for cyclic and monotonic loading for unnotched specimens.

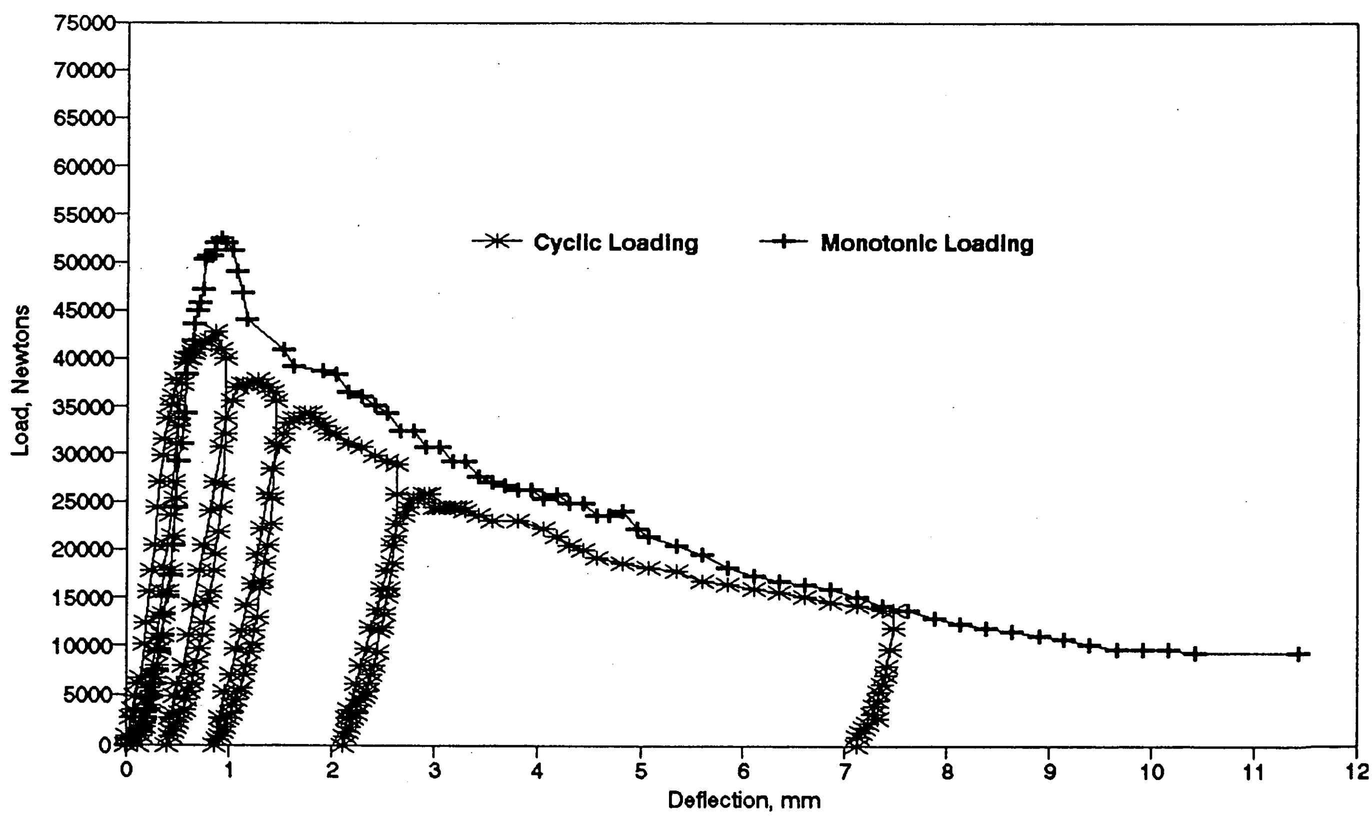

FIGURE 7 Load deflection curves for cyclic and monotonic loading for notched specimens.

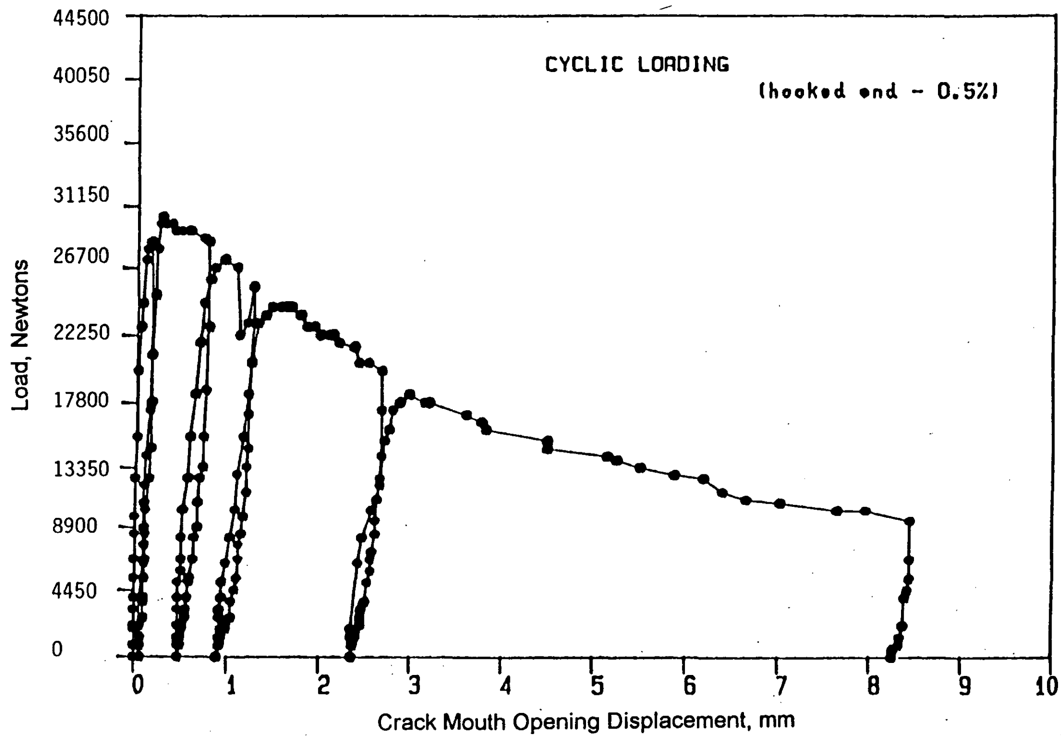

FIGURE 8 Load versus CMOD curve for Beam A1LN-3.

- Significant scatter in the toughness and flexural properties calculated for SFRC is unavoidable because of the inevitable nonuniform distribution of the randomly oriented fibers, particularly in the critical tension zone, both in the laboratory-cast specimens and in concrete in the field.
- In comparing the load-deflection behavior and the flexural properties of FRC specimens subjected to monotonic or cyclic loading, the notch in the specimen did not have any influence on the toughness, other flexural properties, or the behavior of FRC. For the notch-depth/beam-depth ratio used (1:8), the FRC was not notch-sensitive.
- In general, specimen size had an influence on the fracture toughness and the mechanical parameters monitored. The stress at first crack and the ultimate strength were less for the larger specimen size. However, the ultimate strength was more size-dependent than the stress at first crack. Energy absorbed per unit net cross-sectional area, and the initial elastic modulus calculated from the load deflection curves, were both independent of size. For SFRC with hooked-end fibers, the variability of the fiber distribution at the critical section had a much greater influence than specimen size. Therefore, for hooked-end SFRC, the results should be interpreted with caution.
- There was no change in the elastic wave transmission properties of the concrete due to the addition of fibers, as indicated by measured pulse velocities.
- Fracture toughness indexes (I_5, I_{10}, and I_{30}), calculated using ASTM C1018, are not very sensitive to the fiber type, fiber content, or specimen size. The test recommended by the JCI (SF4) is relatively more sensitive to the fiber type and content, and it could be used more effectively to compare fracture toughness of FRC with different fiber types and contents.
- Variability of fiber distribution noticed in the critical sections of the failed specimens cut from a large slab (field concrete), and in those sections of corresponding uncut specimens made in the laboratory in the required sizes, was almost the same. No difference was noticed in performance or mechanical parameters monitored using the specimens cut from the field concrete and the specimens cast in the laboratory.
- Behavior of SFRC under monotonic and cyclic loading indicates that fibers primarily influence the envelope curve; cyclic loading did not have any adverse effect on SFRC's energy absorption capacity or flexural strength.
- Compared with plain concrete, FRC has higher fracture toughness, first-crack strength, static flexural strength, ductility, and post-crack energy absorption capacity.
- For the notched beams, the load versus CMOD curve was very similar to that of the load deflection curve.
- Hooked-end fibers provide greater consistency in terms of toughness index testing. Use of the ASTM C1018 toughness index procedure to derive I_5, I_{10}, and I_{30} is a poor method of determining the end product of the toughness.

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