

Performance of Steel Fiber Reinforced Concrete Using Large Aggregate

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Traditionally, steel fiber reinforced concrete has utilized aggregates not exceeding a maximum size of $\frac{3}{4}$ to 1 in. The purpose of this investigation was to evaluate the performance of steel fiber reinforced concrete mixes containing an aggregate with a maximum size of $1\frac{1}{2}$ in. Mixes were evaluated using three fiber types and three fiber concentrations. Beams were tested in flexure with load-deflection curves plotted for each specimen. Toughness testing was done in accordance with ASTM C 1018-85. Cylinders were cast to obtain specimens for compressive strength and impact resistance testing. Additional beams were cast for fatigue testing up to 2 million cycles. Flexural specimens using the longer fibers, 2 in. or longer, showed improved first-crack strength over conventional concrete mixes and displayed good toughness characteristics. The longer fibers significantly improved the impact resistance and the fatigue performance of steel fiber reinforced concrete with $1\frac{1}{2}$ -inch maximum-size aggregate. The compressive strength of mixes increased with the addition of steel fibers except when fiber loadings interfered with consolidation of the mix.

Concrete is considered a brittle material, primarily because of its low tensile strength and low tensile strain capacity. In many applications, poor tensile performance of the concrete is compensated for by incorporating steel reinforcing bars in the tensile zones of the concrete structure to carry the tensile stress. Concrete can be modified to perform in a more ductile manner by the addition of a random distribution of steel fibers in the mortar-concrete matrix. This results in a composite or two-phase system of brittle concrete and ductile steel fibers combined to form an elastic-plastic system. A primary advantage of this system is the development of post-crack load-carrying capacity of concrete members rather than catastrophic failure of members at fracture. Another advantage is that the fibers increase precrack tensile strengths of the matrix by restraining the formation of microcracks. Also, fatigue properties, strain capacities, and impact resistance are significantly improved.

Typical steel fiber reinforced concrete (SFRC) mixes consist of $\frac{3}{4}$ - or $\frac{3}{8}$ -in. maximum-size aggregate (MSA) with high cement factors. The high cement factors and relatively high sand content in the mixes are usually needed to provide workability. Early research (1) concluded that fiber additions to concretes with MSA larger than $\frac{3}{4}$ to 1 in. showed much-reduced performance. However, steel fibers in lengths greater than $\frac{3}{4}$ to 1 in. were not available at that time. With the use of SFRC increasing, an increasing number of problems have come to light. SFRC mixes are displaying the visible signs of distress that can be expected of concrete with high cement factors. Large thermal volume changes and paste shrinkage generate internal stresses resulting in cracking of thick sections and curling of pavement slabs. In cases where distress is not

evident, it is probable that the fibers are restraining volume change, thereby reducing the fiber and composite strain capacity.

One solution to this problem, which is common in the design of conventional and massive concrete, is to reduce the internal heat generation by lowering the cement contents of the SFRC mixes and consequently also reducing the potential paste volume shrinkage. Since workability is an overriding factor in present mix formulations and is forcing high cementitious material contents, increasing the maximum aggregate size and aggregate volume rather than just decreasing cement content is a reasonable approach.

The advent of longer fibers allows the use of larger coarse aggregate in SFRC mixes. Presently, few research and performance data are available for SFRC mixes with maximum aggregate sizes greater than $\frac{3}{4}$ to 1 in. and containing the longer steel fibers. Study and performance data in this area are needed to dispel notions that the upper limit of aggregate size for SFRC is still 1 in.

The main objective of this study was to verify and document that fiber additions to properly proportioned concrete mixes with $1\frac{1}{2}$ -in. MSA would significantly improve flexural toughness, impact resistance, and fatigue endurance while also allowing a reduction in cement (and cost). It is not intended to show the relative performance of fiber types but rather the beneficial effects of steel fiber additions.

Secondary objectives of this study were to establish a simple guideline for proportioning SFRC with $1\frac{1}{2}$ -in. MSA, to perform load-deflection testing as specified in ASTM C 1018, and to record and analyze data in a cost-effective, relatively simple, and automated manner.

Aggregates used in this study were commercially available concrete aggregates, basaltic in composition. Type I-II, low-alkali cement was used. A vinsol resin air-entraining admixture (AEA) and an ASTM C 494 Type B and D water-reducing admixture (WRA) were used.

Three commercially available fiber types were used in this project: straight fibers (F2 mixes), hooked fibers collated in bundles (B2 mixes), and corrugated fibers (R2 mixes). The latter two fiber types are collectively termed deformed fibers. The straight fibers are slit-sheet mild steel fibers cut to lengths of $\frac{3}{4}$ in. The hooked fiber, measuring 2.4 in. in length, is a high-strength drawn steel wire fiber having each end crimped. The corrugated fiber is a drawn wire steel fiber 3 in. in length. Table 1 summarizes pertinent information of the three fiber types.

MIX DESIGN PROCEDURES

Much work has been done in the area of proportioning SFRC mixes containing maximum aggregate sizes up to 1 in. SFRC

TABLE 1 SUMMARY OF STEEL FIBER DATA

	Fiber Types		
	Hooked	Corrugated	Straight
Fiber title	Dramix ZP 60/80	Xorex-3 in.	Fibercon- $\frac{3}{4}$ in.
Material	Carbon steel	Carbon steel	Carbon steel
Yield strength	170 ksi	140 ksi	55 ksi
Process	Drawn wire	Drawn wire	Slit sheet
Length	2.4 in.	3 in.	0.75 in.
Diameter (equivalent)	0.03 in.	0.035 in.	0.017 in.
Aspect ratio	75	86	45
Mechanical anchorage	Hooked ends	Corrugated shape	None

mixes are significantly different from conventional concrete mixes in that some of the fine aggregate size fractions of SFRC mixes are higher than for conventional concrete. The amount of No. 30 to No. 50 aggregate fractions, as well as cement contents are increased to enhance the workability of the mix. Cement or cement-plus-fly ash contents usually range from 700 to 1,000 lb/yd³ for typical mixes. The inordinately high cement contents encourage workability and ease consolidation of the fiber and concrete composite. Otherwise, in low-workability mixtures, the fibers restrain the mix constituents from orienting into a close-packed condition.

Numerical and laboratory methods of aggregate proportioning have been developed for conventional concretes and asphaltic concretes. Several of these methods were studied for possible use in providing a simple method to combine aggregates up to 1 $\frac{1}{2}$ -in. maximum size for SFRC. However, most of the aggregate-proportioning methods were not suited to this study as the methods were based on criteria that were not intended for, or applicable to, SFRC mixes.

A simple method of combining and proportioning aggregates, cement, water, admixtures, and fibers is available for mixes with MSA up to 1 in. (2). This method, simply stated, blends aggregates in varying proportions until a minimum void space condition is achieved. Paste volume relationships have been empirically developed to provide the desired workability level. This procedure has been successfully used in SFRC mix

proportioning. Similar methods are used to proportion tremie and pumped concrete mixes as workability criteria are similar to those required for SFRC mixes.

This method of optimizing aggregate packing to produce minimum void space did not optimize flexural strength performance nor produce a mix with suitable workability properties for the materials available for this project. The maximum-density, minimum-void aggregate proportions resulted in a coarse mixture completely unsuitable for SFRC mixes.

A more basic mix proportioning approach was then adopted. Data from existing field-proven gradation curves used for 1-in. MSA SFRC mixes were extrapolated to provide a 1 $\frac{1}{2}$ -in. MSA combination. Coupled with gradation curves for 1 $\frac{1}{2}$ -in. MSA tremie and pumped concrete mixes, a visually acceptable gradation band for 1 $\frac{1}{2}$ -in. MSA SFRC was developed, as shown in Figure 1. A typical $\frac{3}{4}$ -in. SFRC gradation curve is also shown as reference in Figure 1. Available aggregates were proportioned in quantities to nearly match the proposed gradation curve. Density-void values of this combination were determined by dry-rodding of aggregates.

An iterative process of mix design and trial batching was performed to establish paste volume requirements for the aggregate combination. Several factors were held constant for all trial mixes and later specimen fabrication. The water-cement ratio was fixed at 0.4, slump at 4 to 5 in. before the addition of fibers, and the air content fixed at 5 percent of the total mix

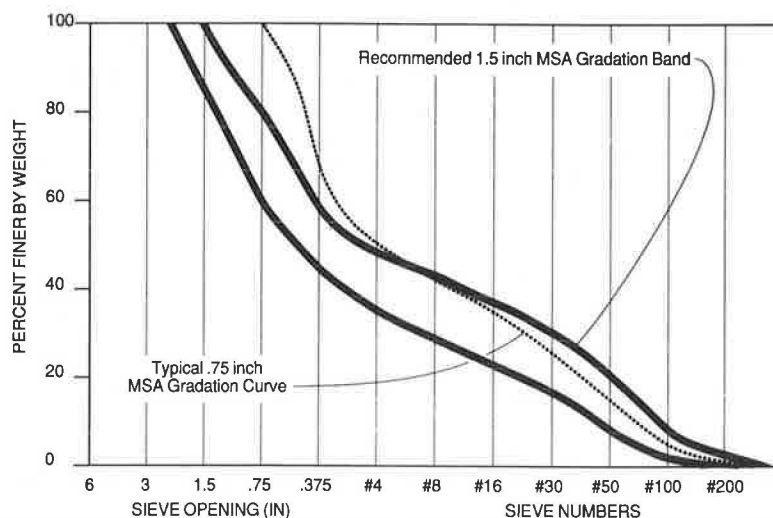


FIGURE 1 Recommended gradation curve for 1 $\frac{1}{2}$ in. MSA fiber reinforced concrete.

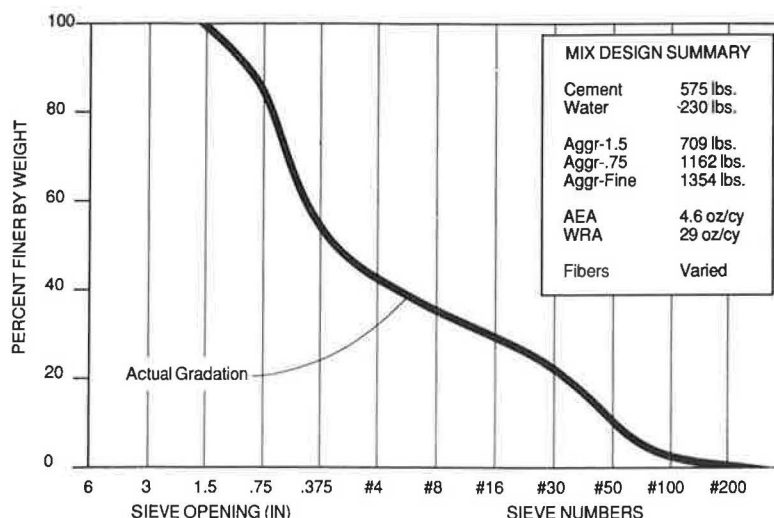


FIGURE 2 Mix design summary and aggregate gradation.

volume. Batch quantity adjustments were not made for differing fiber quantity additions as steel volumes constituted less than 1.5 percent of the total mix volume.

The "fit the aggregates to the gradation curve" proportioning method resulted in a good blend of aggregates in addition to being easy to implement. The 1½-in. MSA gradation curve and mix proportions shown in Figure 2 provided good workable mixes while also attaining respectable strength and performance levels. Sufficient large aggregate was available in the mix to be a truly 1½-in. MSA mix and also provide enough fine aggregate for workability. The increased fine aggregate content provided better strength parameters as well as reduced cement content. The enhanced workability seemed to allow better consolidation of the mix.

LOAD-DEFLECTION TESTING

Load-deflection curves are a standardized method of quantifying the energy a beam absorbs during its load-induced flexural deflection history. The area under the curve represents the energy absorbed by the composite material. Several means of numerically communicating the data have been proposed (3), but only recently has one been shown to be superior.

Briefly, ASTM C 1018 toughness index (4) is a dimensionless parameter that defines or fingerprints the shape of the load-deflection curves. 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. The term I_5 is the toughness index at 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. Figure 3 shows this relationship and the ideal elastic-plastic performance.

Beams, 6 × 6 × 21 in., spanning 18 in., were tested in flexure in pairs at approximately 7, 14, and 28 days. During the flexure test, concurrent load on and deflection of the beam were recorded to establish the load-deflection history. This testing was done as prescribed in ASTM C 1018.

Beams were mounted on a load frame similar to that described in ASTM C 78. Two linear voltage differential transducers (LVDT) were positioned on either side of the beam to track the vertical deflection of each side of the beam centerline during loading. Readings from the LVDTs and a pressure transducer indicating applied load were collected by a micro-computer equipped with an analog-to-digital interface board. Application of load was performed manually, while data acquisition was done automatically at 3-sec intervals.

Beams were loaded at a constant rate of third point deflection of approximately 0.02 in./min, tracked with a 0.0001-in.-increment dial indicator mounted on the testing machine platen.

Table 2 summarizes the results of the load-deflection testing. The effects of fiber type and concentration on ultimate load, load at first crack, toughness indexes, and toughness ratios are shown here. Visual observation of beams after testing shows a high variability in the fiber distribution for some of the beams. Because of the length of the fibers, the large aggregate, and the relative mold dimensions, this variability can be expected. Fiber counts of selected beams that displayed out-of-the-ordinary ultimate strength values showed high fiber concentrations or extreme fiber alignment in the tensile zone of the beam. Low ultimate strength values resulted from low fiber concentrations or nonpreferential alignment of fibers in the beam tensile zone. Because of the large load capacity of some fibers, small

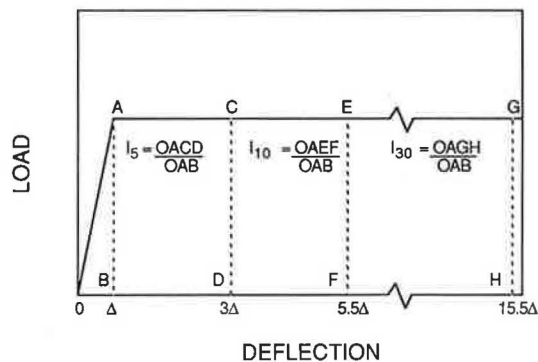


FIGURE 3 Idealized load-deflection curve for elastic-plastic material.

TABLE 2 FLEXURAL LOAD-DEFLECTION DATA SUMMARY

BEAM	DAYS AFTER CAST	MAXIMUM LOAD LBS.	FIRST CRACK LOAD	INDEXES				
				I5	I10	I30	I10/I5	I30/I10
B2-60-A	7	11410	5600	6.62	16.63	54.19	2.50	3.28
B2-60-B	7	9586	5000	5.78	14.14	52.28	2.45	3.70
B2-60-C	17	7762	5780	5.26	11.75	37.52	2.24	3.19
B2-60-D	17	6943	6600	5.00	10.05	29.81	2.01	2.97
B2-60-E	29	9877	7400	5.21	11.31	36.84	2.17	3.26
B2-60-F	29	10097	7600	5.46	11.96	35.81	2.19	2.99
B2-100-A	7	10547	5200	6.23	15.36	53.99	2.47	3.51
B2-100-B	7	14512	6300	6.82	17.26	60.12	2.53	3.48
B2-100-C	13	17349	8400	6.66	16.51	50.05	2.48	3.03
B2-100-D	13	19270	7300	7.64	20.23	68.37	2.65	3.38
B2-100-E	29	21129	9500	6.76	17.09	54.21	2.53	3.17
B2-100-F	29	19111	9500	5.90	14.59	52.17	2.48	3.58
R2-60-A	7	8943	5300	6.61	14.68	38.22	2.22	2.60
R2-60-B	7	9516	5800	5.88	13.95	43.99	2.37	3.15
R2-60-C	12	8494	6100	5.88	12.34	32.58	2.10	2.64
R2-60-D	12	7022	5400	4.46	9.87	16.78	2.21	1.70
R2-60-E	28	11111	7800	5.50	12.27	37.88	2.23	3.09
R2-60-F	28	13472	6600	6.49	15.54	46.75	2.39	3.01
R2-100-A	7	10459	7300	5.90	12.24	29.24	2.07	2.39
R2-100-B	7	8767	4700	5.63	13.70	49.21	2.43	3.59
R2-100-C	18	11683	7000	5.48	13.00	42.06	2.37	3.24
R2-100-D	18	15410	7000	7.26	18.07	57.15	2.49	3.16
R2-100-E	28	14344	8900	5.54	12.51	41.15	2.26	3.29
R2-100-F	28	22635	14400	6.03	13.53	39.51	2.24	2.92
F2-60-A	7	5410	5000	5.29	9.42	19.41	1.78	2.06
F2-60-B	7	5648	5600	4.47	7.45	13.89	1.67	1.86
F2-60-C	18	7287	7200	3.52	3.87	5.49	1.10	1.42
F2-60-D	18	6784	6700	3.85	6.07	8.99	1.58	1.48
F2-60-E	28	8229	8000	4.16	4.51	6.37	1.08	1.41
F2-60-F	28	7939	7600	3.52	4.01	^a	1.14	^a
F2-200-A	9	8485	6800	5.70	11.03	26.73	1.94	2.42
F2-200-B	9	8555	7600	5.28	10.27	23.20	1.95	2.26
F2-200-C	14	12194	9000	6.14	11.72	23.88	1.91	2.04
F2-200-D	14	10873	8600	5.76	10.84	22.90	1.88	2.11
F2-200-H	26	11675	9000	5.63	9.94	17.92	1.76	1.80

^aBeam failure before service level deflection.

changes in concentration can result in large variations in beam load capacities.

From a study of Table 2, it is not difficult to find specimens that contain abnormal fiber distribution. These abnormalities do not prevent sound conclusions' being drawn from these data, though conclusions may not be as specific as hoped.

Flexural testing of control mixes containing no fibers showed typical 28-day load capacities of 7,500 to 8,000 lb. In most cases, the addition of fibers significantly increased the ultimate flexural load capacity of the beams. However, first-crack load capacity of SFRC mixes showed little or no improvement over the control mixes.

The addition of hooked fibers (B2 mixes) and corrugated fibers (R2 mixes) significantly increased ultimate load capacity of beams at all fiber loadings, but most notably at the higher 100 lb/yd³ range. Few data were produced for fiber loadings of 80 lb/yd³, but it appears that the greatest increase is after the fiber loading exceeds 80 lb/yd³. The addition of straight fibers (F2 mixes) showed minor increases in ultimate load capacity for fiber loadings up to 120 lb/yd³, with the highest increase at the 200 lb/yd³ loading.

Review of the toughness data shows that no correlation between toughness values and the age of the specimen at time of loading can be made. This is not surprising as toughness is a relationship of areas under the load-deflection curve. To ease the assimilation of data, the indexes for a set of beams have

been averaged and rounded to the appropriate level of significance. These data are contained in Table 3.

Space limitations prohibit reproducing all the load-deflection curves for each beam tested. Figures 4, 5, and 6 show the load-deflection history of a specific beam that is typical for most of the beams tested for each fiber type. Based on ASTM C 1018 toughness index definitions, an approximate load-deflection curve can be visualized from the data for each beam listed in Table 2.

Nearly ideal load-deflection curve slopes were maintained through the I10 level for all mixes except for the straight fiber

TABLE 3 LOAD-DEFLECTION TOUGHNESS INDEX SUMMARY

Mix	I5	I10	I30	I10/I5	I30/I10
Ideal	5	10	30	2.0	3.0
B2-60	5	13	41	2.3	3.2
B2-100	7	17	56	2.5	3.4
R2-60	6	13	40	2.3	2.9
R2-100	6	14	42	2.3	3.0
F2-60	4	6	^a	1.4	^a
F2-200	6	11	23	1.9	2.1

^aBeam failure before service level deflection.

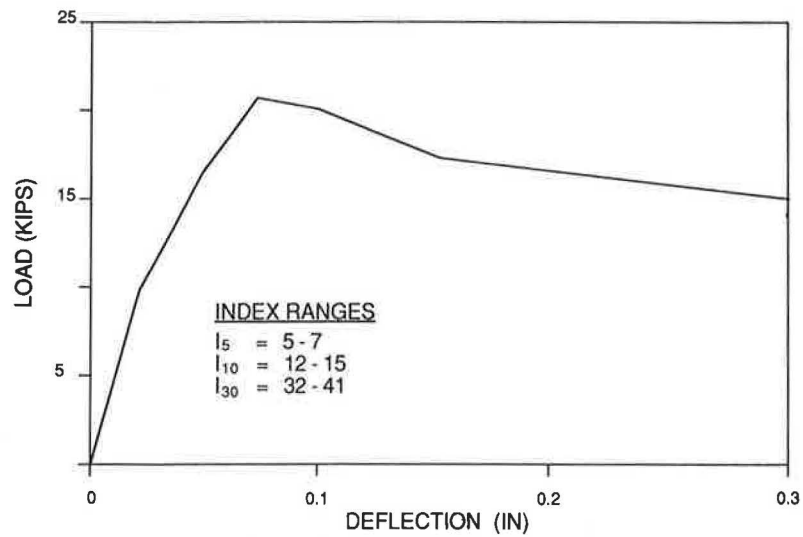


FIGURE 4 Hooked-fiber mix (B2-100-29) load-deflection curve.

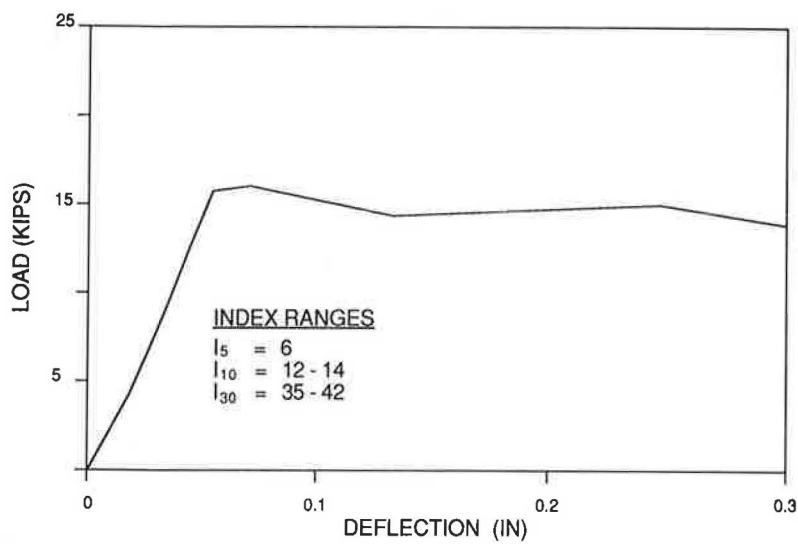


FIGURE 5 Corrugated-fiber mix (R2-100-18) load-deflection curve.

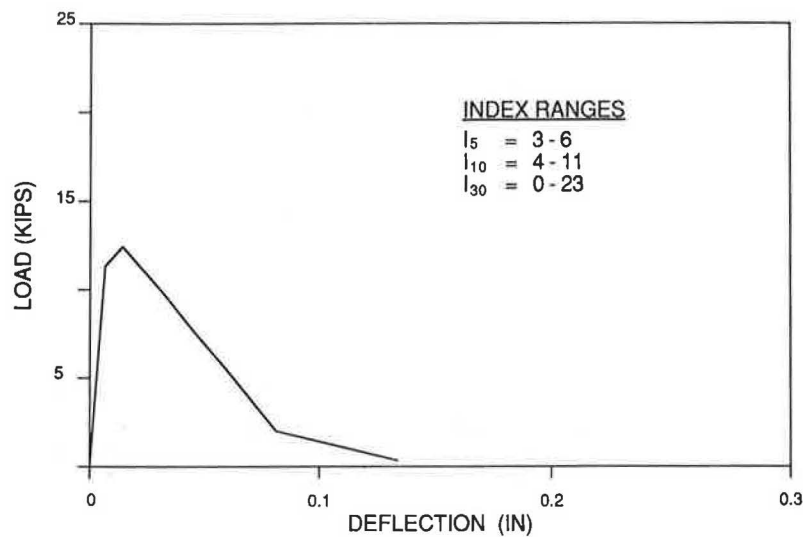


FIGURE 6 Straight-fiber mix (F2-200-14) load-deflection curve.

at low fiber loadings (F2-60 mix), which performed below the ideal level. Less than ideal elastic-plastic performance of the beam is indicated by I5 and I10 indexes less than 5 and 10, respectively.

The toughness performance of the hooked-fiber mixes (B2 mixes) and the corrugated-fiber mixes (R2 mixes) equaled or exceeded the ideal elastic-plastic performance limits, as defined earlier in this paper.

The straight-fiber mixes (F2 mixes) performed poorly at the low fiber loadings. Improved performance was observed at the higher fiber loading; however, ideal elastic-plastic performance was not achieved at the high deflection levels.

Improved load-deflection performance is most efficiently achieved by using fibers that equal or exceed the maximum-aggregate size rather than using large volumes of short fibers. A large volume of short fibers has much less effect on load-deflection performance than does a small volume of long fibers.

COMPRESSIVE STRENGTH TESTING

Cylinders, 6 × 12 in., were tested in pairs at 7, 14, and 28 days of age to determine the ultimate compressive strength.

The addition of fibers produced a slight to moderate increase in compressive strength of cylinders at all the age levels. Although the data show a tendency for higher compressive strength values for mixes with higher fiber concentrations at all age levels and fiber types, the compressive strength is not sensitive to these factors. Rather, the addition of fibers increases the compressive strength to the point where further fiber additions have a minimal effect in the range of fiber loadings considered.

IMPACT RESISTANCE TESTING

Impact resistance testing was performed on specimens sawn from the center of 6 × 12-in. cylinders. Impact specimens measured 2½ in. thick by 6 in. in diameter. Specimen pairs

were tested at 7, 14, and 28 days. A description of the test equipment and procedure is contained in "Measurement of Properties for Fiber Reinforced Concrete," (5).

A 10-lb weight is dropped from a height of 18 in. to impact on the center of the specimen. The number of impacts or blows to the specimen causing the first visible crack and ultimate failure was recorded. Ultimate failure is apparent when the specimen deforms to a diameter of 6¾ in., at which time it contacts the framework supports of the test device. Testing was terminated after 500 blows if failure had not yet occurred.

Past impact resistance testing has provided highly variable results. Unfortunately, no better practical test is presently available, although other methods are available. In this study, the use of large aggregate and long fibers added to the variability of the results. The test does provide an economical measure of specimen performance relative to control specimen performance in an impact environment.

Figure 7 provides a comparison of average impact test results in bar chart form for the three fiber mixes and a control mix. The addition of fibers significantly increased the impact performance, as simulated by this test, of the large-aggregate concrete.

FATIGUE TESTING

Beams for fatigue testing were standard cured for approximately 70 to 90 days before the start of testing. As fatigue testing spanned a period of 2 months, testing of specimens at ages greater than 60 days reduced variability in results, which at earlier ages may have significantly affected the results. Once fatigue testing began, further moist curing was not undertaken. Four sets of 12 beams each were fabricated for testing. The four sets consisted of the control mix (beams C1–C12), the hooked-fiber mix (beams B1–B12), the corrugated-fiber mix (beams R1–R12), and the straight-fiber mix (beams F1–F12).

A minimum of two beams from each set were tested in static flexure to establish the ultimate strength value for each set. Additional beams were tested in static flexure if results were

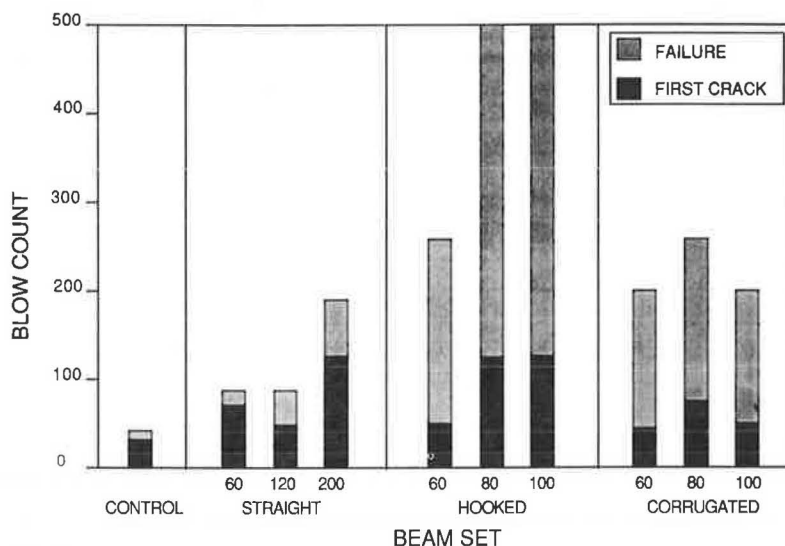


FIGURE 7 Average impact resistance bar chart.

highly variable or questionable. Beams were then tested at varying percentages of the ultimate strength to establish the load at which the beam could tolerate 2 million nonreversed cycles of the applied load. It was not practical to continue testing past 2 million cycles for reasons of time and expense. Using a loading frequency of 20 Hz, testing a single beam to 2 million cycles takes approximately 28 hr. After testing of the two beams verified the value of the endurance limit for the beam set, the remaining beams were tested in static flexure to provide more data to better establish the ultimate strength values.

Fatigue data are generally displayed as an S-N curve (stress ratio versus number of loadings), where the stress ratio is the actual loading stress as a percentage of the modulus of rupture. As beam sizes were nearly constant for all specimens in this study, the load values will be presented in units of force (lb) rather than stress or stress ratio. Figures 8 through 11 show

load versus number of loadings for the four mixes tested in fatigue. The endurance load is the maximum load at which the beam will perform through an infinite number of loadings. The endurance limit was calculated two ways: as the ratio of endurance load to ultimate static load for the same beam set (within set endurance limit), and as the ratio of the endurance load to the ultimate static load for the control beam set that contains no fibers.

From a study of Figures 8 through 11 it is apparent that the data are highly variable. Some data were discarded after observing poor fiber distribution in the fractured face.

The ultimate static load of the control mixes was measured at 6,900 lb with an endurance load of 4,000 lb after 2 million cycles. The fatigue performance for the control mix is shown in Figure 8. The endurance limit is calculated to be 57 percent, which compares favorably with fatigue testing performed by others on conventional concretes.

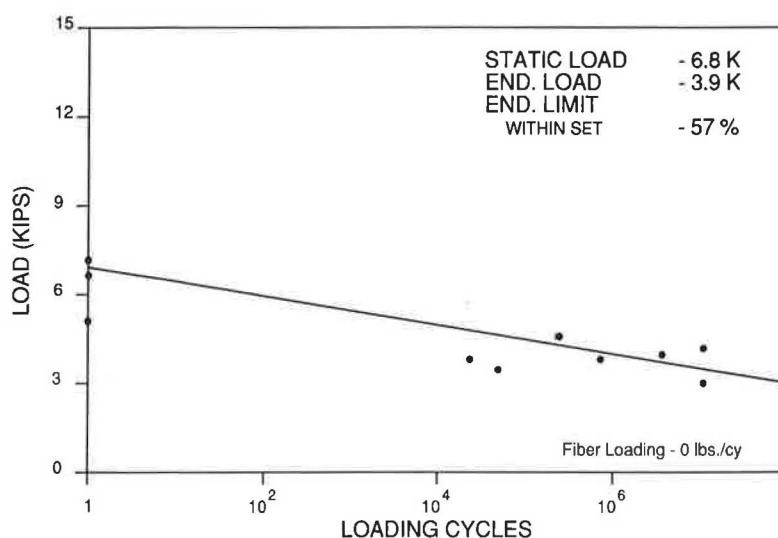


FIGURE 8 Load versus loading cycles for endurance limit of control mix.

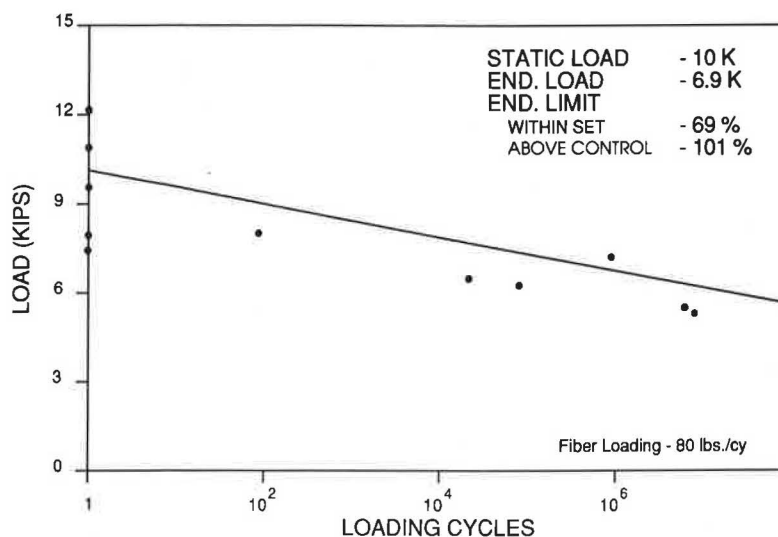


FIGURE 9 Load versus loading cycles for endurance limit of hooked-fiber mix.

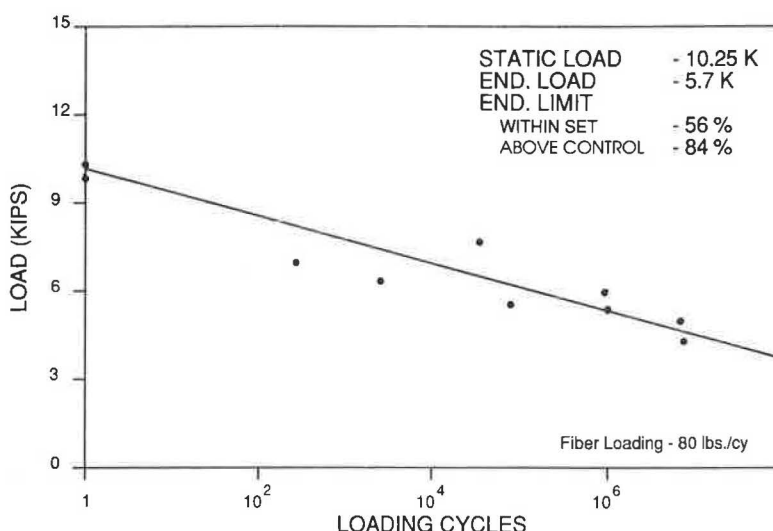


FIGURE 10 Load versus loading cycles for endurance limit of corrugated-fiber mix.

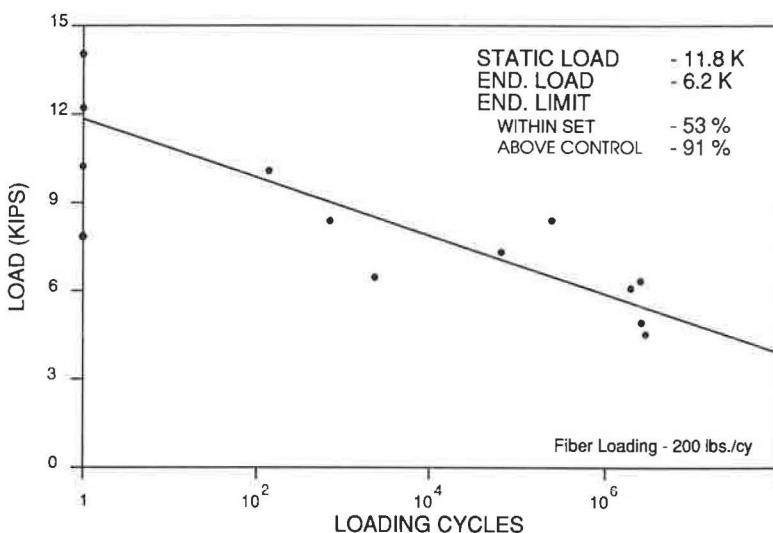


FIGURE 11 Load versus loading cycles for endurance limit of straight-fiber mix.

Ultimate static load capacities for the hooked fiber mixes ranged from 7,500 to 17,075 lb. Highly variable fiber distribution and fiber alignment along beam mold surfaces caused this load range. After visual observation of the fractured faces of the beams, the value of 10,000 lb was determined to be representative of the ultimate static-load capacity for this beam set having a fiber uniformly distributed. The endurance load was 6,500 lb, resulting in a within-set endurance limit of 65 percent. The endurance limit as a percentage of the control ultimate static-load capacity is 94 percent.

Likewise, the corrugated fiber mixes displayed significant variability as seen in Figure 10. The cause of this variability is the use of large aggregate with long fibers and relatively small specimen dimensions. The ultimate static-load capacity was determined to be 10,250 lb, and the endurance load for this beam set was 6,000 lb. The within-set endurance limit for this

beam set is 59 percent, and the endurance limit as a percentage of the control ultimate static-load capacity is 87 percent.

The straight-fiber mixes exhibited an average ultimate static-load capacity of 11,800 lb and an endurance load of 6,500 lb. The within-set endurance limit for this beam set is 53 percent and the endurance limit as a percentage of the control ultimate static-load capacity is 94 percent.

Table 4 summarizes the load capacities and endurance limits for the four beam sets. In general, with the fiber types and fiber concentrations used, the addition of fibers increased the endurance load from 3,900 to 6,800 lb, or 57 percent over the control mix endurance load. The within-set endurance limits for the corrugated (56 percent) and straight (53 percent) beam sets did not significantly change from those of the control beam (57 percent) set, while the hooked-fiber set was slightly higher at 69 percent. The addition of fibers increased ultimate static

TABLE 4 FATIGUE ENDURANCE LIMIT SUMMARY

Beam Set	Maximum Static Load (lb)	Endurance Load (lb)	Endurance Limit Percentage	
			Within Set	Above Control
Control	6,800	3,900	57	
Hooked	10,000	6,900	69	101
Corrugated	10,250	5,700	56	84
Straight	11,800	6,200	53	91

strengths as well as the endurance load capacities, netting minor percentage increases. This is why endurance limits of the SFRC beam sets are not significantly higher than the endurance limit for the control mix. The addition of fibers significantly improved fatigue performance of control mixes, although little within-set improvement was observed. These tests on large-aggregate mixes show much less effect of the fibers on the fatigue properties than do fatigue studies by others, which have shown within-set endurance limits as high as 90 to 95 percent for SFRC mixes with $3/4$ -in. MSA.

CONCLUSIONS

The toughness properties of $1\frac{1}{2}$ -in. MSA concrete were significantly increased by the addition of appropriate-length steel fibers. Better toughness performance of mixes was observed when the fiber length exceeded the maximum-size aggregate than in mixes where the fiber length was less than the maximum-size aggregate.

Slow-load flexural toughness properties of mixes with hooked fibers were excellent at all fiber contents. Most mixes exhibited near-ideal elastic-plastic performance. The addition of hooked fibers to control mixes increased the first-crack load and ultimate load capacities.

Slow-load flexural toughness properties of SFRC mixes with corrugated fibers were excellent at all the fiber contents. The fibrous concrete exhibited near-ideal elastic-plastic performance. The addition of corrugated fibers to control mixes increased the first-crack load capacities and ultimate load capacities.

Slow-load flexural toughness properties of mixes with short, straight fibers were poor for most fiber loadings, although improved performance occurred at extremely high fiber contents. The addition of short, straight fibers to control mixes increased the first-crack load and ultimate load capacities.

The addition of steel fibers to $1\frac{1}{2}$ -in. MSA control mixes tended to increase the compressive strength of 6×12 -in. cylinder specimens. Compressive strength values were not sensitive to the fiber type or to fiber loading, although minor increases in compressive strengths were observed at very high fiber contents.

Impact resistance of specimens was significantly increased by the addition of long hooked and corrugated fibers to mixes. Increased fiber contents increased impact resistance. The addition of short, straight fibers had little effect on impact resistance except at high fiber contents where impact resistance significantly increased.

The addition of steel fibers significantly improved the fatigue properties of SFRC with $1\frac{1}{2}$ -in. MSA when compared to the control specimens. Endurance limits of SFRC mixes when compared to control mixes were increased 87 to 94 percent by the addition of steel fibers, and little percentage change was observed in the within-set endurance limits.

Additional data are necessary for fatigue endurance limits of SFRC mixes containing large maximum-sized aggregate. With these data, correlations between endurance limits, impact resistance, toughness properties, and other properties may be possible. Endurance limits of SFRC can be correlated with slow-load flexural toughness, producing materials that can be more easily specified and tested at much less expense.

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