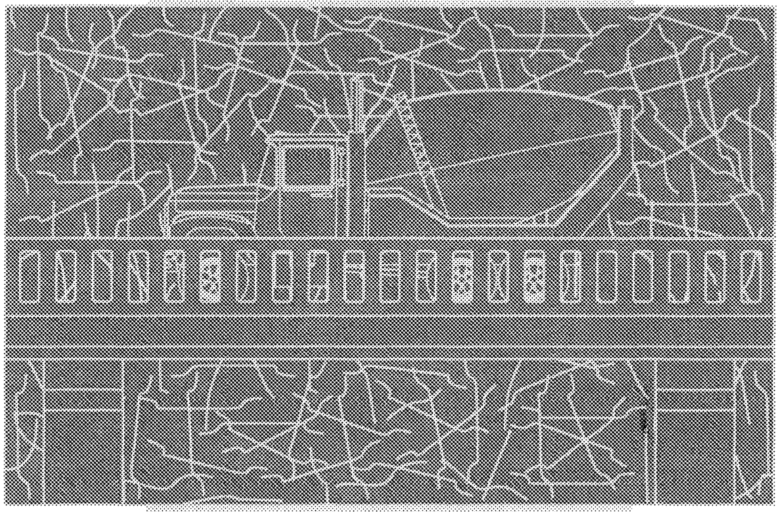
FINAL REPORT

INVESTIGATION OF FIBER-REINFORCED CONCRETE FOR USE IN TRANSPORTATION STRUCTURES



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16. Abstract

This report presents the results of a laboratory investigation to determine the properties of fiber-reinforced concretes (FRCs) with steel (hooked-end), polypropylene (monofilament and fibrillated), and the recently introduced polyolefin fibers (monofilament) for use in pavement and bridge deck overlay applications. Concrete properties in the unhardened and hardened states were evaluated and compared. Although the ultimate splitting tensile strength, compressive strength, and first crack strength were higher in most of the FRCs, when strength values were adjusted for changes in air content, only a few batches had higher strengths. The addition of fibers resulted in great improvements in flexural toughness and impact resistance.

Parallel with this study, three FRC pavement overlays were applied in Virginia in 1995. The FRCs used in these projects were similar to those used in this laboratory investigation, with similar fiber volumes, types, and sizes. To implement the findings of the study successfully, the performance of these FRC pavement overlays is being monitored.

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(The opinions, finding, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

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ABSTRACT

This report presents the results of a laboratory investigation to determine the properties of fiber-reinforced concretes (FRCs) with steel (hooked-end), polypropylene (monofilament and fibrillated), and the recently introduced polyolefin fibers (monofilament) for use in pavement and bridge deck overlay applications. Concrete properties in the unhardened and hardened states were evaluated and compared. Although the ultimate splitting tensile strength, compressive strength, and first crack strength were higher in most of the FRCs, when strength values were adjusted for changes in air content, only a few batches had higher strengths. The addition of fibers resulted in great improvements in flexural toughness and impact resistance.

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INTRODUCTION

Hydraulic cement concrete (HCC) is the most widely used construction material in transportation structures. Although HCC is versatile and economical, in severe environments, the service life of some HCC structures is prematurely shortened, resulting in costly repairs. Ideally, long-lasting concrete should be highly resistant to crack initiation and propagation. Unfortunately, concrete's low tensile strength and brittle characteristics make it prone to cracking. The inclusion of fibers provides an energy absorbing capacity that can maintain the structural integrity of concrete during fracture.[1] Since the 1960s, fiber-reinforced concrete (FRC) has been used to increase the durability of transportation structures. The Virginia Department of Transportation (VDOT) used steel fibers in 1974 for a bridge deck overlay[2] and recently used steel and plastic fibers in bridge deck and pavement overlays on an experimental basis. FRC has also been used in overlays in Ohio to minimize cracking.[3]

Cracks allow the penetration of water or solutions into concrete, which may cause deterioration through four types of environmental distress: corrosion of the reinforcement, alkali-aggregate reaction, freezing and thawing, and attack by sulfates. Corrosion is the most prevalent.[4] In each case, expansion within the concrete results in destructive forces causing cracking and disintegration.

Cracks occur in concrete even before environmental distress occurs. Volumetric changes resulting from variations in moisture and temperature and deformations caused by loading may cause cracking even at very early stages in the service life of a structure.[5,6] In FRCs, cracks are restrained from propagation, decreasing the concrete's rate of deterioration.

Fibers are expected to improve the properties of concrete both in the unhardened and hardened states. In the unhardened state, fibers increase resistance to plastic shrinkage.[7] In the hardened state, fibers improve the strength (impact, tensile, and flexural) and toughness of concrete, depending on fiber type, shape, size, and amount.[8-10] This study evaluated the feasibility of using fibers in transportation facilities.

PURPOSE AND SCOPE

The purpose of this study was to evaluate the effect of different fiber types and volumes on HCC. Commonly used steel and polypropylene fibers and the recently introduced polyolefin fibers were used in different amounts and sizes. FRCs were tested for compressive strength, splitting tensile strength, impact resistance, first crack strength, and flexural toughness. The results of this study will provide an opportunity to compare laboratory results with field performance data from the FRC pavement overlays in Virginia. An initial evaluation is provided in this report, and further evaluation is planned.

EXPERIMENTAL PROGRAM

Materials

The types of fibers used in this investigation were steel (hooked-end), polypropylene, and polyolefin. Table 1 describes the fiber types and their material properties. All batches contained 377 kg/m^3 (635 lb/yd^3) of cementitious material consisting of 60 percent Type I/II cement and 40 percent ground granulated blast furnace slag (slag) by weight. The coarse aggregate was a granite gneiss with a nominal maximum size of 13 mm (0.5 in). The fine aggregate was a

TABLE 1. Fiber Characteristics

Fiber	Length mm (in)	Diameter mm (in)	Aspect Ratio (l/d)	Yield Strength MPA (ksi)	Elastic Modulus MPA (ksi)	Specific Gravity
Steel Fibers 30/50	30 (1.2)	0.5 (0.02)	60	1170 (170)	200000 (29000)	7.87
Steel Fibers 60/80	60 (2.4)	0.8 (0.03)	75	1170 (170)	200000 (29000)	7.87
Polypropylene (fibrillated)	19 (0.75)	N/A	N/A	550-750 (80-110)	3450 (500)	0.91
Polypropylene (monofilament)	19 (0.75)	5.33E-4 (2.1E-7)	35620	550-750 (80-110)	3450 (500)	0.91
Polyolefin	25 (1)	0.40/0.57* (0.016/0.022)	51-77	275 (40)	2650 (384)	0.91
Polyolefin	51 (2)	0.66/1.0* (0.026/0.041)	44-63	275 (40)	2650 (384)	0.91

*Fibers have elliptical cross section (Diameter 1/Diameter 2).

siliceous sand. A commercially available air-entraining admixture, water-reducing admixture, and naphthalene-based high-range water-reducing admixture (HRWRA) were used for all batches.

Mix Proportions

Twenty-four batches of concrete were prepared. The same mixture proportions and ingredients were used for all batches (Table 2). The amount and type of fibers used corresponded to the amounts currently being used in experimental overlay projects in Virginia. Lower and higher fiber amounts were also tested. Tables 3 through 6 present the amounts and types of fibers used in each of the 24 batches.

All batches had a water–cementitious material ratio (W/CM) of 0.45, with varying amounts of HRWRA added to obtain workable concretes (Table 3). The concretes were mixed in accordance with ASTM C192. Fibers were added as the last ingredient. As in the experimental overlays, the mixture proportions were not adjusted for the addition of fibers.

TABLE 2. Mixture Proportions

Ingredients	Amount (kg/m^3)	 (lb/yd^3)
Portland Cement	226	381
Slag	151	254
Coarse Aggregate	890	1500
Fine Aggregate	839	1413
Water	170	286
Air Entraining	67 ml	2.3 oz
Water Reducer	477 ml	16.4 oz
HRWRA	See Table 3	

TABLE 3. Properties of Fresh Concrete

Fiber	Fiber Content kg/m³	% vol	Slump mm (in)	Inverted Slump (sec)	HRWRA mL/m³ (oz)	Air Content (%)	Unit Weight kg/m³(lb/ft³)	Temp. C
None	0.0	0.00	65 (2.5)	3	0	6.0	2310 (144)	23
25 mm Polyolefin	8.9	0.98	20 (0.8)	9	1760 (46)	3.5	2400 (150)	24
	11.9	1.30	5 (0.3)	22	1760 (46)	3.0	2420 (151)	24
	14.8	1.63	15 (0.5)	23	1760 (46)	3.2	2370 (148)	24
51 mm Polyolefin	8.9	0.98	50 (2.0)	4	375 (10)	4.0	2270 (142)	22
	11.9	1.30	25 (1.0)	5	375 (10)	4.4	2270 (142)	21
	14.8	1.63	5 (0.3)	7	375 (10)	4.4	2300 (144)	21
Polyprop. fibrillated	1.8	0.20	30 (1.3)	5	1760 (46)	5.3	2340 (146)	24
	2.7	0.30	25 (1.0)	4	1760 (46)	6.3	2280 (142)	24
	4.6	0.50	15(0.5)	10	1760 (46)	5.7	2280 (142)	23
	6.4	0.70	15 (0.5)	6	2515 (65)	7.5	2250 (140)	24
Polyprop. mono.	0.9	0.10	40 (1.5)	5	1260 (33)	4.5	2350 (146)	24
	2.7	0.30	20 (0.8)	8	1760 (46)	6.0	2290 (143)	21
	4.6	0.50	0	12	1760 (46)	7.0	2260 (141)	24
Steel 30/50	8.9	0.11	65 (2.5)	4	1005 (26)	6.8	2300 (144)	21
	14.8	0.19	50 (2.0)	3	1260 (33)	7.0	2270 (142)	22
	29.7	0.38	57 (2.25)	3	1260 (33)	6.6	2280 (142)	23
	44.5	0.57	50 (2.0)	3	1005 (26)	5.7	2310 (144)	24
	56.4	0.72	40 (1.5)	5	1260 (33)	7.4	2280 (142)	22
	68.3	0.87	45 (1.8)	5	1760 (46)	6.5	2320 (145)	22
Steel 60/80	8.9	0.11	76 (3)	3	1005 (26)	7.1	2260 (141)	23
	14.8	0.19	30 (1.3)	5	1005 (26)	5.0	2400 (150)	23
	29.7	0.38	25 (1.0)	8	1260 (33)	4.2	2400 (150)	24
	44.5	0.57	20 (0.8)	9	1260 (33)	3.8	2440 (152)	24

TABLE 4. Properties of Hardened Concrete

Fiber	Fiber Content kg/m3	 % vol	Compressive MPa (psi)	Split Tensile MPa (psi)
None	0.0	0.00	41.7 (6050)	4.26 (620)
25 mm	8.9	0.98	45.3 (6570)	4.51 (655)
Polyolefin	11.9	1.30	45.6 (6620)	4.14 (600)
	14.8	1.63	47.1 (6830)	4.14 (600)
51 mm	8.9	0.98	51.6 (7490)	5.32 (770)
Polyolefin	11.9	1.30	55.7 (8080)	5.91 (855)
	14.8	1.63	49.8 (7220)	5.52 (800)
Polyprop.	1.8	0.20	46.6 (6760)	4.44 (645)
fibrillated	2.7	0.30	42.0 (6100)	4.56 (660)
	4.6	0.50	45.5 (6600)	4.80 (695)
	6.4	0.70	39.7 (5760)	4.70 (680)
Polyprop.	0.9	0.10	54.9 (7960)	4.67 (675)
mono.	2.7	0.30	45.3 (6560)	4.60 (670)
	4.6	0.50	42.0 (6090)	4.24 (615)
Steel	8.9	0.11	47.3 (6860)	4.49 (650)
30/50	14.8	0.19	40.3 (5850)	4.26 (620)
	29.7	0.38	47.1 (6830)	4.79 (695)
	44.5	0.57	40.1 (5820)	4.48 (650)
	56.4	0.72	44.1 (6390)	5.86 (850)
	68.3	0.87	46.7 (6770)	5.81 (840)
Steel	8.9	0.11	45.9 (6660)	4.53 (655)
60/80	14.8	0.19	51.4 (7450)	5.11 (740)
	29.7	0.38	51.4 (7450)	6.32 (915)
	44.5	0.57	54.8 (7950)	7.30 (1060)

TABLE 5. Impact Data

Fiber	Fiber Content kg/m^3	Fiber Content % vol	Number of Blows First crack	Number of Blows Failure	Impact Endurance
None	0.0	0.00	65	68	3
25 mm Polyolefin	8.9	0.98	51	96	45
	11.9	1.30	71	134	63
	14.8	1.63	130	207	77
51 mm Polyolefin	8.9	0.98	137	280	143
	11.9	1.30	138	362	224
	14.8	1.63	148	498	350
Polyprop. fibrillated	1.8	0.20	60	69	9
	2.7	0.30	56	69	13
	4.6	0.50	79	94	15
	6.4	0.70	111	131	20
Polyprop. mono.	0.9	0.10	75	77	2
	2.7	0.30	106	112	6
	4.6	0.50	57	65	8
Steel 30/50	8.9	0.11	59	76	17
	14.8	0.19	103	128	25
	29.7	0.38	83	105	22
	44.5	0.57	47	101	54
	56.4	0.72	140	239	99
	68.3	0.87	93	157	64
Steel 60/80	8.9	0.11	57	68	11
	14.8	0.19	66	91	25
	29.7	0.38	161	208	47
	44.5	0.57	200	269	69

TABLE 6. First Crack Strength and Flexural Toughness

	Fiber Content		First Crack	Toughness Indices			Residual Factors		
Fiber	kg/m^3	% vol	MPa (psi)	I_5	I_{10}	I_{20}	$R_{5,10}$	$R_{10,20}$	Japan
None	0.0	0.00	4.95 (720)	1	1	1	0	0	-----
25 mm Polyolefin	8.9	0.98	5.10 (740)	2.7	4.7	8.4	39.4	37.3	113
	11.9	1.30	5.35 (775)	3.1	5.5	10.5	49.3	49.8	159
	14.8	1.63	5.15 (745)	3.4	6.1	11.7	54.9	56.2	185
51 mm Polyolefin	8.9	0.98	5.65 (820)	2.6	4.6	8.6	39.4	40.3	151
	11.9	1.30	6.30 (915)	2.8	5.0	9.5	44.2	45.0	195
	14.8	1.63	5.60 (810)	3.5	6.5	13.2	59.4	67.6	247
Polyprop. fibrillated	1.8	0.20	5.40 (785)	1.7	2.4	3.9	14.9	14.8	48
	2.7	0.30	4.25 (615)	2.4	4.1	7.3	33.8	31.7	88
	4.6	0.50	5.05 (730)	2.8	5.0	9.2	44.3	42.5	129
	6.4	0.70	5.15 (745)	3.8	6.9	13.0	61.0	61.1	157
Polyprop. mono.	0.9	0.10	5.75 (835)	1.0	1.0	1.0	0.0	0.0	----
	2.7	0.30	5.40 (785)	1.7	2.5	4.0	16.0	15.3	38
	4.6	0.50	4.95 (720)	3.0	5.4	9.9	47.5	44.4	109
Steel 30/50	8.9	0.11	5.25 (760)	1.8	2.7	4.5	18.9	18.1	57
	14.8	0.19	5.10 (740)	2.6	4.5	8.3	37.8	37.7	117
	29.7	0.38	5.10 (740)	3.9	7.4	14.5	68.6	71.5	232
	44.5	0.57	5.20 (755)	4.4	8.4	16.8	80.3	83.9	263
	56.4	0.72	5.85 (850)	4.6	9.1	18.6	89.9	94.5	324
	68.3	0.87	6.05 (875)	4.9	10.2	21.2	106.0	110.0	355
Steel 60/80	8.9	0.11	4.90 (710)	1.6	2.3	3.8	14.5	14.5	54
	14.8	0.19	5.70 (825)	2.4	4.2	7.9	35.0	37.7	135
	29.7	0.38	6.00 (870)	3.5	6.5	12.7	59.2	62.5	225
	44.5	0.57	6.75 (905)	4.5	8.6	17.8	83.6	91.8	358

Test Samples

The concretes were tested in the freshly mixed state for slump (ASTM C143), inverted slump (ASTM C995), air content (ASTM C231), unit weight (ASTM C138), and temperature (ASTM C1064).

Specimens were then prepared for tests in the hardened state. Three concrete cylinders (100 by 200 mm, 4 by 8 in) were prepared for compression testing (ASTM C39). Three additional cylinders were prepared for splitting tensile strength testing (ASTM C496). Four specimens 100 by 100 by 355 mm (4 by 4 by 14 in) were prepared for first crack strength and flexural toughness (ASTM C1018) testing. Finally, a cylinder (152 by 305 mm, 6 by 12 in) was cast from which four concrete disks (152 by 63.5 mm, 6 by 2.5 in) were cut for impact testing (ACI 544.2R). Five specimens were averaged in impact testing, so an additional cylinder (152 by 305 mm) was partly filled, from which the fifth specimen was obtained.

Each mold was filled with concrete in two layers, and each layer was consolidated using a vibrating table. Vibrating time depended on the workability of the mix and was limited to 5 to 10 seconds to avoid segregation of the constituents and fiber alignment. After 24 hours, the specimens were removed from the molds and moist cured in accordance with ASTM C192 until they were tested at 28 days.

TESTS AND RESULTS

Properties of Fresh Concrete

Results of tests conducted in the freshly mixed state are presented in Table 3.

Slump and Inverted Slump

Satisfactory workability was obtained with all fibers at some addition rate, although the fibers decreased the workability of the concretes. To obtain sufficient workability, variable amounts of HRWRA were added (Table 3). Even with the use of HRWRA, slump values were low and indicative of poor workability. Inverted slump test values provide a more accurate assessment of FRC workability (ACI 544.2R). In general, inverted slump values less than 8 seconds demonstrate satisfactory workability.

Concretes with steel fibers demonstrated satisfactory workability and consolidation at the fiber volumes of 0 to 0.87 percent tested in this study. Satisfactory workability and consolidation were also obtained for the polyolefin fibers up to the 1.63 percent volume tested. A large increase in inverted slump times between the polyolefin fibers 51 and 25 mm long was observed at 1.3 and 1.63 percent volume additions and can be attributed to the larger number of fibers per unit volume associated with the reduction in fiber size (length and diameter). The larger number of fibers produced clogging at the bottom of the inverted slump cone, reducing the flow of concrete through the end of the cone. Concretes with polypropylene fibers demonstrated satisfactory workability and consolidation at fiber volumes of 0.3 percent and below. Proper consolidation was not achieved at fiber volumes greater than 0.3 percent, although workability was satisfactory with the addition of sufficient HRWRA. It appears that the use of the inverted slump test for comparing FRC workability is most significant when the comparison is made within each fiber type and geometry.

Air Content

The air content of the concretes ranged from 3 to 7.5 percent, most of them meeting the VDOT paving concrete specification (6 ± 2%). The variability of the air content, and unit weight, among batches indicates that considerable care must be used in preparing FRCs.

Properties of Hardened Concrete

In general, the properties of all the hardened FRCs tested were better than those of the control concrete. It is likely that the addition of HRWRA, among other variables, contributed to these improvements. However, in many cases, the improvements can be related to the addition of fibers.

Using a large amount of fibers without adjustments in mix proportions decreases the mechanical properties of concretes.[11] The fiber volumes investigated in this study did not appear to affect the hardened properties adversely. At fiber volumes in excess of those investigated in this study, an adjustment in mixture proportions may be necessary to counteract the increase in yield and resulting decrease in the amount of cementitious material per volume of concrete.

Compressive Strength

Three concrete cylinders were tested for compressive strength at 28 days. Table 4 shows the test results, as an average of three specimens, for the batches.

The compressive strength for the control concrete was 41.7 MPa (6050 psi). The compressive strength of the FRCs increased at least slightly at some fiber addition. In general, the FRCs with longer steel and polyolefin fibers showed the greatest increases in compressive strength (Figure 1). The FRCs with polypropylene fibers showed decreasing compressive strengths with higher volumes. This is believed to be related to difficulty in consolidation.[12]

Recent studies have indicated that adding fibers has only a minor effect on compressive strength.[13] The improvements observed in this study may be due to between-batch variability, the use of HRWRA, and the decreased air content. As for the great improvements with the longer fibers, ACI 544.2R indicates that this may be due to preferential alignment of the fibers caused by a conflict in fiber length and specimen mold size. ACI 544.2R recommends that the smallest dimension of the specimen be at least 3 times the length of the fiber. This recommendation was not followed with the longer fibers. Therefore, the compressive strength of the concretes containing 60/80 steel fibers and 51-mm polyolefin fibers may have been affected by preferential alignment.

Splitting Tensile Strength

Splitting tensile strength tests were conducted at 28 days. The averages of the three specimens are given in Table 4.

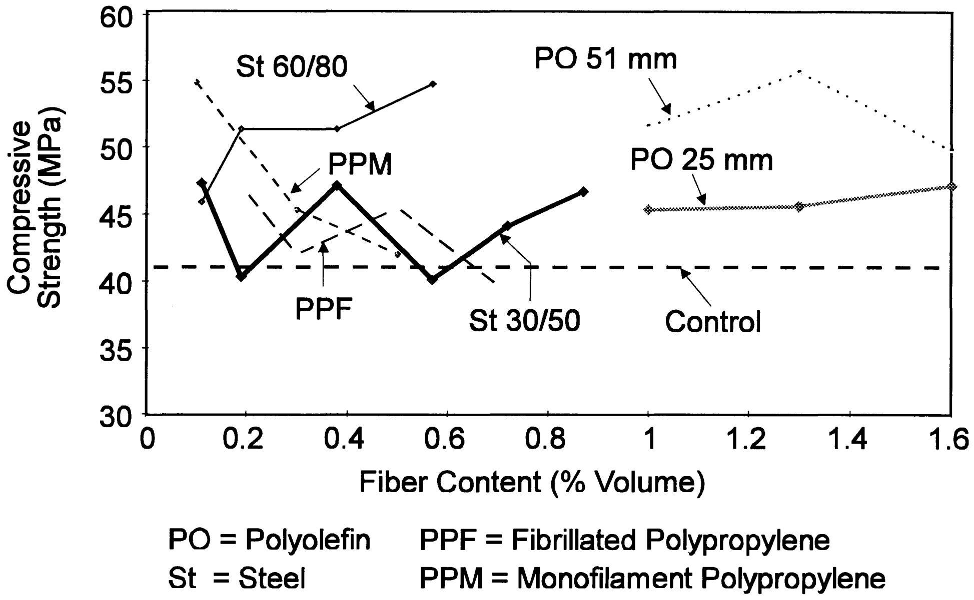

FIGURE 1. Compressive Strength

The ultimate splitting tensile strength for the control concrete was 4.26 MPa (620 psi). The FRC with polypropylene fibers showed increases of up to 10 percent. The steel FRCs showed increases of up to 70 percent. The FRC with polyolefin fibers had increases of up to 33 percent for the 50-mm fibers, but no increase for the 25-mm fibers (Figure 2). These

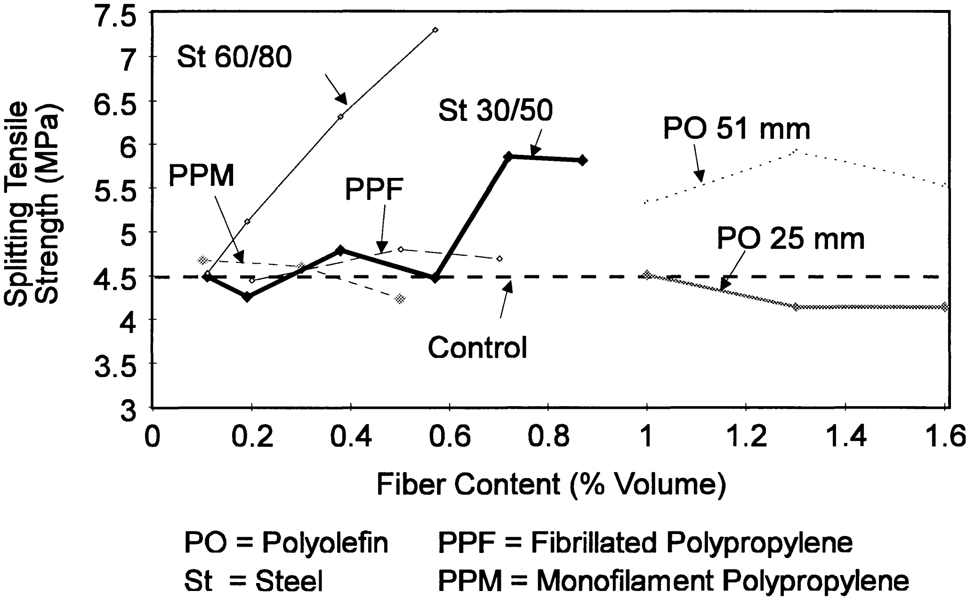

FIGURE 2. Splitting Tensile Strength

increases in ultimate strength are related to the increased resistance provided by fiber pullout and straightening as the specimen is being split.[1]

The literature indicates that the splitting tensile strength at first crack does not increase with low volumes of fibers similar to the ranges tested in this study.[14] Instead, improvements in the postcracking behavior of the specimen occur as the fibers bridge the crack. The ultimate splitting tensile strength results in this study are representative of this postcracking contribution. The first crack splitting tensile strength was not determined.

It is unlikely that the splitting tensile strength results are biased by preferential alignment of fibers. Stresses in the splitting tensile strength test are comparable to those in the compressive strength test and, therefore, any adjustment in fiber alignment that would improve compressive strength would most likely be detrimental to splitting tensile strength. ACI 544-2R does not address preferential alignment in splitting tensile strength tests.

Impact Strength: Drop Weight Test

At 28 days, the impact resistance of the concretes was determined by the drop weight test as an average of five specimens from each batch. Testing was performed using an automated impact testing machine manufactured in accordance with ACI 544.2R. The levels of distress investigated were first crack and ultimate failure. *Ultimate failure* is defined as the opening of cracks in the specimen to a point at which pieces of concrete are touching three of the four positioning lugs on the baseplate. The difference between the number of blows until first crack and ultimate failure is related to the energy-absorbing capacity of the concrete and is referred to in this report as impact endurance. The impact endurance indicates the ability of the concrete to inhibit crack propagation and widening. The results of the impact tests are given in Table 5 and Figure 3.

The results indicate that the number of blows to first crack and ultimate failure increases with increasing fiber volume and length. This effect is much more pronounced in the FRCs with polyolefin and steel fibers. There was significant variability in the number of blows to first crack, but the impact endurance was consistent within each test batch.

First Crack Strength and Flexural Toughness

To determine the first crack strength and toughness values in accordance with ASTM C1018 and eliminate the effects of settlement of the supports and crushing at the load points, a Japanese yoke was used in combination with a closed loop, servo-controlled, universal testing machine (UTM) (Figure 4). The first crack strength, toughness parameters, and toughness results

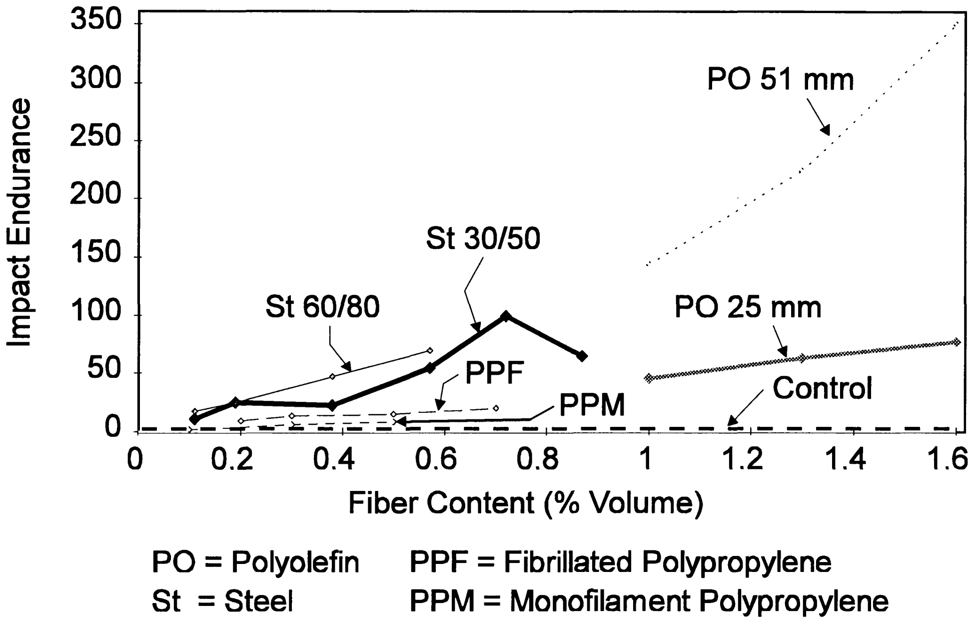

FIGURE 3. Impact Endurance

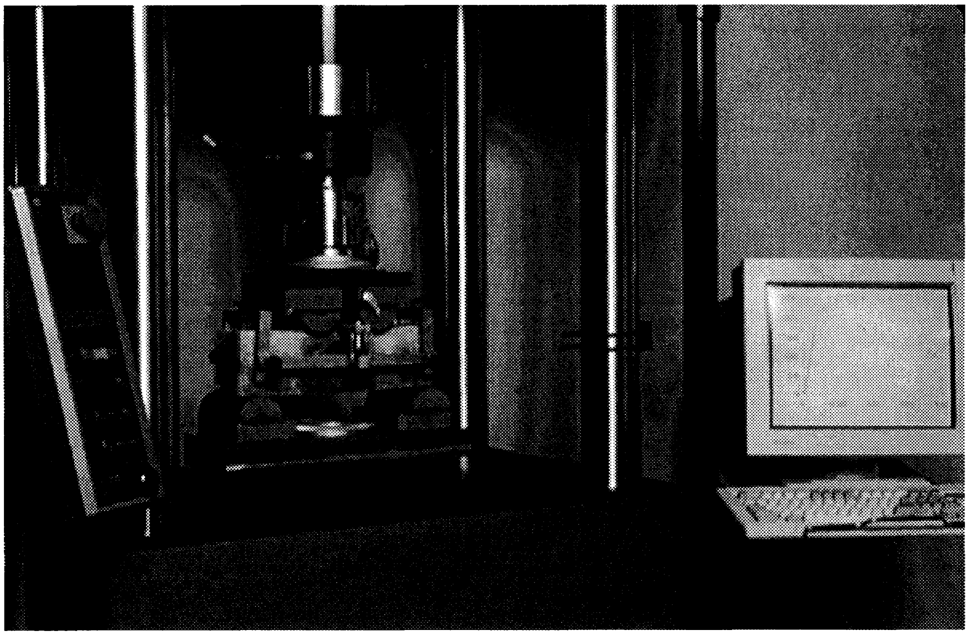

FIGURE 4. Universal Testing Machine with Japanese Yoke

using the Japanese Standard Method SF-4 are given in Table 6 as an average of four beams. In Japanese Standard SF-4, *toughness* is defined as the area under the load-deflection curve up to a deflection of span/150 or 2 mm (0.08 in) for a span length of 300 mm (12 in).[3]

The first crack strength of the control concrete was 4.95 MPa (720 psi). The results indicate that the use of fibers in concrete will result in an increase in first crack strength (Figure 5). These increases, however, may also be attributable to the use of HRWRA and changes in air content.

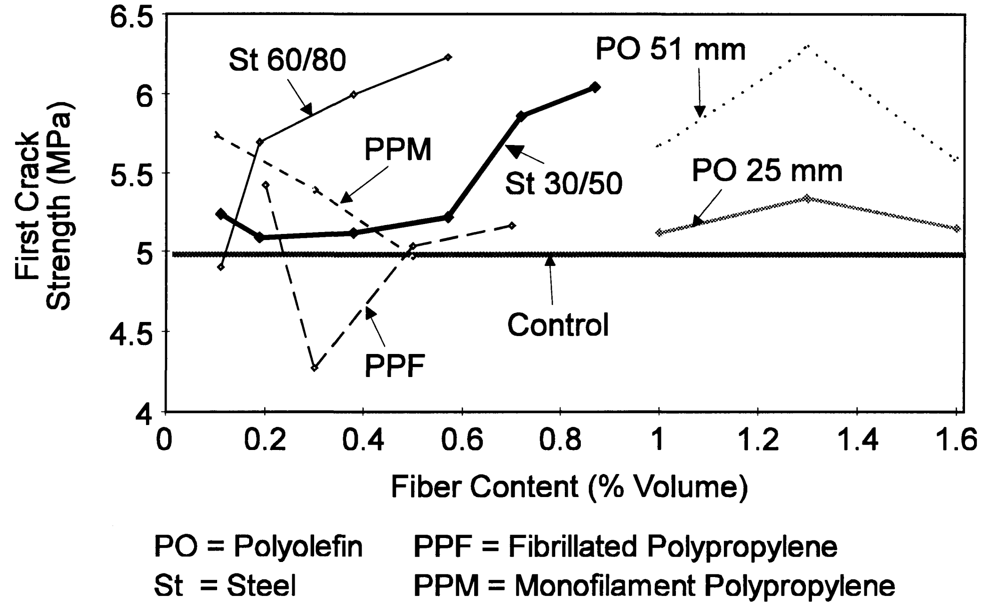

FIGURE 5. First Crack Strength

Beyond first crack, FRCs do not lose their load-carrying capability but instead transfer the load to the fibers spanning the cracked region. *Toughness* is defined as a measure of the concrete's ability to absorb energy during fracture. It is measured by a series of indices that are determined from the area under the load-deflection curve (Figures 6 through 9). The indices are computed by dividing the total area under the load-deflection curve up to a specific deflection by the area under the curve up to first crack. Toughness indices I_5, I_{10}, and I_{20} are calculated at 3, 5.5, and 10.5 times the first crack deflection, respectively. These indices are tabulated in Table 6. The results indicate increased toughness with increased fiber volume. In general, steel fibers provide the highest toughness values, followed by polyolefin and then polypropylene fibers.

In addition to the toughness indices, ASTM C1018 provides for the determination of residual strength factors. The residual strength factors represent the average postcrack load over

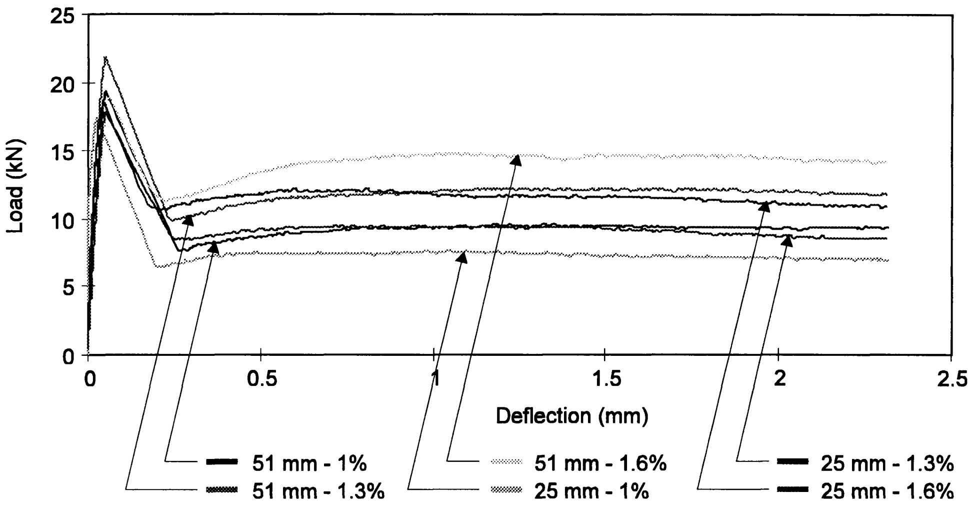

FIGURE 6. Comparison of Load: Deflection Curves for FRC with Polyolefin Fibers

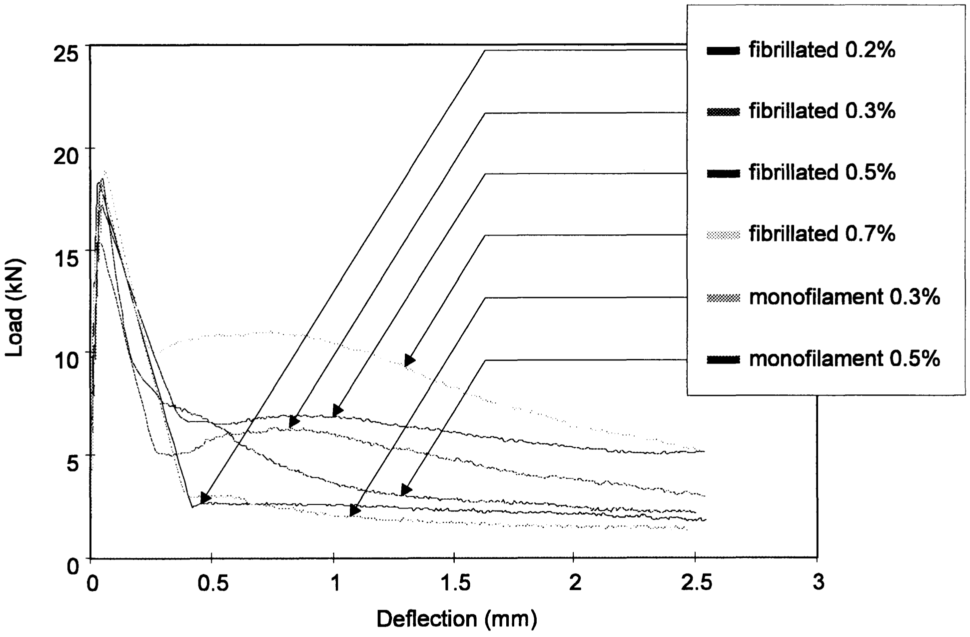

FIGURE 7. Comparison of Load: Deflection Curves for FRC with Polypropylene Fibers

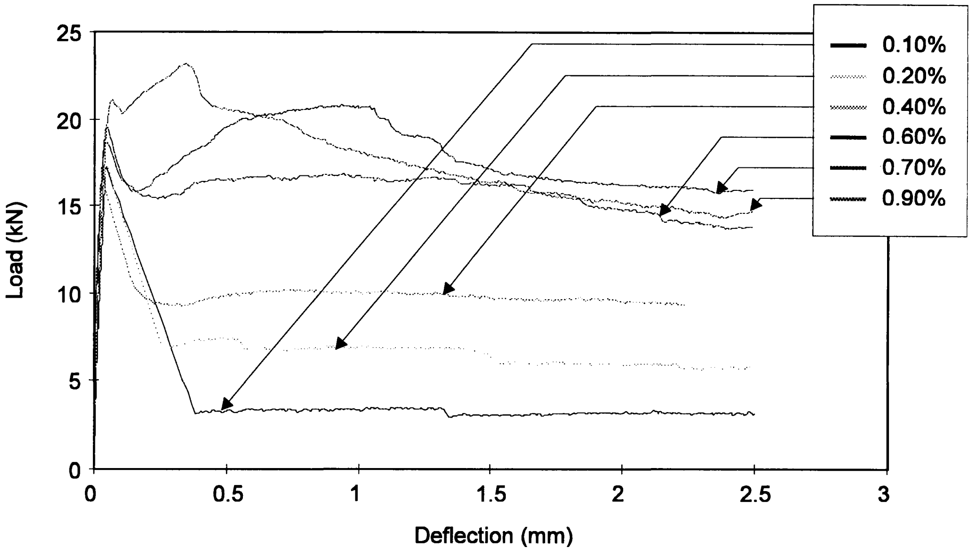

FIGURE 8. Comparison of Load: Deflection Curves for FRC with Steel Fibers (30/50)

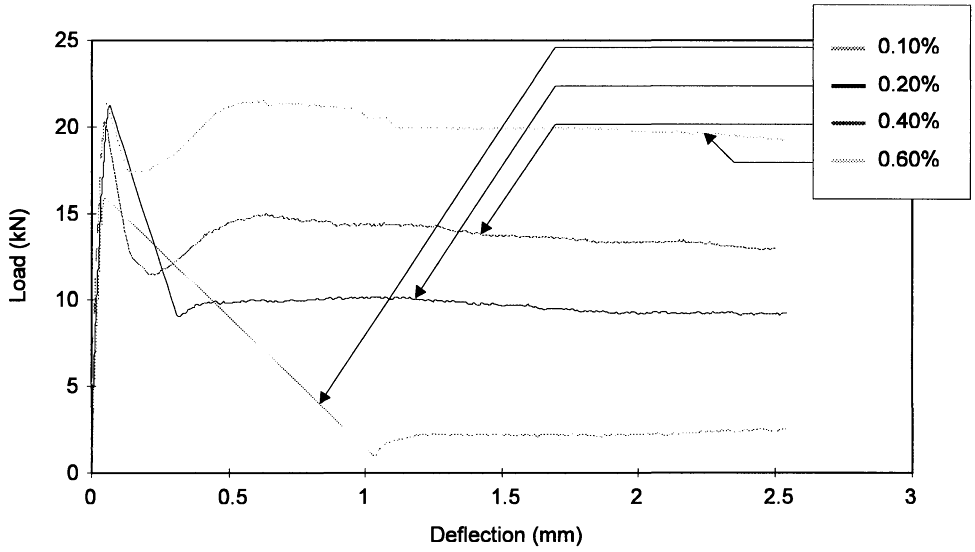

FIGURE 9. Comparison of Load: Deflection Curves for FRC with Steel Fibers (60/80)

a specific deflection interval as a percentage of the load at first crack. Thus, $R_{5,10}$ is the average percentage of first crack strength over the interval from 3 to 5.5 times the first crack deflection. The residual factors are tabulated and reported in Table 6. Since control concrete fails at first crack, it has no residual strength.

The highest residual strength values were obtained with steel fibers, followed by polyolefin fibers and then polypropylene fibers. The concrete with the highest volume of steel fibers (30/50 at 0.87 percent) used in this study had residual strength factors greater than 100, indicating that the first crack strength was exceeded after cracking.

Toughness indices and residual strength factors are both highly dependent on the first crack strength. If first crack strengths vary greatly, comparison between the indices and strength factors have little merit in comparing FRCs. The concretes tested in this investigation had similar first crack strengths; the majority of the results varied no more than 15 percent of the control result, and no result varied more than 25 percent.

DISCUSSION

The addition of fibers improves many of the properties of hardened HCC. The effectiveness of fibers in this study depended on the type, size, and addition rate. A similar strength or toughness can be achieved by the addition of different fibers at different addition rates. However, the workability of the concrete is a practical limitation to the amount of fibers that can be added and, thus, the level of improvement.

Three FRC pavements placed in Virginia in June and July 1995 are being evaluated to establish the relationship between the properties of FRC and field performance. The concretes used in these projects contained steel (hooked-end) (0.4 and 0.6 percent by volume), fibrillated polypropylene (0.2 percent by volume), monofilament polypropylene (0.1 and 0.3 percent by volume), and polyolefin (1.3 and 1.6 percent by volume). The properties of the concretes in these overlay projects and in the concretes prepared for this study were similar, and the laboratory testing of field concretes yielded results similar to the ones obtained in this study.

After a preliminary evaluation of the overlays after construction and at 1 year, it appears that the FRC in the field is functioning as expected, controlling crack propagation and widening. In one project, the concrete shows extensive cracking toward the end sections, which contained concretes with and without fibers. The cracks have widened over the year. Indications are that the widths of the cracks in areas with fibers were less than those in the control section. Cracks in areas with steel and polyolefin fibers had the narrowest widths.

These field studies are expected to provide data on the effectiveness of fibers and the level of improvement needed. Further field evaluations will be proposed to evaluate the performance of FRC.

CONCLUSIONS

- The use of fibers reduces the workability of concrete. However, with the addition of HRWRAs, workability similar to that of concretes without fibers is achieved.
- Although the ultimate splitting tensile strength, compressive strength, and first crack strength are higher in most FRCs, only a few demonstrate increased strength after adjustments for air content.
- The impact resistance of concretes is greatly improved with increases in fiber volume and length. Concretes with polyolefin and steel fibers have the highest impact resistance.
- The toughness of concretes improves with increases in fiber volume. The highest toughness values are achieved with steel fibers, followed by polyolefin and then polypropylene fibers.
- Field results are in accordance with laboratory results. After 1 year, crack propagation and widening appear to be controlled in FRCs in the field.

RECOMMENDATIONS

To quantify the degree of improvement gained by the addition of fibers to HCC, additional sections of FRC should be installed in the field and the evaluation of existing installations should continue.

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