Flexural Fatigue Strength, Endurance Limit, and Impact Strength of Fiber Reinforced Concretes

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In many applications, particularly in pavements, bridge deck overlays, and offshore structures, the flexural fatigue strength and endurance limit are important design parameters because these structures are designed on the basis of fatigue load cycles. This paper presents the results of an extensive experimental investigation to determine the behavior and performance characteristics of the most commonly used fiber reinforced concretes (FRC) subjected to fatigue loading. A comparative evaluation of fatigue properties is presented for concretes with and without four types of fibers (hooked-end steel, straight steel, corrugated steel, and polypropylene) at two different quantities (0.5 and 1.0 percent by volume), using the same basic mix proportions for all concretes. The test program involved the determination of fresh concrete properties, including slump, vebe time, inverted cone time, air content, unit weight, and concrete temperature; and the determination of hardened concrete properties, including flexural fatigue strength, endurance limit, and impact strength. The addition of the four types of fibers caused a considerable increase in the flexural fatigue strength and the endurance limit for 4 million cycles, with the hooked-end steel fiber providing the highest improvement (143 percent) and the straight steel and polypropylene fibers providing the least. The impact strength was increased substantially by the addition of all four types of fibers, with straight steel fiber producing the lowest increase.

The recent interest in reinforcing portland cement based materials with randomly distributed fibers was spurred by pioneering research on fiber reinforced concrete (FRC) conducted in the United States in the 1960s. Earlier work (*1–19*) has established that the addition of steel fibers improves the static flexural strength, flexural fatigue strength, impact strength, shock resistance, ductility, and failure toughness in concrete.

In many applications, particularly in pavements and bridge deck overlays, the flexural fatigue strength and endurance limit are important design parameters because these structures are designed on the basis of fatigue load cycles. The greatest advantage of adding fibers to concrete is the improvement in fatigue resistance. Plain concrete has a fatigue endurance limit of 50 to 55 percent of its static flexural strength (*15–17*). A properly designed FRC can achieve a 90 to 95 percent endurance limit. Theoretically, with a higher endurance limit, the concrete cross sections could be reduced. Alternatively, using the same cross section could result in a longer life span or higher load carrying capacity or both.

However, the research cited above involved small-scale, independent pilot projects for various types of fibers. A need remained for an extensive scientific investigation to determine the fatigue performance characteristics of the most commonly used types of fibers and mix proportions. There was a further need to evaluate the comparative fatigue behavior of various types and quantities of fibers. Particularly, little information is available about the flexural fatigue behavior of concretes with different types and quantities of fibers.

The primary objective of this research was to determine the behavior and performance characteristics of FRC subjected to fatigue loading. The other major objectives were

- 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 the fresh and hardened concrete properties due to the addition of the four types of fibers at 0.5 and 1.0 percent by volume of fibers to a plain concrete mix; and
- To conduct a detailed investigation of the flexural fatigue strength including the endurance limit for concretes with and without the four types of fibers in two different quantities, using the same basic proportions for all concretes.

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 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 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. It has an aspect ratio of approximately 40.
3. *Type C*. The 2-in.-long corrugated fibers used were pro-

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duced from a mild carbon steel. The diameter of the fiber (or equivalent diameter) was 0.03 to 0.05 in. with an aspect ratio of about 40 to 65.

4. *Type D*. The ¾-in.-long polypropylene fibers used were collated, fibrillated fibers.

Cement

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

Coarse Aggregate

The aggregates used were blended in two sizes: (a) in a mixture of 60 percent aggregate with a 1-in. maximum size, and (b) 40 percent aggregate with a ⅜-in. maximum size. The mixture satisfied ASTM C33.

Fine Aggregate

The fine aggregate used was natural sand. It had 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 for the entire investigation. The water-to-cement ratio was maintained at 0.4 for all the concretes. For flexural fatigue testing, two mixes each for plain and Type A, B, C, and D fibers were made with 0.5 percent and 1.0 percent by volume of fibers. The control mix design was as follows:

Cement	658 lb/yd^3
Coarse aggregate	1,560 lb/yd^3
Fine aggregate	1,560 lb/yd^3
Air content	5 ± 1.5 percent

Test Specimens

For the fatigue test, 18 beams of 6 in. × 6 in. × 21 in. (152 mm × 152 mm × 533 mm) were cast in each of plain, 1.0 percent fiber, and 0.5 percent fiber concretes. Cylinders 6 in. × 2.5 in. (152 mm × 64 mm) were made for the impact test.

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

Flexural Fatigue Test

Third point loading was used in the flexural fatigue strength test. The test beams had a span of 18 in. and were subjected to a nonreversed fluctuating load.

The lower load limit was set at 10 percent of the average maximum load obtained from the static flexure test. The upper load limit was set at 90 percent of the average maximum flexural load for the first beam in each mix, and 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. Three specimens were tested at each maximum load level.

The frequency of loading used was 20 cycles/sec (Hz) for all tests. The control and monitor system for all tests consisted of a MTS 436 control unit, a Hewlett-Packard oscilloscope, and a digital multimeter working with a MTS load cell.

Impact Test

The impact specimens were tested at 28 days by the drop-weight test method (*7*). Equipment for this test consisted of

- A standard, manually operated, 10 lb (4.54 kg) weight hammer with an 18 in. (457 mm) drop (ASTM D1557);
- A 2.5 in. (63.5 mm) diameter hardened steel ball; and
- A flat steel base plate with a positioning bracket and four positioning lugs.

The specimen was placed on the base plate within the positioning lugs with its rough surface upward. The hardened steel ball was placed on top of the specimen within the positioning bracket, and the compactor was placed with its base on the steel ball. The test was performed on a smooth, rigid floor to minimize the energy losses. The hammer was dropped consecutively, and the number of blows required to cause the first visible crack on the top of the specimen was recorded. The impact resistance of a specimen to ultimate failure was also measured by recording the number of blows required to open the cracks enough that the pieces of the specimen touched three positioning lugs on the base plate.

TEST RESULTS AND DISCUSSION

Fresh Concrete Properties

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

Workability

Three test were done to determine the workability of the mixes: slump, inverted cone time, and vebe time. The test

results indicated that, in general, satisfactory workability can be maintained even with a relatively high fiber content. This was achieved by adjusting the amount of superplasticizer used; the water-to-cement ratio remained constant (0.4) for all mixes.

Balling tendency for the straight steel fiber mixes was observed at 1.5 percent fiber volumes. To avoid balling, the fibers had to be carefully sprinkled by hand. The concrete had poor workability and more bleeding and segregation with higher quantities of polypropylene fibers. In all other mixes with an appropriate quantity of fibers, there was no balling, bleeding, or segregation. Even though slump values decreased with increasing amounts of fibers, no difficulty was encountered in placing and consolidating the concrete in the laboratory.

It seems that the relationship between vebe time and slump for each fiber type is not affected by fiber contents for the range tested in this investigation. However, the relationship is different for other types of fibers, and markedly different for hooked-end fibers. The rheological properties of fresh concrete with hooked-end steel fibers are different than those for other fibers. This may be due to the higher frictional resistance for movement in hooked-end fibers.

The relationship between vebe time and slump is independent of the air content. Fibrous concrete has less slump than plain concrete. In general, FRC seems to be more workable under vibration than is indicated by the slump. Nevertheless, the energy needed to compact the concrete appears to be proportional to the fiber content in the concrete.

The inverted cone test was specially developed (*12*) 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, there is a linear correlation between the two tests. This facilitates the transfer of laboratory test results to field practice more accurately.

Finishability

Excellent finishability was achieved with the appropriate dosage of superplasticizer.

Hardened Concrete Properties

Flexural Fatigue Behavior

The fatigue properties of FRC were evaluated thoroughly in this study. Beams made with plain concrete and concretes reinforced with 0.5 percent and 1.0 percent by volume of fibers were tested for flexural fatigue. Three specimens were tested at each strength level. Figures 1 through 11 present the various relationships between the number of cycles (N), log N, fatigue strengths, and endurance limits. Based on the data presented in these figures, the following three main properties are discussed:

- Fatigue strength,
- Endurance limit expressed as a percentage of modulus of rupture of plain concrete, and
- Endurance limit expressed as a percentage of its modulus of rupture.

Fatigue Strength Fatigue strength (f_{fmax}) is defined as the maximum flexural fatigue stress at which the beam can withstand 2 million cycles of nonreversed fatigue loading.

The fatigue strength was increased substantially with the addition of fibers to the concrete, as shown in Table 1 and Figure 1. The fatigue strength was 508 psi for plain concrete and 549 psi and 676 psi, respectively, for concrete mixes reinforced with 0.5 percent and 1.0 percent corrugated steel fiber. The increase in fatigue strength was 8 percent and 33 percent, respectively.

Graphs of flexural fatigue stress versus the number of cycles are shown in Figures 2 and 3. The relationship is curvilinear until the fatigue strength of that particular concrete is reached, then the line becomes parallel to the X-axis; the same behavior can be observed for all concretes. Figures 4 and 5 present fatigue flexural stress versus the logarithm of the number of cycles for all the concretes. These figures reveal a linear relationship between fatigue stress and log N. The fatigue strengths of concretes with and without fibers are compared

TABLE 1 FATIGUE PROPERTIES OF CONCRETES WITH DIFFERENT TYPES OF FIBERS

Fiber Type	A		B		C		D		Plain
Fiber Content(%)	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0	Conc.
f_{fmax} (in psi)	749	1242	559	594	549	676	478	508	508
EL_1 (%)	95	158	71	76	71	86	61	65	65
EL_2 (%)	76	85	67	59	70	55	70	65	65

f_{fmax} - flexural strength.
EL_1 - Endurance limit expressed as a percentage of modulus of rupture of plain concrete.
EL_2 - Endurance limit expressed as a percentage of its modulus of rupture.

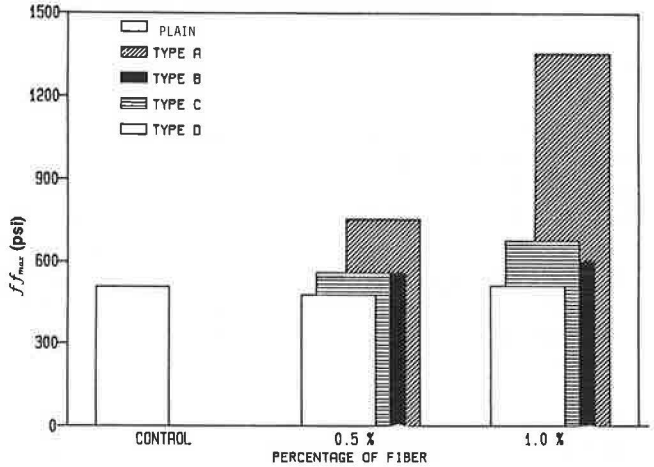

FIGURE 1 Fatigue strength.

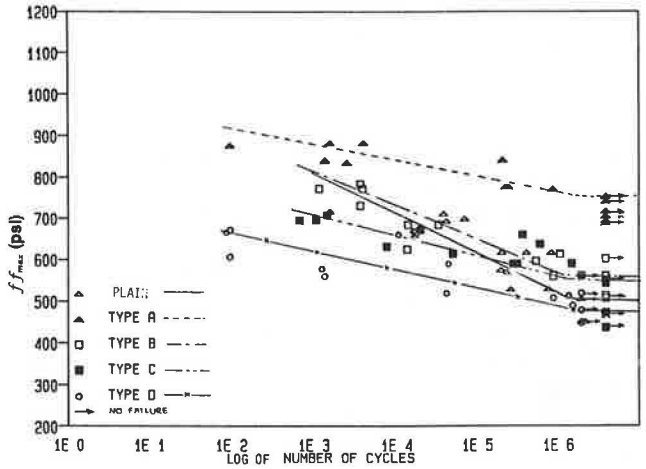

FIGURE 4 Fatigue stress versus log *N* for 0.5 percent fiber fatigue beams.

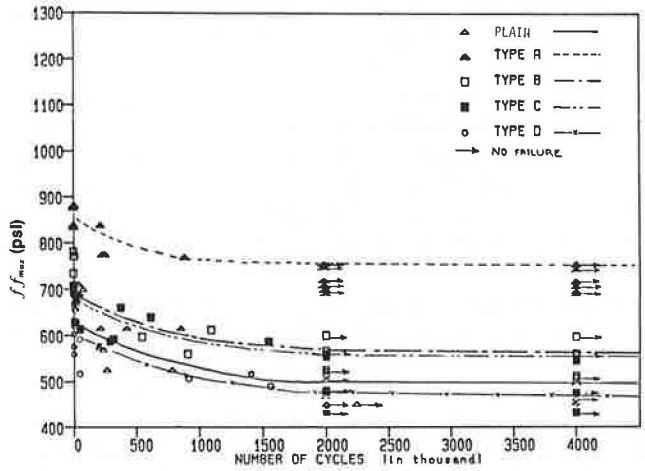

FIGURE 2 Number of cycles versus fatigue stress for 0.5 percent fiber fatigue beams.

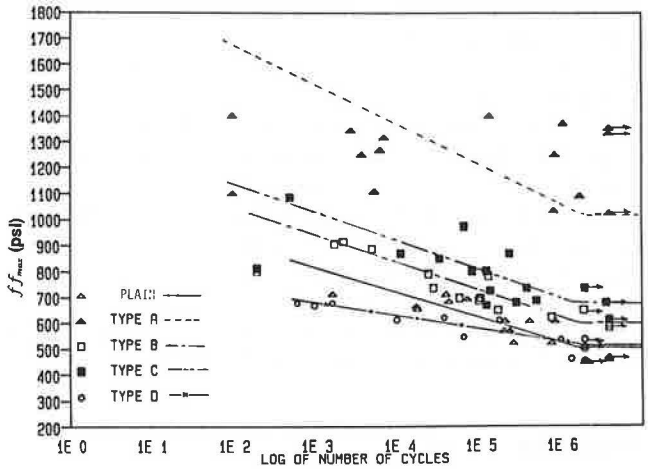

FIGURE 5 Fatigue stress versus log *N* for 1.0 percent fiber fatigue beams.

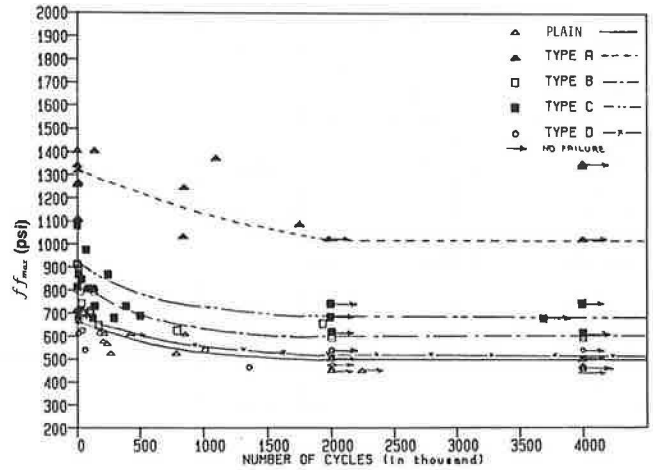

FIGURE 3 Number of cycles versus fatigue stress for 1.0 percent fiber fatigue beams.

in Figure 1. As can be seen, the fatigue strength increases with the fiber content for all fiber types. However, there is a larger increase in the fatigue strength with hooked-end fibers (47 percent and 144 percent, respectively, for 0.5 percent and 1.0 percent fiber contents) than with other fibers. The smallest increase in fatigue strength was found with polypropylene and straight steel fibers (see Table 1).

Endurance Limit Expressed as a Percentage of Modulus of Rupture of Plain Concrete The endurance limit (EL_1) is defined as the maximum flexural fatigue stress at which the beam could withstand 2 million cycles of nonreversed fatigue loading, expressed as a percentage of modulus of rupture of plain concrete.

Figure 6 compares the endurance limit values for all fiber concretes and plain concrete. Beams with 0.5 percent and 1.0 percent corrugated steel fiber contents show an appreciable

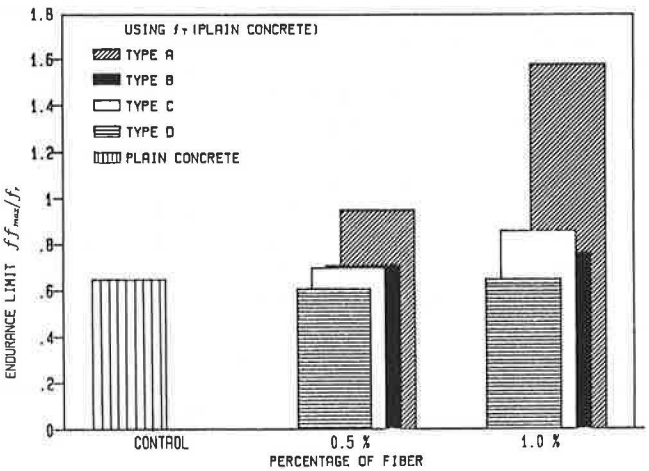

FIGURE 6 Comparison of FRC and plain concrete for endurance limit EL_1.

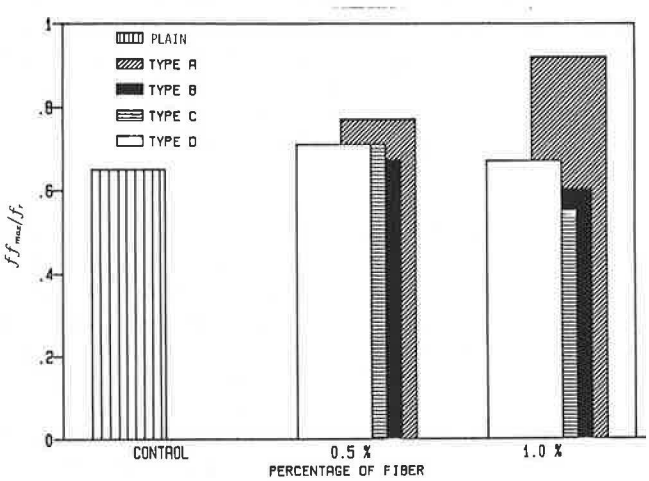

FIGURE 7 Comparison of FRC and plain concrete for endurance limit EL_2.

increase in endurance limit expressed as a percentage of modulus of rupture of plain concrete. The endurance limit was 71 percent for the mix with 0.5 percent fiber content and 86 percent for the mix with 1.0 percent fiber content, whereas the endurance limit for plain concrete was 65 percent. Thus, the endurance limit was increased by 9 percent and 32 percent, respectively, when 0.5 percent and 1.0 percent of fiber contents by volume were added to the concrete. The highest increase was experienced with hooked-end fiber (46 percent and 143 percent for 0.5 percent and 1.0 percent fiber contents, respectively) and the least increase with straight and polypropylene fibers (see Table 1).

Endurance Limit Expressed as a Percentage of Its Modulus of Rupture The endurance limit of concrete (EL_2) can also be defined as the flexural fatigue stress at which the beam could withstand 2 million cycles of nonreversed fatigue loading, expressed as a percentage of its modulus of rupture. Thus defined, endurance limit values are compared for plain concrete and FRC in Figure 7. Unfortunately, this comparison is misleading and shows some fibers unfavorably. For example, corrugated steel fiber concrete with 1.0 percent fiber content by volume had a high fatigue strength compared with plain concrete, although it has a lower endurance limit. This also indicates that the increased benefit due to the increased fiber content is not proportional at higher quantities of fibers.

For Type C fibers, the endurance limit was 70 percent for the mix with 0.5 percent fiber content and 55 percent for the mix with 1.0 percent fiber content (Table 1). The limit for the 1.0 percent mix is low because its modulus of rupture was high compared with that of plain concrete. Hence, the improvement in endurance limit is evident only when the endurance limit is expressed as a percentage of plain concrete modulus of rupture.

With an increase in fiber content, the apparent decrease in endurance limit expressed as a percentage of its modulus of rupture was also true with straight steel fiber and polypropylene fiber. The endurance limits for the straight steel fiber concretes were 67 percent and 60 percent, respectively, for 0.5 percent and 1.0 percent fiber contents. They were 70 percent and 67 percent, respectively, for the concretes with 0.5 percent and 1.0 percent of polypropylene fiber contents (see Table 1). However, the endurance limits for the hooked-end steel fiber concretes were 76 percent and 82 percent, respectively, for 0.5 percent and 1.0 percent fiber contents, which shows an increasing trend with the increase in fiber content. This phenomenon may also be a function of the aspect ratio of the fiber. Further research is necessary to study this aspect more thoroughly.

It was also observed that the variability in fatigue strength of the concrete with 1.0 percent fiber content is high compared with the concrete with 0.5 percent fiber content. Some of the beams that had much lower values than the mean were studied closely; when a fiber count in the fracture zone was performed, it was found that they had a subnormal number. The inconsistency in the distribution of the fibers, particularly in the tension zone, is inherent in fiber concretes with randomly oriented fibers. This is probably the main reason for the high variability in fatigue and static flexural strengths.

Graphs of the ratio of flexural fatigue stress to modulus of rupture (f_{fmax}/f_r) versus the number of cycles are presented in Figures 8 and 9, respectively, for 0.5 percent and 1.0 percent

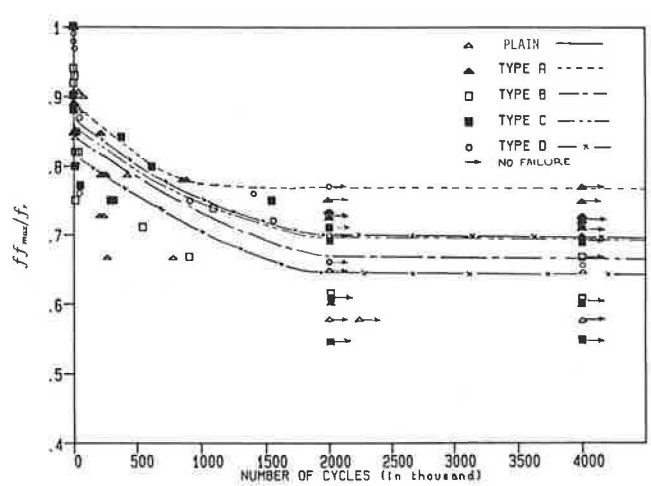

FIGURE 8 Ratio of fatigue stress to flexural stress versus number of cycles for 0.5 percent fiber beams.

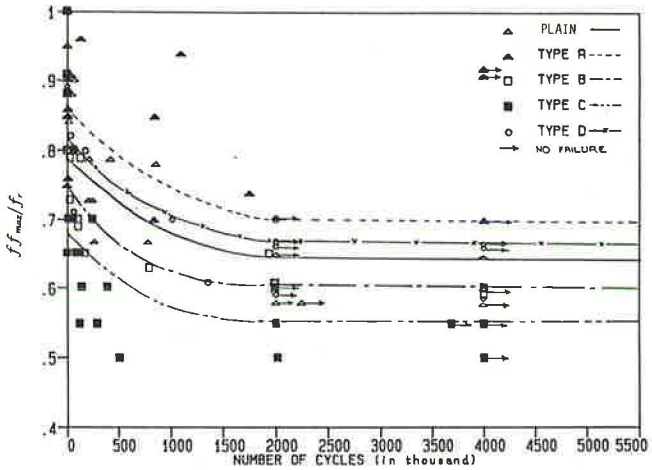

FIGURE 9 Ratio of fatigue stress to flexural stress versus number of cycles for 1.0 percent fiber beams.

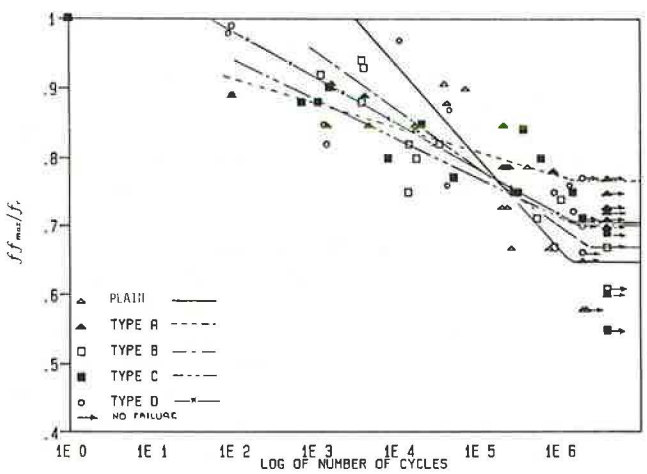

FIGURE 10 Ratio of fatigue stress to flexural stress versus log *N* for 0.5 percent fiber beams.

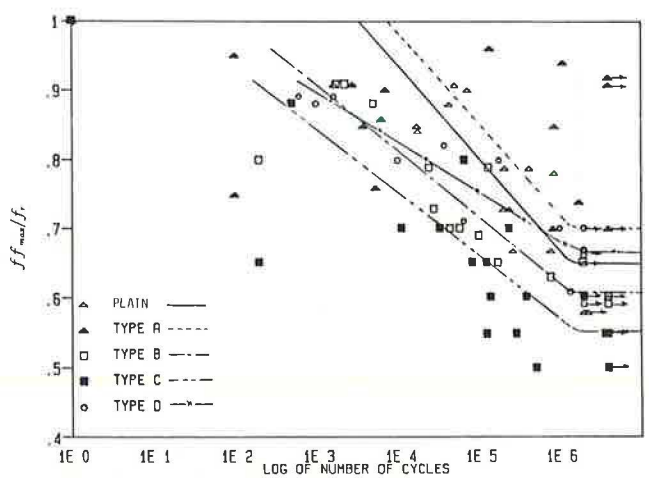

FIGURE 11 Ratio of fatigue stress to flexural stress versus log *N* for 1.0 percent fiber beams.

of fiber contents. The relationship is curvilinear until the fatigue strength of that particular mix is reached, then the line becomes parallel to the X-axis. The same behavior can be observed for all concretes. Graphs were also presented for f_{fmax}/f_r versus the logarithm of the number of cycles for all concretes (Figures 10 and 11). In this case, the relationship between log *N* and the ratio f_{fmax}/f_r is linear for all concretes.

After a time gap, all beams that had withstood 2 million cycles were further tested for flexural fatigue with an additional 2 million cycles at the same load range. All other beams, except one with 1.0 percent by volume of steel fiber content, withstood 4 million cycles without showing signs of additional distress or cracking. In other words, when a beam is subjected to a stress lower than its fatigue stress (as defined in this paper), then the beam may never fail in fatigue.

Fiber Anchorage and Bond An interesting phenomenon observed in this research was that beams reinforced with hooked-end steel fibers did not fail in fatigue even after extensive cracking. A minor crack was observed in a particular beam with 0.5 percent by volume of hooked-end steel fibers at 426,000 cycles. This crack extended progressively to a height of 5.12 in. in a 6-in.-deep beam and a width of 0.12-in. at 3,850,000 cycles. This shows the excellent anchorage and bond provided by the hooked end of the fibers.

Flexure Test After Fatigue Table 2 compares the results of the flexure test done after fatigue loading for all four types of fibers with 0.5 percent and 1.0 percent by volume. There seems to be an increase in flexural strength for both plain concrete and FRC after they were tested for fatigue. This increase seems to be higher than can be attributed to the increase in age alone and appears to depend on the flexural fatigue stress (f_{fmax}) to which the specimens were subjected earlier. With lower f_{fmax} values, the increase in flexural strength is higher. The same increasing trend is present for all four types of fiber concretes. Thus, it can be said that the increase in flexural strength is inversely proportional to the applied fatigue stress. In general, when fiber concrete is subjected to a fatigue stress below the endurance limit value, there is an increase in the potential flexural strength.

Impact Strength

The drop-weight test (*7*) used in this investigation is not a truly scientific test and was not expected to give accurate values for impact resistance. However, it is a simple, inexpensive test that can be done anywhere, including in the field. If a greater number of specimens can be tested, the mean values are a good qualitative index of the material's impact resistance. For comparison purposes, this is an acceptable test.

Figure 12 shows the number of blows for first crack and full failure. The maximum increase in impact resistance results from the use of Type A fiber; Type C fiber also contributes a higher impact resistance at higher fiber contents. The impact strength at first crack increased considerably with the increase in fiber content. Compared with plain concrete, the increase in impact strengths at full failure were 640 percent, 847 per-

TABLE 2 FLEXURAL STRENGTH AFTER FATIGUE LOADING

Sp. No.	Fiber Type & Percentage	f_{fmax} (psi)	f_{r1} (psi)	f_{r2} (psi)	$(f_{r2}-f_{r1})$ (percentage)
GP3-III13	Plain	455	785	789 *	-
GP3-III16	Concrete	508	"	780 *	-
GP3-I1	"	508	"	633 *	-19%
GP3-III15	"	464	"	1055	+34%
GP3-II9	"	475	"	980	+25%
A4-III6	'A' (0.5%)	689	986	1495	+52%
A4-I6	(Hooked End	697	"	1595	+62%
A4-II4	Fiber)	706	"	1139	+16%
A4-I4	"	719	"	1310	+33%
A4-II5	"	743	"	1118	+13%
A4-III5	"	755	"	688	-30%
A5-II3	'A' (1%)	1028	1473	1559	+6%
A5-I1	"	1342	"	2120	+44%
A5-I2	"	1356	"	2107	+6%
SCC5-III2	'B' (0.5%)	508	834	1015	+22%
SCC5-I3	(Straight	509	"	1120	+34%
SCC5-III3	Steel Fiber)	559	"	1150	+38%
SCC5-II6	"	558	"	965	+16%
SCC5-III5	"	598	"	1225	+47%
SCC60-III1	'B' (1%)	587	1003	1405	+40%
SCC6-III3	"	594	"	1390	+39%
SCC6-I2	"	602	"	1405	+40%
SC6-II1	'C' (0.5%)	433	788	1165	+48%
SC6-III2	(Corrugated	472	"	1210	+54%
SC6-II2	Steel Fiber)	541	"	1010	+28%
SC6-II3	"	546	"	808 *	+3%
SC6-I3	"	560	"	925	+17%
SC5-III6	'C' (1%)	615	1227	1300	+6%
SC5-III2	"	678	1227	1420	+16%
D5-III4	'D' (0.5%)	446	678	940	+39%
D5-III6	(Polypropylene	477	"	901	+33%
D5-II6	Fiber)	478	"	923	+36%
D5-III5	"	520	"	892	+32%
D6-III5	'D' (1%)	453	764	979	+28%
D6-II5	"	454	"	978	+28%
D6-II6	"	503	"	923	+21%
D6-III6	"	509	"	875	+15%
D6-I6	"	512	"	904	+18%
D6-III4	"	535	"	854	+12%

f_{fmax} - max. fatigue flexural stress.
f_{r1} -static flexural strength at the time of fatigue loading
f_{r2} -static flexural strength of the beam after it has been subjected to 4 million cycles of fatigue loading.
+ values of $(f_{r2}-f_{r1})$ indicate increase in flexural strength.
- values of $(f_{r2}-f_{r1})$ indicate decrease in flexural strength
* Beams were tested after 2 million cycles of fatigue loading.

cent, 1,824 percent, and 2,806 percent, respectively, for concretes with 0.5 percent, 1.0 percent, 1.5 percent, and 2.0 percent Type C fiber content. The results prove that fiber concretes incorporating hooked-end and corrugated steel fibers (Types A and C) have excellent impact resistance.

The four fibers used in this investigation are common, commercially available fibers that have substantially different aspect ratios. Type A has an apparent aspect ratio of 100, while Type B has an aspect ratio of only 40. It is well known that the aspect ratio of straight fibers has considerable impact on the performance of fresh and hardened concrete. However, it is not practical to determine the realistic value of the aspect ratio for deformed or modified fibers such as corrugated, hooked, collated, or fibrillated fibers. Therefore, the aspect

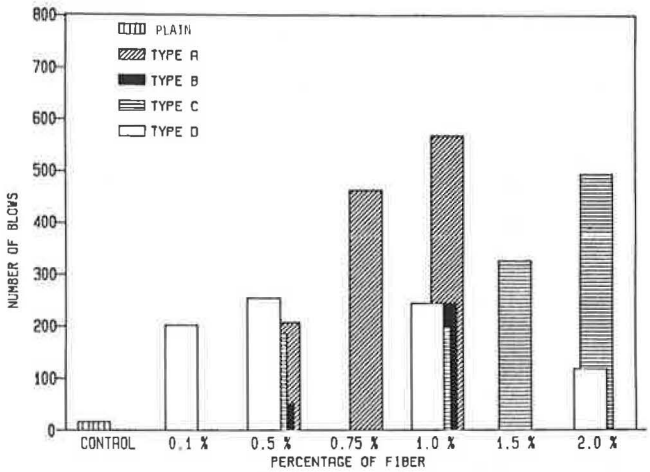

FIGURE 12 Impact results for FRC and control concrete.

ratio was not considered in the analysis. There is also a vast difference in the cost per pound of these fibers: one fiber may cost twice as much as another fiber. Prices were also not taken into account in the comparisons. Hence, the conclusions do not reflect the economy or efficiency of the individual 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 laboratory-prepared FRC test specimens with less than 1 percent by volume of fibers.
- The fatigue strength of FRC increases with increasing fiber content.
- The endurance limit expressed as a percentage of modulus of rupture of plain concrete increases with increasing fiber content.
- The endurance limit expressed as a percentage of its modulus of rupture increases with increasing fiber content for hooked-end steel fibers. However, the opposite is true for straight steel, corrugated, steel, and polypropylene fibers.
- The static flexural strength of beams that had been subjected to 4 million cycles of fatigue loading was higher than that of corresponding beams that had no previous fatigue loading.

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