Performance Characteristics of Monofilament Polypropylene Fiber-Reinforced Concrete

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Results of an experimental evaluation of the physical and elastic properties of monofilament polypropylene fiber reinforced concretes are presented. Fiber concentrations used were 0.05, 0.067, 0.1, and 0.2 percent by volume. Performance characteristics of the fiber-reinforced concretes were compared with that of a control concrete without fibers. Fresh concrete properties, such as slump, unit weight, vebe time, inverted cone time, and concrete temperature, were measured. For hardened concrete, 7- and 28-day compressive strength, static modulus, modulus of rupture, and 28-day impact strength were determined. Load deflection curves were plotted from the data obtained in the modulus of rupture test to determine the toughness indexes by the ASTM method and the flexural toughness factor and equivalent flexural strength by the Japanese standard method. There was no balling of fibers during mixing and placing for all the concretes. There was less bleeding in the fiber concretes compared to that of the control concrete. There was no segregation and the finishability was good. There was a significant increase in impact strength with the addition of fibers. The toughness calculated according to the ASTM and the Japanese standard methods increased with an increase in fiber content. There is a positive improvement in the concrete's fatigue resistance with the addition of fibers.

Randomly oriented fiber reinforcement is an effective way of improving concrete properties. Fiber-reinforced concrete has a wide range of applications, particularly for airport and highway pavements, bridge deck overlays, curtain walls, sewer pipes, and cavitation and erosion-resistant structures, such as spillways, sluiceways, bridge piers, and navigation locks. Fiber-reinforced concrete also has found its way into precast products, earthquake-resistant structures, and explosion-resistant structures, such as missile silos and energy dissipators, shotcrete for rock-fill stabilization, tunnel linings, and dome structures. Considerable research has been done on the performance characteristics of fibrillated polypropylene fiber-reinforced concrete (*1–12*). An investigation (*5,13*) showed an increase in performance as measured by better resistance to impact loads, and higher toughness and endurance when subjected to fatigue loading. Polypropylene fibers have been proposed as an alternative to using welded fabric wire for crack-control purposes in concrete slabs (*12*).

Polypropylene fibers in general have some unique properties that make them suitable for use in concrete. The fibers are chemically inert, are noncorrosive, and have high chemical resistance to mineral acids, bases, and inorganic salts. They are very stable and do not absorb water. The fibers have high tensile strength and are economical to use. The low-modulus and high-elongation fibers are capable of large energy absorption characteristics.

Most currently available information about properties and performance of polypropylene fiber-reinforced concrete has been obtained for fibrillated polypropylene fibers of lengths varying from 12.7 mm to 63.5 mm (0.5 to 2.5 in.). There is very little information available about the performance of monofilament polypropylene fibers in concrete. Therefore, the authors conducted this study to determine the elastic and mechanical properties of concrete reinforced with monofilament polypropylene fibers.

OBJECTIVES

The primary objective of the investigation was to determine the physical properties of the monofilament polypropylene fiber-reinforced concrete specimens. That was achieved by carrying out tests to determine

- Properties of fresh concrete mixtures reinforced with polypropylene fibers;
- Characteristics of hardened concrete, such as compressive strength, static modulus, static flexure strength, unit weight, and impact resistance;
- Toughness indexes according to ASTM C1018, and flexural toughness and equivalent flexural strength according to the Japanese standard, using deflection-controlled load deflection curves; and
- Qualitative evaluation of flexural fatigue strength and whether there is any increase in the endurance limit with the addition of small amounts of fibers.

EXPERIMENTAL PROGRAM

Materials

Type I/II normal portland cement that satisfies ASTM C150 requirements was used for all mixtures. The maximum size of the coarse aggregate was 19 mm (3/4-in.) with absorption coefficient of 0.45 percent and fineness modulus of 6.57. The fine aggregate used was natural sand with a water absorption coefficient of 1.60 percent and a fineness modulus of 2.56. Coarse and fine aggregates satisfy the grading requirements of ASTM C33. Fibers used in this program were monofilament polypropylene fibers manufactured by Dura Fiber Company. The fibers were 19-mm (3/4-in.) long.

Mixtures

Basic mix proportions used for the research were as follows: coarse aggregate (926 kg/m^3), fine aggregate (926 kg/m^3), cement

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(390 kg/m^3), and water (163.8 kg/m^3). The water cement ratio was maintained at 0.45. Seven mixtures were made, and one mixture was without fibers. The basic mix designations are detailed in Table 1. All the mixing was done according to ASTM C192.

Specimens

The following specimens were cast from each mix: 150 × 300-mm (6- × 12-in.) cylinders for compressive strength and static modulus tests; 100- × 100-mm × 350-mm (4- × 4- × 14-in.) beams for static flexural toughness tests; and 100- × 63.5-mm (6- × 2½-in.) specimens for impact strength. The specimens were covered with plastic sheets for 24 hours at room temperature. They were then demolded and placed in a lime-saturated water tank maintained at 23°C (74°F). They remained in water until they were tested after 7 and 28 days.

TESTS FOR FRESH CONCRETE

Freshly mixed concrete was tested for slump (ASTM C143), air content (ASTM C231), fresh concrete unit weight (ASTM C138), inverted slump cone (ASTM C995), concrete temperature, and vebe time. Results of the tests are presented in Table 1.

TESTS FOR HARDENED CONCRETE

Cylinders were tested for compressive strength at 7 and 28 days, according to ASTM C39. They were also tested for the static modulus (ASTM C469). A pulse-velocity test (ASTM C597) was conducted.

Static Flexure Test

Beams were tested at the age of 7 and 28 days, 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 midwidth of the specimen to minimize the effect of twisting on deflection measurements. A specially constructed frame (*13*) was fixed to the specimen over the supports at neutral axis points. The dial gauge was attached to the frame, enabling accurate measurement of the actual midspan deflection and thereby eliminating extraneous deflections caused by crushing at supports and load points, and elastic shortening of the testing machine columns and platens. The device also eliminates the influence of specimen warping from torsion on the measured deflection. Rate of loading was maintained in the range of 0.0508 to 0.101 mm/min (0.002 to 0.004 in./min), per ASTM C1018. Loads were recorded at regular intervals; specimens were loaded up to a minimum midpoint deflection of 1/150 of the span, thereby allowing for computation of ASTM and JCI and JSCE fracture toughness indexes.

Flexural Fatigue Test

In the test for flexural fatigue, third-point loading was used with a span of 304.8 mm (12 in.), and the beams were subjected to a nonreversed fluctuating load. The procedure used for the test was as follows: the lower load limit was set at 10 percent of the average maximum load obtained from the static flexure test. For the first beam in each mix, the upper load limit was set at 90 percent of average maximum flexural load for the set. The fatigue test was run between these limits. If the beam failed before completing 2 million cycles, the upper limit was reduced for the next specimen. If the beam survived, another beam was tested at the same upper load, as a replicate.

The frequency of loading used was 20 cycles/sec (Hz) for all tests. It has been shown elsewhere (*2,3*) that frequency has little or no effect, unless extremely high rates are used. Therefore, for purposes of expediency, a rate of 20 Hz was used. The MTS testing machine was used for all tests. The control and monitor system consists of an MTS 436 control unit, a Hewlett-Packard oscilloscope, and a digital multimeter working with an MTS load cell. There was a counter in the machine that kept track of the number of cycles, and when a beam failed, the counter reading was recorded as the number of cycles at failure. A mechanical cut off switch allowed the operator to turn off the machine when a beam broke.

TEST RESULTS AND DISCUSSIONS

The monofilament polypropylene fiber used for the research performed well. Results of the tests for slump, air content, vebe time, inverted cone time, and unit weight are given in Table 1. The unit weight for all seven mixtures was almost the same, implying that different fiber volumes do not influence the unit weight of concrete. Fiber-reinforced concrete specimens were placed with relative ease and compacted using a vibrating table. Fresh concrete containing fibers had very little or no surface bleeding and no segregation.

TABLE 1 Mix Designations and Fresh Concrete Properties

Mix #	Type of fiber	% Fiber by volume	Slump	Air Content	Unit Weight	Vebe		Inverted Cone Time
						Slump	Time	
			mm	%	kg/m^3	mm	seconds	seconds
DF1	Monofilament	0.050	32	1.9	2434.5	25	2.6	11.0
DF2	Monofilament	0.067	25	1.8	2434.3	25	2.8	16.0
DF3	Monofilament	0.100	25	1.9	2432.0	25	3.6	20.0
DF4	None	-	57	2.3	2434.1	51	2.0	4.0
DF5	Monofilament	0.067	44	2.1	2464.9	51	2.2	6.8
DF6	Monofilament	0.100	32	2.4	2438.9	25	4.5	6.6
DF7	Monofilament	0.200	19	2.4	2477.6	13	6.0	11.0

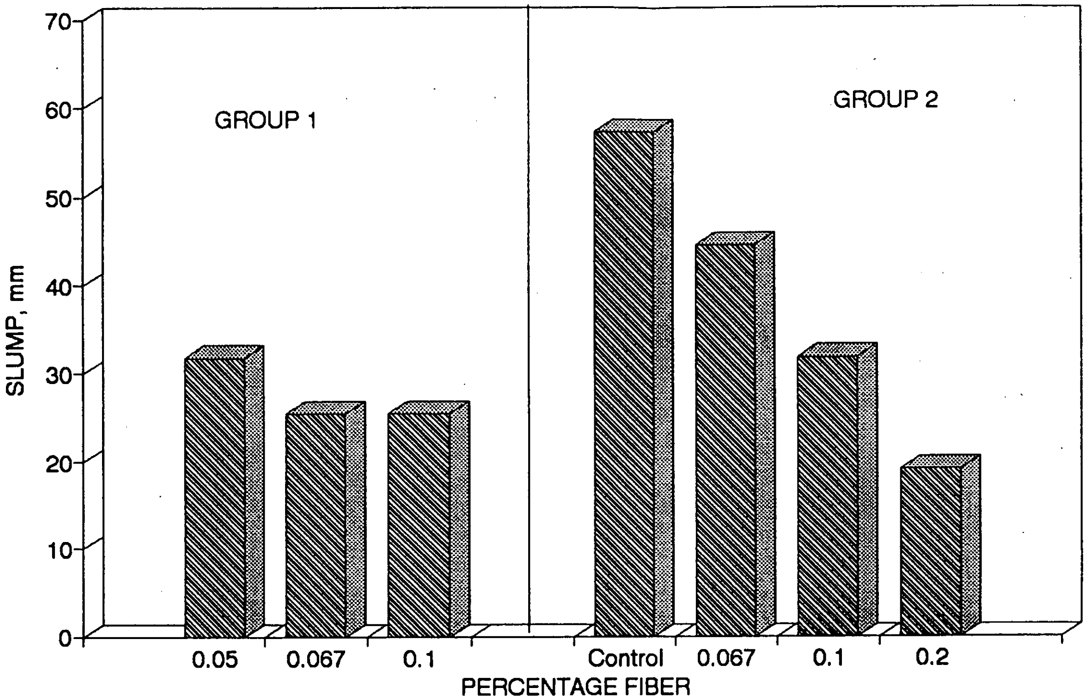

FIGURE 1 **Comparison of slump.**

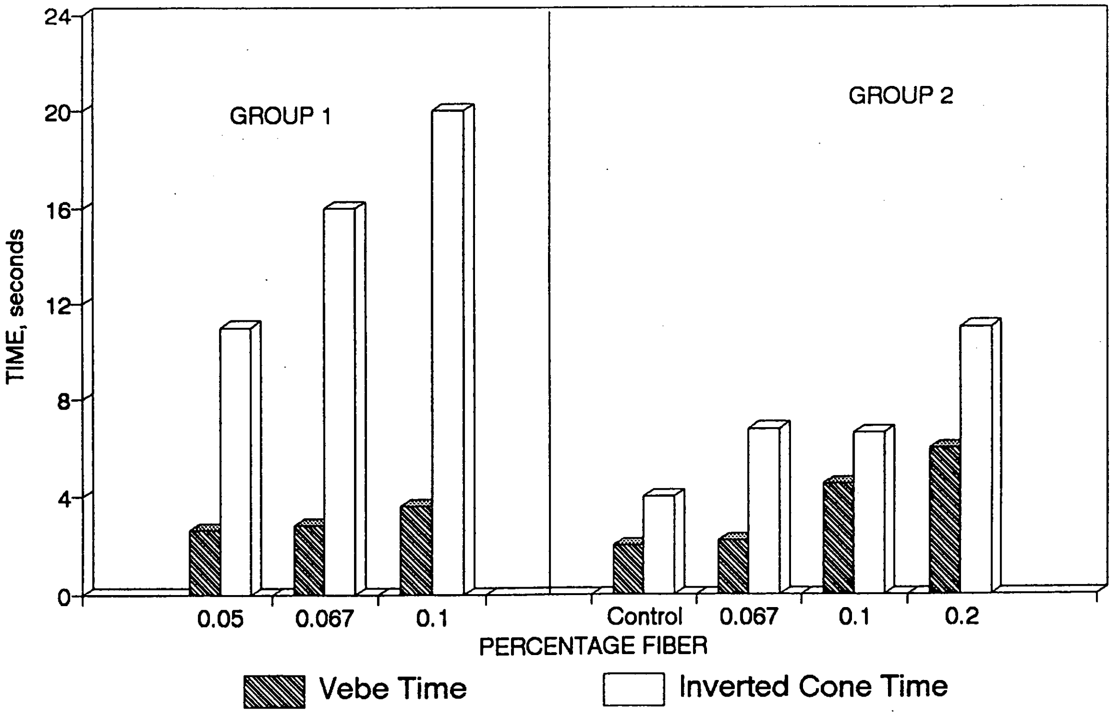

FIGURE 2 **Comparison of vebe time and inverted cone time.**

Slump, vebe time, and inverted cone time tests were conducted to determine the workability of the concrete mixtures. Results of a comparison of fresh concrete properties are presented in Figures 1 and 2. The water cement ratio was maintained at 0.45, and satisfactory workability was maintained for all the mixtures by adding an approximate amount of superplasticizer. The finishability was good.

HARDENED CONCRETE PROPERTIES

Compressive Strength

Compressive strength test results are shown in Table 2. There was a significant increase in strength from the 7- to the 28-day period. However, the increase of fiber content did not affect the compressive strength of the fiber-reinforced concrete.

There is a slight difference in compressive strength between Group 1 and Group 2 concretes. Group 1 concretes were made in February 1991 and Group 2 concretes were made in July 1992. The difference in compressive strength may have been related to different temperature and humidity conditions at the time the concretes were made. The quality of the cement used may have contributed to the difference in compressive strength between Group 1 and Group 2 concretes.

Static Modulus

Static modulus values are presented in Table 2. The values were reasonably consistent for all the mixtures. There was an increase in static modulus from 7 to 28 days.

Flexural Strength

Static flexural strength test results, also presented in Table 2, indicate an increase in flexural strength from 7 to 28 days. There was no significant increase in the modulus of rupture with an increase in the fiber content from 0.05 to 0.20 percent by volume. Fractured surfaces were inspected visually. Most of the fibers were broken and were not pulled out, indicating that there was a good bond between the fibers and concrete.

Pulse Velocity

Pulse velocity measurements indicated that the addition of fibers to the concrete did not affect the elastic wave transmitting property of the concrete. Measurements also indicated a significant degree of uniformity in the manufactured specimens and consistency in their quality.

Toughness Indexes (ASTM)

Values of calculated toughness indexes are presented in Table 3. Toughness indexes were defined on the basis of three service levels, multiples of first-crack deflection. The toughness 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 indexes I_5, I_{10}, and I_{20} are calculated as ratios of the area of the load deflection curve up to deflections of 3, 5.5, and 10.5, respectively, times the first crack deflection divided by the area of the load deflection curve up to the first crack deflection. There was a significant increase in toughness from age 7 to 28 days. A slight increase in first crack toughness with an increase in fiber volume was observed. A comparison of the toughness indexes, I_5, I_{10}, and I_{20} with respect to fiber content is exhibited in Figure 4. The ratios of I_{10}/I_5 and I_{20}/I_{10} were less than 2, as indicated in Table 3. The ratios indicate that even though the concrete was not perfectly elastoplastic, it had adequate ductility and toughness. The toughness index increased with an increase in fiber content, signifying that with a higher percentage volume of fiber, a greater capacity for energy absorption is achieved.

TABLE 2 Compressive Strength, Static Modulus, and Flexural Strength

Mix #	Age, days	Compressive Strength, MPa	Static Modulus, MPa	Flexural Strength, MPa	First Crack Toughness, Nm
DF1	7	32.93	31211	4.18	0.19
	28	42.82	36654	4.79	0.23
DF2	7	32.12	29351	3.91	0.23
	28	40.05	34450	4.89	0.25
DF3	7	32.24	36861	4.19	0.22
	28	39.22	32796	4.82	0.24
DF4	7	34.34	26733	3.51	0.12
	28	49.29	36172	4.32	0.19
DF5	7	30.90	32796	3.85	0.23
	28	52.95	36310	4.68	0.24
DF6	7	35.17	36689	4.13	0.12
	28	52.50	36482	4.41	0.26
DF7	7	29.79	32796	4.68	0.24
	28	47.09	36551	4.82	0.49

TABLE 3 Toughness Indexes

Mix #	Age Days	I5	I10	I20	I10/I5	I20/I10	JCI	
							T[a], Nm	Fe[b], MPa
DF1	7	3.27	5.39	8.87	1.71	1.89	-	-
	28	3.55	6.26	9.29	1.75	1.76	10.51	1.38
DF2	7	3.80	5.62	8.91	1.51	1.57	-	-
	28	3.53	6.45	11.0	1.82	1.70	10.64	1.42
DF3	7	3.55	6.55	10.84	1.85	1.64	-	-
	28	3.95	6.59	11.51	1.65	1.75	11.33	1.55
DF4	7	2.29	3.36	6.29	1.87	1.87	-	-
	28	3.21	5.37	8.27	1.56	1.56	8.41	1.13
DF5	7	2.50	3.93	6.71	1.75	1.75	-	-
	28	3.32	6.75	11.90	1.76	1.76	10.10	1.31
DF6	7	3.53	6.98	10.90	1.56	1.56	-	-
	28	3.60	6.73	11.70	1.73	1.73	10.92	1.47
DF7	7	4.07	8.64	13.64	1.58	1.58	-	-
	28	4.52	8.73	13.93	1.59	1.59	13.42	1.78

a - Toughness (JCI)
b - Equivalent Flexural Toughness Factor (JCI)

Japanese Standard Method

Values for the flexural toughness factor are presented in Table 3. The Japanese standard method, unlike the ASTM method, sets the deflection limit equal to 1/150 of its span. The span for beams used in this program was 304.8 mm (12 in.). The deflection value used for this method is greater than that used for the ASTM method of calculating toughness. Results from a comparison of flexural toughness values for different fiber contents are presented in Figure 5. Equivalent flexural strengths for various fiber contents are indicated in Figure 6. Results show that flexural toughness and equivalent flexural strength increased with an increase in fiber content for Group 1 and Group 2 concretes.

Impact Strength

The American Cement Institute's drop weight test was used in this investigation. The comparison presented in Figure 3 indicates that the number of blows until first crack and the number of blows to failure increase the higher the fiber content.

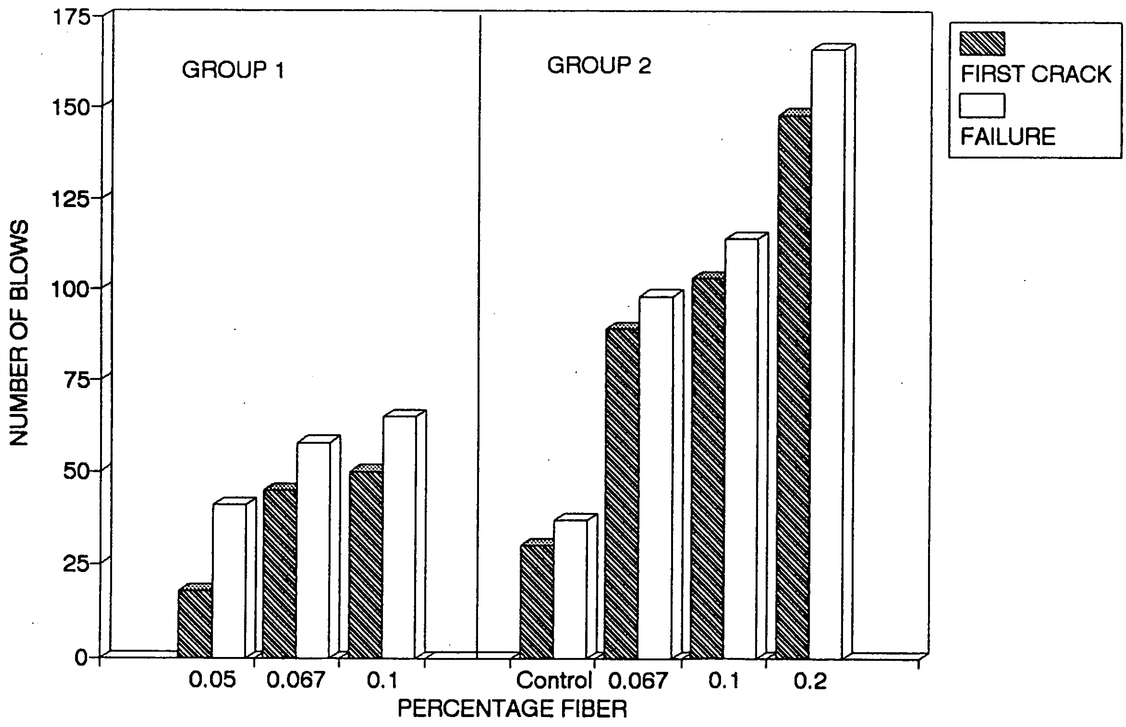

FIGURE 3 Comparison of impact strength.

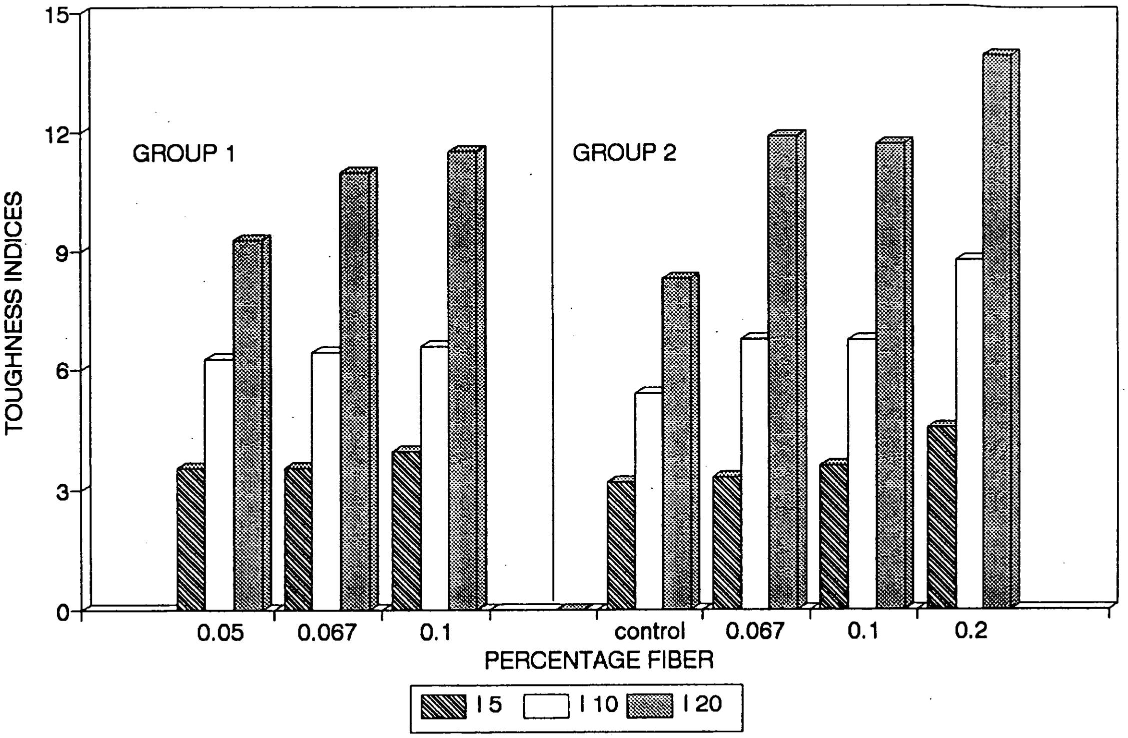

FIGURE 4 **Comparison of toughness indexes.**

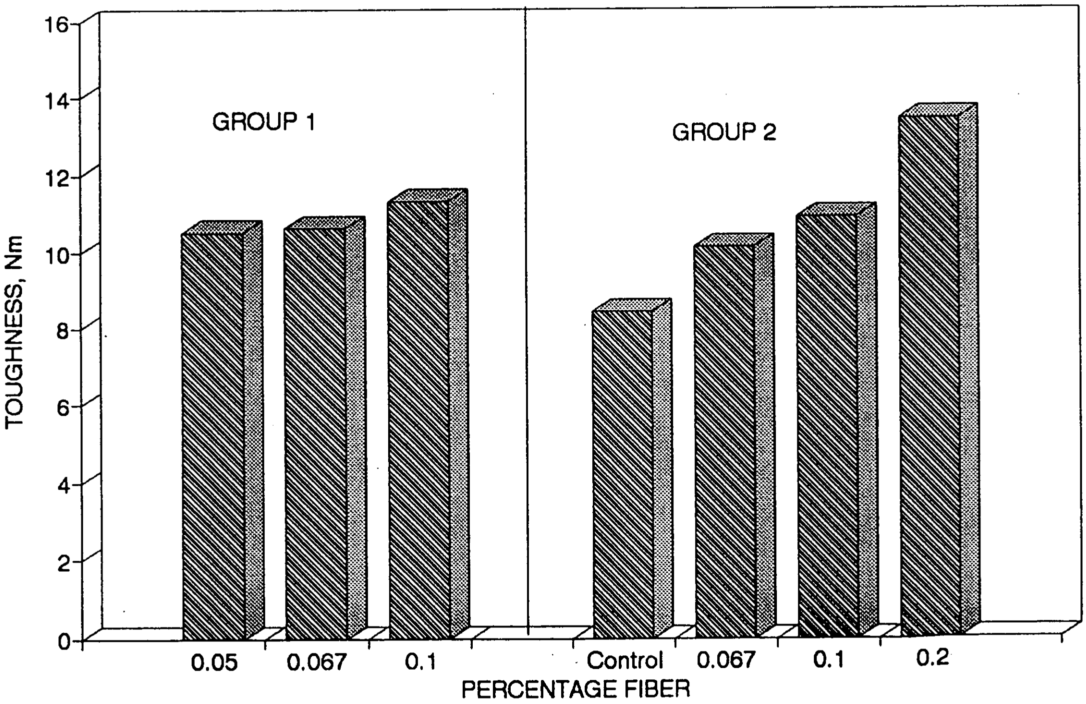

FIGURE 5 **Comparison of toughness (JCI).**

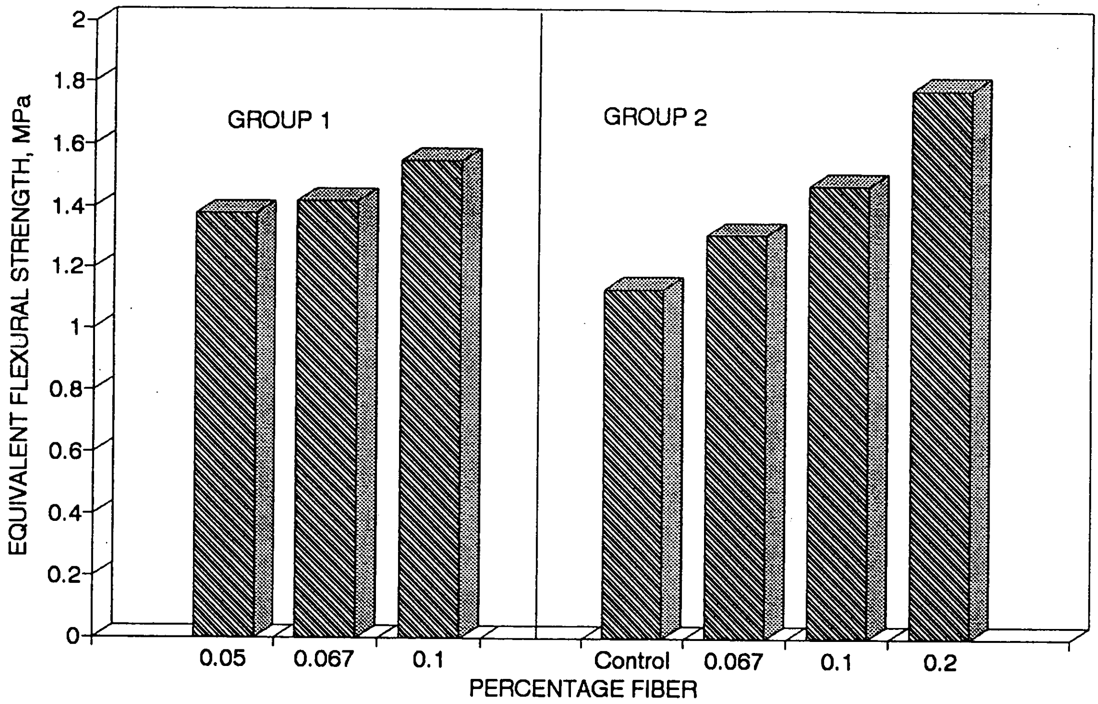

FIGURE 6 Comparison of equivalent flexural strength (JCI).

Comparing earlier investigations with the same amount of fibrillated polypropylene fiber-reinforced concretes with the present study of the monofilament polypropylene concretes, the authors found no significant difference in performance characteristics.

Flexural Fatigue Behavior

A small number of specimens were tested in flexural fatigue (*6*) to evaluate qualitatively the trend in the fatigue performance of monofilament polypropylene fiber-reinforced concrete. Beams made with plain concrete, with 0.1 and 0.067 percent fiber contents by volume, were tested for flexural fatigue. Results of fatigue tests are presented in Figures 7 and 8.

Fatigue Strength

Fatigue strength is defined as the maximum fatigue flexural stress at which point the beam can withstand 2 million cycles of nonreversed fatigue loading.

The authors observed that fatigue strength increased slightly with the addition of monofilament polypropylene fibers to the concrete.

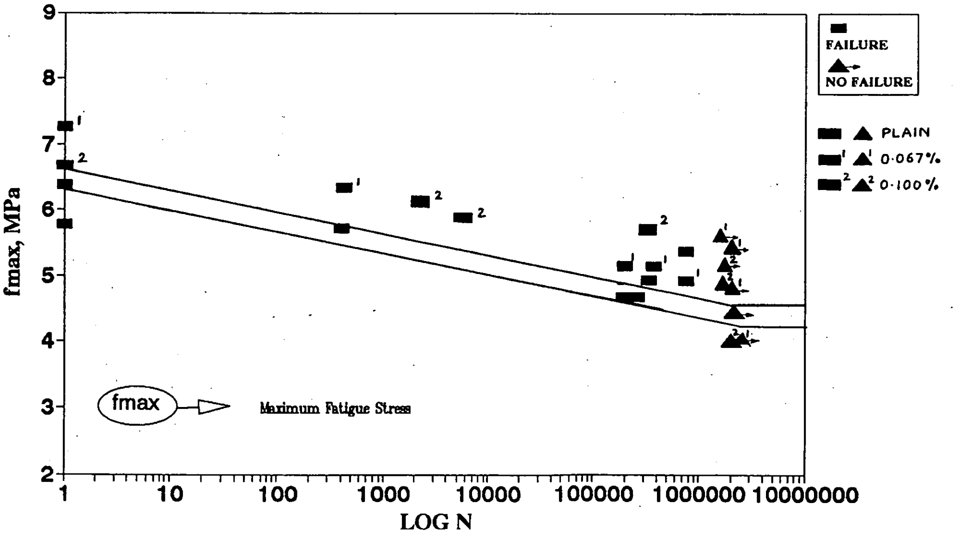

FIGURE 7 Log of number of cycles versus f_{max} for all mixtures.

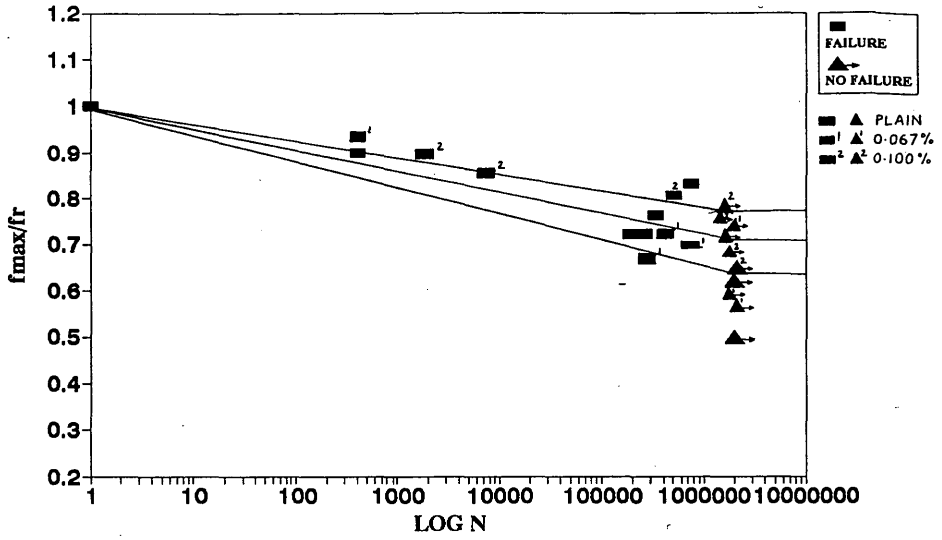

FIGURE 8 Log of number of cycles versus f_{max}/fr for all mixtures.

The fatigue strength was 4.46 MPa (647 psi) for plain concrete; it was 4.49 MPa (652 psi) and 4.86 MPa (705 psi) for 0.067 and 0.1 percent fiber concrete mixtures, respectively—an increase of 1 and 9 percent, respectively. Figure 7 illustrates the relation for fatigue flexural stress versus the logarithm of number of cycles for all the mixtures. Fatigue strength increases with fiber content.

Endurance Limit Expressed as a Percentage of Plain Concrete's Modulus of Rupture

Endurance limit is defined as the maximum fatigue flexural stress at which point the beam could withstand 2 million cycles of nonreversed fatigue loading, expressed as a percentage of modulus of rupture of plain concrete.

For beams made of 0.067 and 0.1 percent of fiber, there is a slight increase in the endurance limit, expressed as a percentage of modulus of rupture of plain concrete. The endurance limit is 69 percent for the mix with the 0.067 percent fiber content. It is 75 percent for the mix with 0.1 percent fiber content. The endurance limit for plain concrete is 65 percent. Thus the endurance limit was increased by 6 and 15 percent, respectively, when 0.067 and 0.1 percent by volume of fibers, respectively, were added to the concrete.

Endurance Limit Expressed as a Percentage of Mixtures Modulus of Rupture

Endurance limit of concrete can also be defined as the fatigue flexural stress at which a beam could withstand 2 million cycles of nonreversed fatigue loading, expressed as a percentage of its modulus of rupture.

The endurance limit for the mix with 0.067 percent fiber content was 70 percent, whereas it was 75 percent for the mix with 0.1 percent fiber content. Hence, the improvement in endurance limit is evident when the endurance limit is expressed as a percentage of its modulus of rupture.

Figure 8 shows the relation between the ratio of the fatigue stress to the average modulus of rupture (fmax/fr) versus logarithm of number of cycles for all mixtures. In this case the relationship is linear for all mixtures. Comparisons of flexural fatigue strength, endurance limit expressed as a percentage of modulus of rupture of plain concrete, and the endurance limit expressed as a percentage of its modulus of rupture are all given in Table 4.

CONCLUSIONS

- Fiber-reinforced concrete mixtures achieve good workability. Placement and compaction is done with relative ease.
- Static modulus, pulse velocity, and compressive strength do not change significantly with an increase in fiber content.
- Toughness indexes (ASTM) indicate improved behavior with an increase in the volume percentage of polypropylene fiber.
- Flexural toughness and equivalent flexural strength increase with a higher volume percentage of fiber.
- Impact strength increases with greater volume percentage of fiber.

TABLE 4 Fatigue Properties

Fiber Content	f max[a], MPa	EL1[b]	EL2[c]
Control	4.45	65	65
0.067%	4.49	69	70
0.100%	4.86	75	75

a - Flexural fatigue strength.
b - Endurance limit expressed as a percentage of modulus of rupture of plain concrete.
c - Endurance limit expressed as a percentage of its modulus of rupture.

- Polypropylene fiber performs well, with no problems with regard to workability, placing, or balling.
- Good finishability is achievable. (No protruding fibers were seen from the finished concrete specimens.)
- No difference in performance characteristics is observable between the monofilament polypropylene fiber-reinforced concrete and fibrillated polypropylene fiber-reinforced concrete.
- There is positive improvement in the fatigue resistance of concrete when monofilament polypropylene fiber is added in small quantities. There is an increase of 6 and 15 percent in the endurance limit for concretes with 0.067 and 0.1 percent fiber by volume, as compared with plain concrete.

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