Flexural Behavior and Toughness of Fiber Reinforced Concretes

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This paper presents the results of an extensive investigation to determine the behavior and performance characteristics of the most commonly used fiber reinforced concretes (FRC) for potential airfield pavements and overlay applications. A comparative evaluation of static flexural strength is presented for concretes with and without four different types of fibers: hooked-end steel, straight steel, corrugated steel, and polypropylene. These fibers were tested in four different quantities (0.5, 1.0, 1.5, and 2.0 percent by volume), and the same basic mix proportions were used for all concretes. The test program included (a) fresh concrete properties, including slump, vebe time, inverted cone time, air content, unit weight and concrete temperature, and hardened concrete properties; (b) static flexural strength, including load-deflection curves, first-crack strength and toughness, toughness indexes, and post-crack load drop; and (c) pulse velocity. In general, placing and finishing concretes with less than 1 percent by volume for all fibers using laboratory-prepared test specimens was not difficult. However, the maximum quantity of hooked-end fibers that could be added without causing balling was limited to 1 percent by volume. Corrugated steel fibers (Type C) performed the best in fresh concrete; even at higher fiber contents (2 percent by volume), there was no balling, bleeding, or segregation. Higher quantities (2 percent by volume) of straight steel fibers caused balling, and higher quantities of polypropylene fibers (2 percent by volume) entrapped a considerable amount of air. Compared with plain concrete, the addition of fibers increased the first-crack strength (15 percent to 90 percent), static flexural strength (15 percent to 129 percent), toughness index, post-crack load-carrying capacity, and energy absorption capacity. Compared with an equal 1 percent by volume basis, the hooked-end steel fiber contributed to the highest increase, and the straight steel fiber provided the least (but appreciable) increase in the above-mentioned properties.

Previous research by Ramakrishnan (*1–5,9–13*) and others (*6–8*) has established that the addition of fibers to concrete considerably improves static flexural strength, impact strength, shear and torsional strength, direct tensile strength, fatigue strength, shock resistance, ductility, and failure toughness. The degree of these improvements, however, depends on the type, size, shape, and aspect ratio of the fibers.

The research cited above involved small-scale, independent pilot projects for various types of fibers. Yet an extensive scientific investigation was still needed to determine the performance characteristics of the fibers and mix proportions most commonly used in field practice. Evaluation of the comparative behavior and properties of various fiber types at different fiber contents was also necessary. Furthermore, lack of sufficient information on the toughness and static flexural behavior of concretes with different types and quantities of fibers underscores the need for more research. This information is essential for fiber reinforced concrete (FRC) in potential airfield overlay applications.

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OBJECTIVES

The objectives of this investigation are as follows:

- To determine the fresh concrete properties, including workability, balling characteristics, and finishability, of concretes reinforced with four types of fibers (hooked-end steel, straight steel, corrugated steel, and polypropylene) and to compare their properties with those of corresponding plain concrete;
- To study the effect on fresh and hardened concrete properties due to the addition of the four types of fibers at 0.5, 1.0, 1.5, and 2.0 percent by volume for steel fibers and 0.1, 0.5, 1.0, and 2.0 percent by volume for polypropylene fibers to a plain concrete mix; and
- To conduct a detailed investigation of the static flexural behavior, including first-crack strength, modulus of rupture, load-deflection curve, post-crack deformation characteristics, post-crack load drop, and toughness indexes.

MATERIALS, MIXES, AND TEST SPECIMENS

Materials

Fibers

The following four types of fibers were used in this investigation:

1. *Type A*. The 2-in.-long hooked-end steel fibers used were glued together side by side into bundles with a water-soluble adhesive. During the mixing process, the glue dissolved in water and the fibers separated into individual fibers, creating an aspect ratio of 100.
2. *Type B*. The straight steel fibers used were made from low carbon steel with a rectangular cross section of 0.009 in. × 0.030 in. and a length of 0.75 in. Their aspect ratio was approximately 40.
3. *Type C*. The 2-in.-long corrugated steel fibers used were produced from a mild carbon steel with an aspect ratio of 40 to 65.
4. *Type D*. The polypropylene fibers used were collated, fibrillated, and ¾ in. long.

Cement

ASTM Type I/II (dual purpose) portland cement was used.

Coarse Aggregate

The aggregates used were maximum size ⅜ in. and maximum size 1 in. They were blended in a mixture of 60 percent aggregate with a 1-in. maximum size and 40 percent aggregate with a ⅜-in. maximum size. The mixture satisfied ASTM C33.

Fine Aggregate

The fine aggregate used was natural river sand with a water absorption coefficient of 1.64 percent and a fineness modulus of 3.02.

Admixtures

A superplasticizer satisfying the requirements of ASTM C494 for chemical admixtures and an air-entraining agent satisfying the requirements of ASTM C260 were used.

Mixes

The same proportions were used for the plain (control) and FRC mixes. The mix design is as follows:

Cement	658 lb/yd³
Coarse aggregate	1,560 lb/yd³
Fine aggregate	1,560 lb/yd³
Air content	5 ± 1.5 percent

The water-to-cement ratio was maintained at 0.4 for all concretes.

For the static flexure strength test, two mixes without fibers and four mixes each for Type B and C fibers were made with 0.5, 1.0, 1.5, and 2.0 percent by volume (66, 132, 198, and 264 lb/yd³, respectively). In the case of Type A fibers (hooked end), the maximum quantity of fibers that could be added without creating balling was 132 lb/yd³ (1 percent by volume). Therefore, only three mixes with 0.5, 0.75, and 1.0 percent by volume (66, 99, and 132 lb/yd³) of hooked-end fibers were used. For Type D fibers (polypropylene), four mixes with 0.1, 0.5, 1.0, and 2.0 percent by volume (1.5, 7.5, 15, and 30 lb/yd³) were made.

Test Specimens

For static flexural testing, beams of size 6 in. × 6 in. × 21 in. (152 mm × 152 mm × 533 mm) were cast. Cylinders 6 in. × 12 in. (152 mm × 305 mm) were cast for compression and modulus of elasticity tests. Specimens were made with a mechanical table vibrator.

TESTS FOR FRESH CONCRETE

The freshly mixed concrete was tested for slump (ASTM C143), air content (ASTM C231), fresh concrete unit weight (ASTM C138), temperature, time of flow through an inverted cone (ASTM C995), and vebe time.

TESTS FOR HARDENED CONCRETE

Cylinders were tested for compressive strength (ASTM C39) and static modulus (ASTM C469) at 28 days of age.

STATIC FLEXURE TEST

Beams were tested at 28 days for static flexural strength (ASTM C1018) and pulse velocity (ASTM C597). Some of the beams were also tested at 7 days. Toughness indexes were calculated using the load-deflection data. According to ASTM C1018, third point loading was applied to the beams in the static flexural test. The span length was 18 in. (457 mm). Deflection was measured at mid span using a dial gauge accurate to 0.001 in. (0.0254 mm). This test was a deflection-controlled test, with the rate of deflection kept in the 0.002 to 0.004 in./min range as per ASTM C1018. The loads were recorded at every 0.002-in. increment in deflection until the first crack appeared. Thereafter, the loads were recorded at different intervals.

TEST RESULTS AND DISCUSSION

Aspect Ratio

It is well known that the aspect ratio of straight fibers has a considerable effect on the performance of fresh and hardened concrete. Yet it is not practical to assess the relative value of the aspect ratio with regard to deformed or modified fibers (corrugated, hooked, collated, or fibrillated). Hence, the aspect ratio was not selected as a parameter for study. In this investigation, four commercially available and commonly used fibers were selected. Each has substantially different apparent aspect ratios (Type A fiber has twice as much as that of Types B and C). The cost difference between the fibers is also substantial (one fiber costs twice as much as another fiber).

Fresh Concrete Properties

Room temperature, humidity, and concrete temperature were recorded to ensure that all the mixes were combined under similar conditions. The room temperature and humidity varied in the range of 18°–27°C and 33 percent–58 percent, respectively. The concrete temperature range was 20.4°–27.2°C.

Workability

Three tests were performed to determine the workability of the mixes: slump, inverted cone time, and vebe time. Test results indicated that, in general, satisfactory workability can be maintained even with a relatively high fiber content for corrugated steel fiber concretes. This was achieved by adjusting the amount of superplasticizer used; the water-to-cement ratio remained constant (0.40) for all mixes. For the plain concrete, about 675 cc of superplasticizer was needed. The mix with 2 percent fibers by volume required 1735 cc of superplasticizer, representing an increase of 157 percent. The superplasticizer dosage varied from 860 cc to 1735 cc for the fiber concrete.

For the straight steel fiber mixes, balling tendency was observed with higher fiber quantities. In the case of hooked-end steel fibers, the maximum amount of fibers that could be added without inducing balling and segregation was 1.0 percent by volume.

With higher quantities of polypropylene fibers, the concrete had poor workability and more bleeding and segregation. For mix D4 with 2.0 percent by volume of polypropylene fibers, the water-to-cement ratio was increased to 0.49, and a higher quantity of superplasticizer was added to obtain better workability. In spite of this, the concrete was difficult to place and finish, resulting in bleeding and segregation. Concretes with higher quantities of polypropylene fibers also had higher quantities of entrapped air.

Based on test results, the relationship between vebe time and slump for each type of fiber is not affected by fiber contents for the range tested in this investigation. The relationship is different, however, for other types of fibers.

The inverted cone test was specifically developed to measure the workability of FRC in the field. Since both the inverted cone test and the vebe test are based on the energy requirements for flowability and compaction, a linear correlation exists between the two tests.

Finishability

Good finishability was achieved with an appropriate dosage of superplasticizer.

Hardened Concrete Properties

Compressive Strength and Static Modulus

The average values of compressive strength (f'_c) and static modulus of elasticity (E_c) for different concretes with four types of fibers and different volumes are shown in Tables 1 through 4. Each value in the tables represents the average of four tests.

The compressive strength was 7,040 psi for plain concrete. For the fibrous concrete with 0.5 percent and 1.0 percent fiber contents, the strength decreased slightly except for Type A fiber. For higher quantities of fibers (1.5 percent and 2.0 percent by volume), there was appreciable reduction in compressive strength with Type B and Type C fibers and a tremendous decrease with Type D fibers. The low compressive strength is due to the entrapped air content (13.9 percent) and low unit weight. The lower strength in fibrous concretes may be attributed to the difficulty in controlling the air content. The decrease in strength is also due to the increase in yield with a consequent reduction in cement factor. In this investigation, a basic mix proportion was maintained, and fibers in different quantities were added without considering

TABLE 1 HARDENED CONCRETE PROPERTIES FOR 0.5 PERCENT FIBER CONTENT

Fiber Type	f'_c (psi)	E_c (10^6 psi)	Pulse Velocity (fps)	f_r (psi)
Plain concrete	7,040	3.56	14,639	620
A	7,450	3.68	14,927	1,130
B	7,030	3.53	14,671	715
C	6,830	3.54	14,520	775
D	6,070	3.38	14,598	770

NOTES:
f'_c = compressive strength at 28 days
E_c = static modulus at 28 days
f_r = modulus of rupture at 28 days

TABLE 2 HARDENED CONCRETE PROPERTIES FOR 1.0 PERCENT FIBER CONTENT

Fiber Type	f'_c (psi)	E_c (10^6 psi)	Pulse Velocity (fps)	f_r (psi)
Plain concrete	7,040	3.56	14,639	620
A	8,340	3.55	14,732	1,420
B	6,830	3.49	14,743	880
C	6,070	3.38	14,113	820
D	5,550	3.30	14,215	680

NOTES:
f'_c = compressive strength at 28 days
E_c = static modulus at 28 days
f_r = modulus of rupture at 28 days

TABLE 3 HARDENED CONCRETE PROPERTIES FOR 1.5 PERCENT FIBER CONTENT

Fiber Type	f'_c (psi)	E_c (10^6 psi)	Pulse Velocity (fps)	f_r (psi)
Plain concrete	7,040	3.56	14,639	620
B	7,010	3.57	14,618	1,010
C	5,630	2.92	13,764	1,065

NOTES:
f'_c = compressive strength at 28 days
E_c = static modulus at 28 days
f_r = modulus of rupture at 28 days

TABLE 4 HARDENED CONCRETE PROPERTIES FOR 2.0 PERCENT FIBER CONTENT

Fiber Type	f'_c (psi)	E_c (10^6 psi)	Pulse Velocity (fps)	f_r (psi)
Plain concrete	7,040	3.56	14,639	620
B	5,190	3.38	13,820	900
C	5,530	3.05	13,882	1,120
D	1,470	1.44	12,120	440

NOTES:
f'_c = compressive strength at 28 days
E_c = static modulus at 28 days
f_r = modulus of rupture at 28 days

the fiber factor. If optimum mix proportions were obtained by trail mixes and used for different fiber contents, then the same compressive strengths could have been maintained.

Pulse Velocity

The results for pulse velocity are also given in Tables 1 through 4. The average pulse velocity at 28 days was 14,184 fps with a maximum of 14,639 fps (3.21 percent) and a minimum of 13,764 fps (2.96 percent), indicating a significant degree of consistency and quality control. The results also demonstrate that fiber content has little or no effect on pulse velocity. Finally, it indicates that the addition of steel fibers does not affect the elastic wave transmitting property of concrete.

Static Flexural Strength (Modulus of Rupture)

Results of static flexural strength (f_r) are tabulated in Tables 5 and 6. The values given in the tables represent the average of four test results. Within-test standard deviation and coefficient of variation values calculated for all the mixes were found to be very low. However, the variations between the beams for a given type of mix are likely to be larger for fiber reinforced specimens than those without fibers. This is due to the difficulty of achieving the same uniform distribution of the random oriented fibers. For approximately the same first-crack deflection, there is an increase in first-crack load for the concretes with increasing fiber content. It can also be observed that the flexural strength increases by 25 percent, 32 percent, 72 percent, and 81 percent for the concretes with corrugated steel fiber contents 0.5 percent, 1.0 percent, 1.5 percent, and 2.0 percent compared with that of plain concrete.

For 2.0 percent by volume polypropylene FRC, the compressive strength was very low, and hence the flexural strength was also significantly low. Similarly, for 1.5 percent and 2.0 percent fiber volumes of Type B and C fibers, the compressive strengths were low, and hence the flexural strengths were less. As a result, the direct flexural strength comparison may be misleading. Figure 1 illustrates the true effect of adding different types of fibers and quantities to a basic plain concrete mix. The maximum increase in flexural strength occurred when Type A fibers (hooked end) were added (Table 1). The increase was higher when higher quantities of fibers were added for all four fiber types. The smallest increase occurred in the case of polypropylene and straight steel FRC. Appreciable increase in flexural strength occurred when corrugated steel fibers were added. Higher quantities caused higher increases up to 2.0 percent by volume of fibers.

The values of $f_r/\sqrt{f'_c}$ for different types of fibers with various fiber contents are shown in Figure 2. A linear relationship between the fiber quantity expressed as a volume percentage (p_f) and the normalized flexural strength ($f_r/\sqrt{f'_c}$) is indicated for each type of fiber. However, the relationship varies for different types of fibers. Therefore, four separate linear equations were obtained for four types of fibers and are used

TABLE 5 MODULUS OF RUPTURE (FLEXURAL STRENGTH)

	Fiber Type							
	A		B		C		D	
Fiber Content (%)	f_r	$f_r/\sqrt{f'_c}$	f_r	$f_r/\sqrt{f'_c}$	f_r	$f_r/\sqrt{f'_c}$	f_r	$f_r/\sqrt{f'_c}$
0.5	1,130	13.09	715	9.08	775	9.38	770	9.88
1.0	1,420	15.55	880	10.65	820	10.41	680	9.13
1.5	—	—	1,010	12.06	1,065	14.19	—	—
2.0	—	—	900	12.49	1,120	15.06	440	11.48

NOTES:
f_r = modulus of rupture
f'_c = compressive strength

TABLE 6 FLEXURAL STRENGTH AT FIRST CRACK

	Fiber Type							
	A		B		C		D	
Fiber Content (%)	f_{fc}	$f_{fc}/\sqrt{f'_c}$	f_{fc}	$f_{fc}/\sqrt{f'_c}$	f_{fc}	$f_{fc}/\sqrt{f'_c}$	f_{fc}	$f_{fc}/\sqrt{f'_c}$
0.5	990	11.47	715	8.53	750	9.08	770	9.88
1.0	1,180	12.92	880	10.65	745	9.56	680	9.13
1.5	—	—	1,010	12.03	880	11.73	—	—
2.0	—	—	895	12.42	930	12.51	435	11.35

NOTES:
f_{fc} = flexural strength at first crack
f'_c = compressive strength

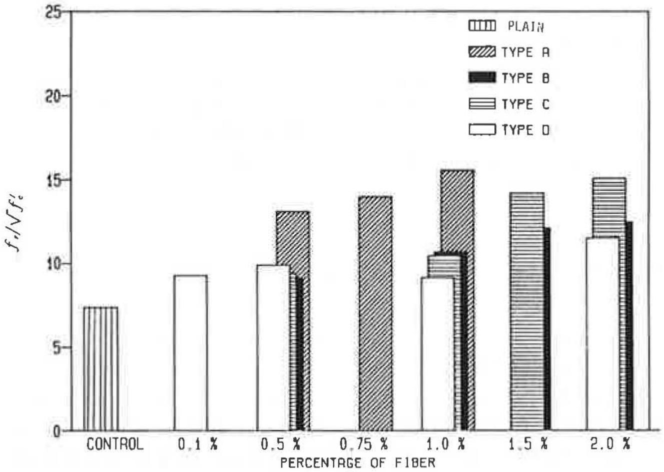

FIGURE 1 Fiber content vs. $f_r/\sqrt{f'_c}$.

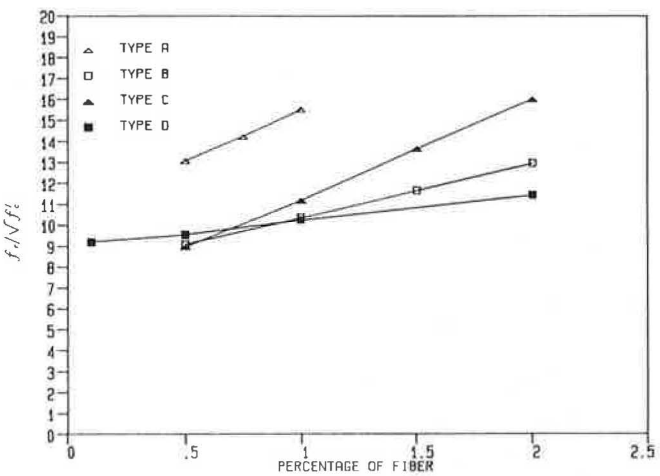

FIGURE 2 Percentage of fiber vs. $f_r/\sqrt{f'_c}$.

below. These equations are valid for fiber contents varying from 0.5 to 2.0 percent by volume except for Type A fiber (the experimental range used in this investigation). Equation 1 is only valid for fiber contents from 0.5 to 1.0 percent by volume. This range covers almost all the fiber contents currently used in the field.

$$f_{ra} = (4.82p_f + 10.68)\sqrt{f'_c} \quad (1)$$

$$f_{rb} = (2.613p_f + 7.773)\sqrt{f'_c} \quad (2)$$

$$f_{rc} = (4.667p_f + 6.667)\sqrt{f'_c} \quad (3)$$

$$f_{rd} = (1.184p_f + 9.032)\sqrt{f'_c} \quad (4)$$

where f_{ra}, f_{rb}, f_{rc}, and f_{rd} are the modulus of rupture of concretes with Type A, B, C, and D fibers, respectively, and p_f is the fiber content expressed as a volume percentage. The equations are valid only for the aspect ratios used in this investigation.

Load-Deflection Behavior

A significant performance difference of concretes with and without fibers is observed in the load-deflection curves, first-crack strengths, and toughness indexes.

Load-deflection curves are a standardized method of quantifying the energy a beam absorbs during its load-induced flexural deflection. The area under the curve represents the energy absorbed by the beam.

Load-deflection curves were drawn using the data from the static flexure test. Typical load-deflection comparison curves are given for the four fiber contents used in this investigation: 0.5 percent, 1.0 percent, 1.5 percent, and 2.0 percent by volume for Types A, B, C, and D, respectively. These curves are shown in Figures 3 through 6. Unlike plain concrete, FRC does not fail in a brittle, catastrophic manner at the formation of the first crack under a clearly identifiable maximum load. Well before signs of significant material distress are visible, the load-deflection curve becomes nonlinear; microscopic examination of the specimen revealed fine cracks. An increase in fiber content caused an increase in first-crack strength for all fiber types as shown in Figures 3 through 6. As explained

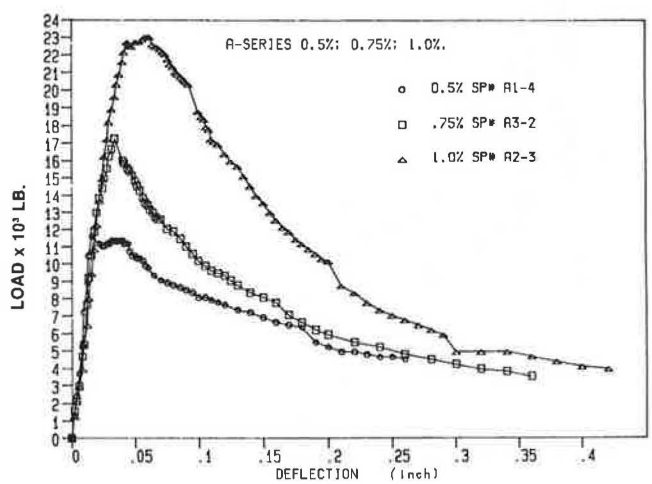

FIGURE 3 Comparison of load-deflection curves for hooked-end steel fiber.

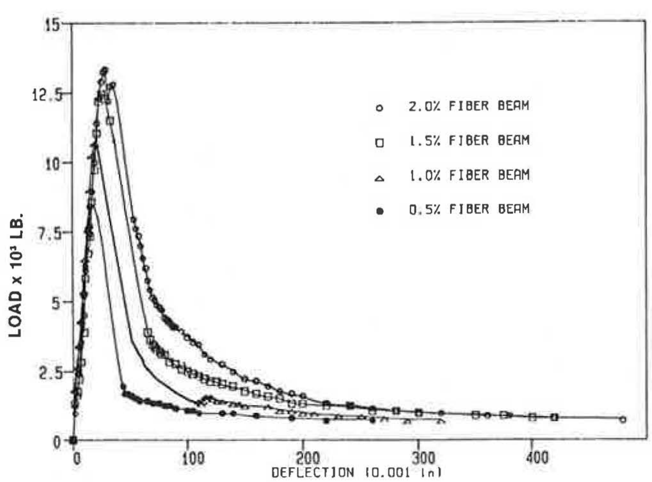

FIGURE 4 Comparison of load-deflection curves for straight steel fiber.

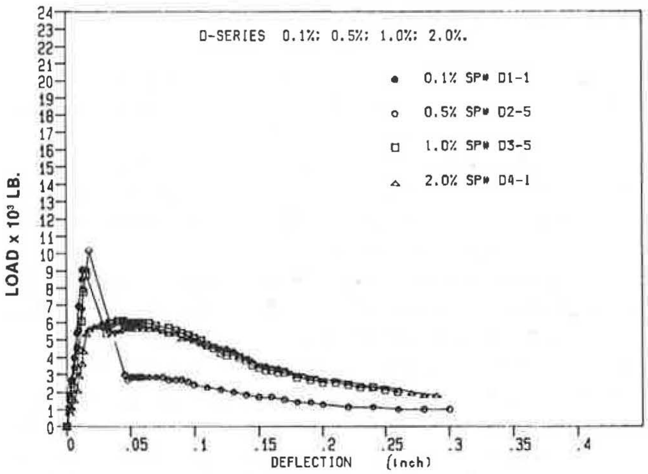

FIGURE 5 Comparison of load-deflection curves for corrugated steel fiber.

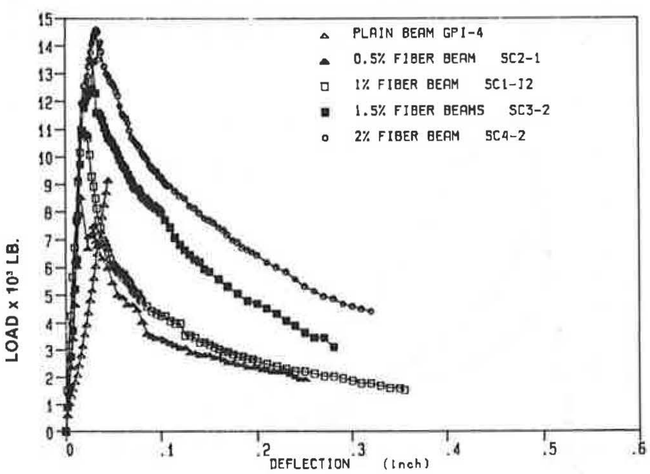

FIGURE 6 Comparison of load-deflection curves for polypropylene fiber.

previously, in the case of concretes with higher quantities of Type B and Type D fibers (2.0 percent by volume), the compressive strength (hence the flexural strength and the first-crack strength) decreased compared with the control concrete due to the balling of fibers and a considerable increase in entrapped-air content.

The load-deflection comparison curves also show an improvement in the elastic-plastic behavior of the fiber concrete composite with an increase in fiber content from 0.5 percent to 2.0 percent with plain concrete, however, the beam failed immediately after the appearance of the first crack. These curves indicate that the load-carrying capacity and the flexural rigidity of the beams rise with an increase in fiber content, resulting in a lower deflection at the corresponding load level. Compared with plain concrete, the reduction in the flexural rigidity value with increased deflection is not severe for FRC. In other words, the rate of degeneration at the moment of inertia decreases as the fibers resist the propagation of the crack growth. The observed crack widths at corresponding load levels were also smaller with increased fiber contents.

The load-deflection curves for different types of fibers are compared for 0.5 percent, 1.0 percent, 1.5 percent, and 2.0 percent by volume fiber contents in Figures 7, 8, 9, and 10, respectively. The maximum increase in first-crack strength is provided by Type A fiber (hooked-end steel), and the smallest increase is due to Type B and D fibers (straight steel and polypropylene fibers).

Post-Crack Load Drop Phenomenon

Post-crack load drop is the difference between the maximum load and the load recorded at a deflection equal to three times the deflection measured at first crack. The post-crack load drop phenomenon decreases with increasing fiber content. The load drops expressed as a percentage of maximum loads are 21 percent, 15 percent, 13 percent, and 7 percent, respectively, for the beams with 0.5 percent, 1.0 percent, 1.5 percent, and 2.0 percent corrugated steel fiber contents (Figure

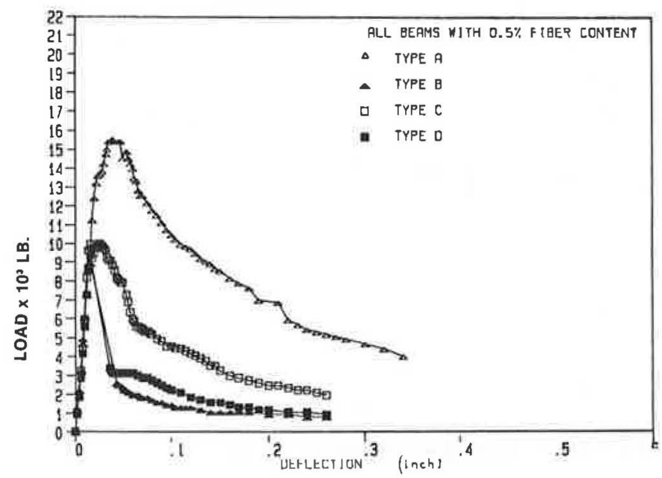

FIGURE 7 Load-deflection comparison for all fibers (0.5 percent fiber content by volume).

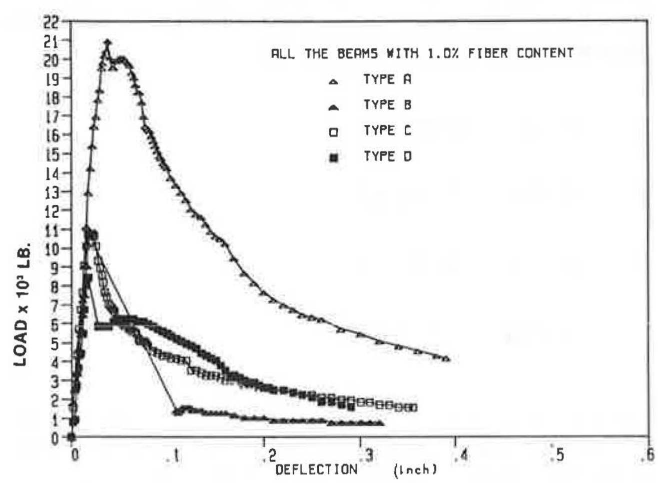

FIGURE 8 Load-deflection comparison for all fibers (1.0 percent fiber content by volume).

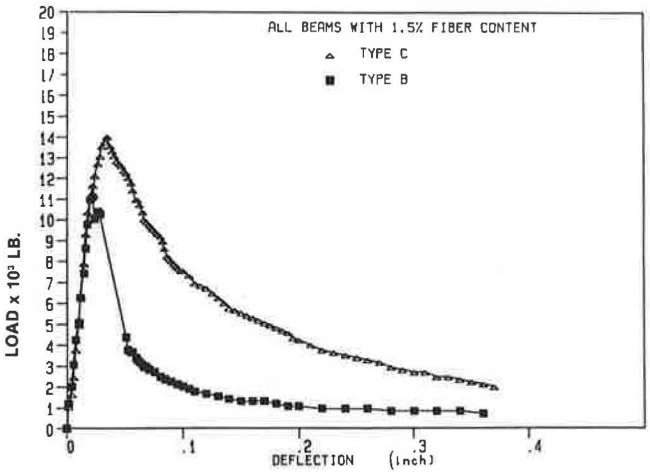

FIGURE 9 Load-deflection comparison for fibers B and C (1.5 percent fiber content by volume).

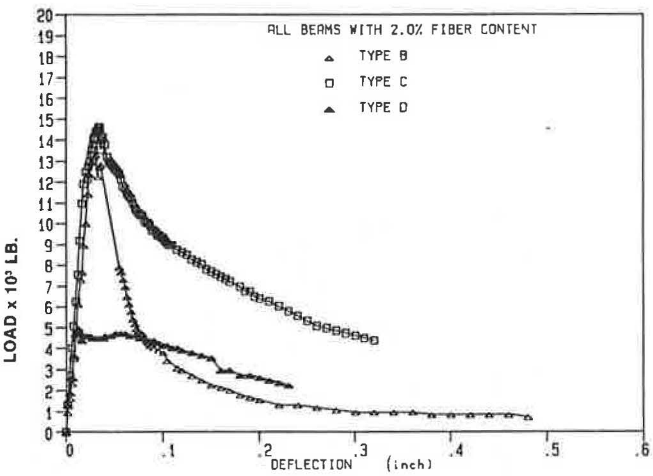

FIGURE 10 Load-deflection comparison for fibers B, C, and D (2.0 percent fiber content by volume).

5). The post-crack load drop for straight steel and polypropylene fibers is considerable as shown in Figure 4 and 6. However, in the case of hooked-end fiber, the load drop is considerably less (Figure 3). Table 7 presents a comparison of load drops calculated from the typical load-deflection curves for four types of fibers (Figures 3 through 6).

TABLE 7 POST-CRACK LOAD DROP

Fiber Content (%)	Fiber Type (%)			
	A	B	C	D
0.1	—	—	—	100[a]
0.5	21	80	21	68
0.75	14	—	—	—
1.0	11	77	15	32
1.5	—	69	13	—
2.0	—	60	7	18

[a]Failed fully.

TABLE 8 TOUGHNESS INDEXES FOR 0.5 PERCENT FIBER CONTENT

Fiber Type	I_5	I_{10}	I_{30}	I_{10}/I_5	I_{30}/I_{10}
Plain concrete	1	1	1	1	1
A	5.460	10.109	21.988	1.848	2.178
B	4.379	5.862	8.823	1.331	1.716
C	4.464	8.049	15.618	1.815	1.868
D	3.606	5.675	9.295	1.568	1.653

TABLE 9 TOUGHNESS INDEXES FOR 1.0 PERCENT FIBER CONTENT

Fiber Type	I_5	I_{10}	I_{30}	I_{10}/I_5	I_{30}/I_{10}
Plain concrete	1	1	1	1	1
A	5.266	10.129	21.151	1.914	2.084
B	3.204	4.068	5.952	1.270	1.462
C	4.833	8.219	16.025	1.699	1.945
D	4.043	7.516	15.332	1.855	2.016

Toughness Indexes

Toughness index (ASTM C1018) is a dimensionless parameter that defines or fingerprints the shape of the load-deflection curve. By including the percentage post-crack load drop values as suggested above, the fingerprinting of the shape of the load-deflection curve can be further improved. Indexes have been defined on the basis of three service levels, 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 deflection of three times the first-crack deflection. Likewise, I_{10} and I_{30} are the indexes up to 5.5 and 15.5 times the first-crack deflection, respectively.

The toughness index for plain concrete is equal to 1 because all plain concrete beams failed immediately after first crack. The toughness indexes for fiber concretes vary greatly depending on the position of the crack, the type of fiber, the aspect ratio, the volume fraction of the fiber, and the distribution of fibers.

The calculated values of toughness indexes I_5, I_{10}, and I_{30} are tabulated in Tables 8 through 11. The I_5 values increase by 8 percent, 23 percent, and 21 percent, respectively, as the fiber content is increased from 0.5 percent to 1.0 percent, 1.5 percent, and 2.0 percent by volume for Type C fiber. Similar improvement can be observed for I_{10} and I_{30} values. The ratios of I_{10}/I_5 and I_{30}/I_{10} are good indicators of the plastic behavior of that particular specimen. The values equal to 2 and 3 for I_{10}/I_5 and I_{30}/I_{10}, respectively, indicate perfect plastic behavior.

TABLE 10 TOUGHNESS INDEXES FOR 1.5 PERCENT FIBER CONTENT

Fiber Type	I_5	I_{10}	I_{30}	I_{10}/I_5	I_{30}/I_{10}
Plain concrete	1	1	1	1	1
B	3.602	4.599	6.559	1.273	1.424
C	5.478	9.387	17.276	1.725	1.845

TABLE 11 TOUGHNESS INDEXES FOR 2.0 PERCENT FIBER CONTENT

Fiber Type	I_5	I_{10}	I_{30}	I_{10}/I_5	I_{30}/I_{10}
Plain concrete	1	1	1	1	1
B	4.275	5.987	9.077	1.401	1.517
C	5.366	9.588	21.623	1.783	2.135
D	5.341	10.653	25.542	1.993	2.392

The hooked-end and corrugated steel FRC demonstrate very close plastic behavior after first crack until 5.5 times the first-crack deflection, since the ratios I_{10}/I_5 are very close to 2. The beams with corrugated steel fiber, however, showed a decline in the load-carrying capacity after a deflection of 5.5 times the first-crack deflection, as indicated by the I_{30}/I_{10} ratios, which are considerably less than 3.0, in the region between 5.5 and 15.5 times the first-crack deflection.

Comparison of toughness indexes are shown in Figures 11, 12, and 13. For straight steel fibers (Type B), the I_{10} and I_{30} values are very low compared with those of other fibers.

CONCLUSIONS

Based on the experimental investigation, the following conclusions can be made:

- The workability of fresh FRC can be improved and maintained with the addition of an appropriate amount of superplasticizer. Generally, there was no difficulty in placing and finishing.
- There was no change in the elastic wave transmission properties of the concrete due to the addition of fibers, as indicated by the measured pulse velocities.
- Compared with plain concrete, FRC has higher first-crack strength, static flexural strength, toughness index, ductility, and post-crack energy absorption capacity. The improvement increases with increasing fiber content.
- For each fiber, there is a unique relationship between the flexural strength and the fiber content.
- The failure mode of FRC is ductile. The degree of ductility depends on the fiber type and is directly proportional to the fiber content.
- The higher the fiber content of FRC, the lower the corresponding post-crack load drop.

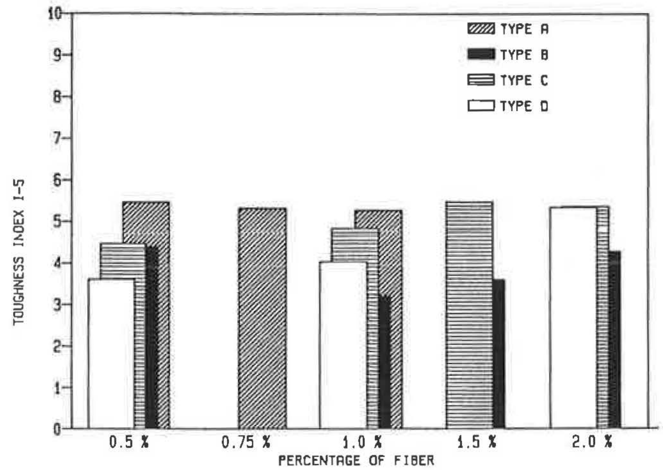

FIGURE 11 Toughness index I_5 comparison.

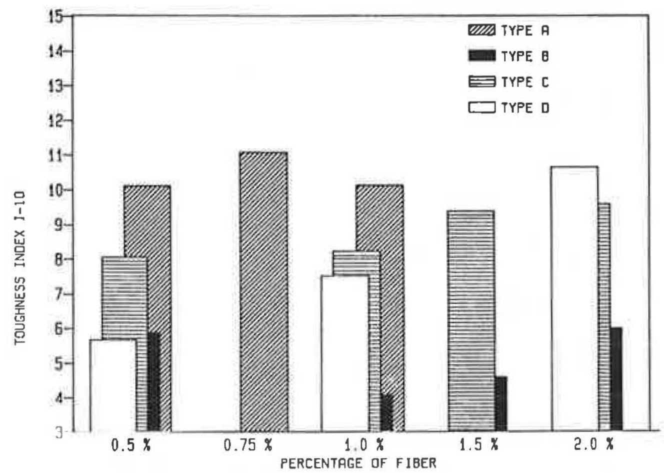

FIGURE 12 Toughness index I_{10} comparison.

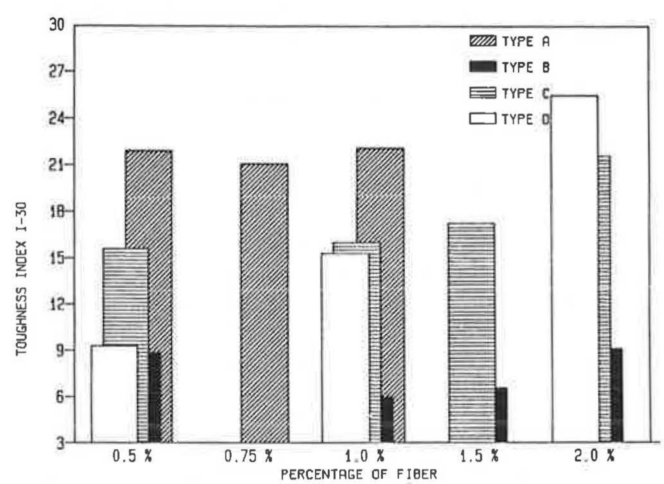

FIGURE 13 Toughness index I_{30} comparison.

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