

Fatigue Strength of Fibrillated Polypropylene Fiber Reinforced Concretes

M. NAGABHUSHANAM, V. RAMAKRISHNAN, AND GARY VONDRAN

This paper presents the results of an experimental investigation to determine the flexural fatigue strength of concrete reinforced with three different concentrations of fibrillated polypropylene fibers. The properties and the performance of fresh and hardened concretes with and without fibers are compared. The test program included the evaluation of 1) Flexural fatigue strength and endurance limit; 2) hardened concrete properties, such as compressive strength, static modulus, pulse velocity, modulus of rupture, and toughness indexes; and 3) fresh concrete properties, including slump, vebe time, inverted cone time, air content, and concrete temperature. The test results indicated an appreciable increase in post-crack energy absorption capacity and ductility due to the addition of fibers. When compared with corresponding plain concrete, the flexural fatigue strength and the endurance limit (for 2 million cycles) significantly increased. The static flexural strength increased after being subjected to fatigue loading.

Concrete is one of the most important and widely used construction materials in the world. It has many advantages, including relatively low cost, general availability, and usage of local materials. It is also among the most variable with regard to material properties. The low tensile strength and brittle failure tendency are, however, two major design problems. In an attempt to increase concrete ductility and energy absorption, a relatively new technology of fiber reinforced concrete (FRC) has been introduced. (1–4). In FRC, millions of fibers are introduced into the concrete as it is mixed. These fibers are dispersed randomly throughout the concrete and thus improve concrete properties in all directions. Because of their discontinuity and random distribution, they are not intended to replace the function of conventional reinforcement. The random and uniform distribution of fibers throughout the concrete mass also helps to eliminate temperature and shrinkage cracks. Other advantages include the increase in pre-crack tensile strength, fatigue strength, impact strength, and shock resistance.

Fiber has been used in shotcrete for rockfill stabilization and tunnel and canal linings. It is also rapidly gaining acceptance as a suitable material for repair and rehabilitation of concrete structures. In many applications, particularly in pavement and bridge deck overlays, flexural fatigue strength and endurance limit are considered important design parameters, mainly because these structures are subjected to the fatigue load cycles (1,4,5).

Several fiber materials in various sizes and shapes have been developed for use in FRC. Fibrillated polypropylene has been one of the most successful due to some unique properties that make it suitable for reinforcement in concrete. The fibers have very high tensile strength. Further, their high elongation enhances energy absorption and leads to improved ductility, higher fatigue strength, and higher impact resistance of concrete (1,5).

OBJECTIVES

The primary objectives of this investigation were to determine the behavior of fibrillated polypropylene FRC when subjected to nonreversed fatigue bending and to determine the effect of fiber concentration. Other objectives of this investigation were to

- Determine the behavior of fibrillated polypropylene fibers during and after mixing;
- Determine the properties of the fresh concrete reinforced with three different concentrations of fibrillated polypropylene fibers; and
- Determine the characteristics of hardened concrete, such as compressive strength, static modulus, unit weight, pulse velocity, modulus of rupture, and toughness indexes for concretes with and without fibers but otherwise identical mixes.

MATERIALS, MIXES, AND TEST SPECIMENS

Materials

Type I portland cement satisfying the requirements of ASTM C150 was used for all mixes. The fine aggregate used was natural sand that had a saturated surface dry specific gravity of 2.63 and an absorption of 1.64 percent. The coarse aggregate used was crushed limestone with a maximum size of $\frac{3}{4}$ in., a saturated surface dry specific gravity of 2.68 and an absorption of 0.54 percent. Both coarse and fine aggregates satisfied grading requirements of ASTM C33.

Tap water from the Rapid City municipal water supply system was used. The air-entraining admixture was a neutralized vin-sol resin, satisfying ASTM C260, and the superplasticizers used conformed with Type F ASTM C494 specifications.

The fibrillated polypropylene fibers used in this study were commercially available under the brand name Fiber-mesh.

M. Nagabhushanam and V. Ramakrishnan, South Dakota School of Mines & Technology, Rapid City, S.D. 57701. Gary Vondran, Fiber-mesh Company, 1550 F Dell Ave, Campbell, Calif. 95008.

During mixing, the small bundles in the mesh separate into individual multifilament fibers. These fibers are rectangular in cross section with fibril links to other main fibers. This geometry, with branching of fibers into spurs or fibrils, enhances bonding and provides excellent mechanical anchoring. Other polypropylene and synthetic fibers may not offer these bonding characteristics. Thus, the results are only applicable to the specific fiber tested. For this investigation, a $\frac{3}{4}$ -in. fiber was used, having a specific gravity of 0.91, a modulus of elasticity of 500 ksi, and a yield tensile strength of 80 to 100 ksi.

Mixes

Twelve mixes were made for the investigation. Three were control mixes without fibers, and the other nine contained varying amounts of fibers. Each mix was made in a batch size of 3.25 ft³. The mix quantities and designations are given in Table 1. The batching and mixing of all the mixes were performed according to ASTM C192 specifications.

Test Specimens

For the compression and static modulus tests, three to five 6 in. \times 12 in. cylinders were cast from each mix. In all mixes, excluding two (NF1 and NF2), two to four 6 in. \times 2.5 in. cylinders were made for impact tests. For both the static flexural and flexural fatigue tests, the following specimens were cast:

- Twelve to fifteen 4 in. \times 4 in. \times 14 in. beams for the NF series, and
- Six to seven beams of 4 in. \times 4 in. \times 14 in. and six to seven beams of 3.5 in. \times 4.5 in. \times 16 in. for the G series.

The specimens were cast in steel molds immediately after mixing and then covered with a plastic sheet and cured for 24 hours at room temperature. They were then demolded and immersed in lime-saturated water tanks maintained at 72°F. The specimens for the compression, static flexural, and impact

tests remained in the water until they were tested at 7 and 28 days. The specimens for the fatigue test were taken out of the water at 28 days of age and painted with a curing compound.

TESTS FOR FRESH CONCRETE

The freshly mixed concrete was tested for temperature, slump (ASTM C143), air content (ASTM C231), time of flow through an inverted slump cone (ASTM C995), and vebe time (British Standard 1881). The results of these tests are given in Table 2.

TESTS FOR HARDENED CONCRETE

Compressive Strength and Static Modulus

The cylinders were tested for compressive strength and static modulus according to ASTM C39 and C469, respectively.

Static Flexure Test

The beams were tested for static flexural strength by applying third point loading according to ASTM C1018. The load-deflection data recorded for the static flexural strength test was used to calculate the toughness indexes and to investigate the ductility of concrete. A dial gauge accurate to 0.0001 in. was placed under the beam at the centerline to measure the deflection. The rate of deflection was kept in the 0.002 to 0.004 in./min range according to ASTM C1018.

Impact Test

The impact specimens were tested by the drop weight test method (6). Equipment for the test consisted of

- A standard, manually operated 10 lb weight with an 128 in. drop (ASTM D1557);

TABLE 1 MIX QUANTITIES AND DESIGNATION

MIX #	FIBER CONTENT (%)	COARSE AGGREGATE (lbs)	FINE AGGREGATE (lbs)	CEMENT (lbs)	W/C RATIO	SPD (cc)	AEA (cc)
NP4		187.8	187.8	79.2	0.40	180	25
NF1	0.1	187.8	187.8	79.2	0.40	240	25
NF7	0.1	187.8	187.8	79.2	0.40	240	25
NF3	0.5	187.8	187.8	79.2	0.40	330	25
NF5	0.5	187.8	187.8	79.2	0.40	330	25
NF2	1.0	187.8	187.8	79.2	0.40	380	25
NF6	1.0	187.8	187.8	79.2	0.40	550	30
G1		215.8	169.8	65.0	0.50	78	18
G2	0.1	215.8	169.8	65.0	0.50	78	18
G3B	1.0	181.8	142.5	86.9	0.50	208	23
G4	0.5	181.8	142.5	86.9	0.42	156	22
G5	----	181.8	142.5	86.9	0.42	123	22

SPD - Superplasticizer Dosage
AEA - Air Entraining Agent Dosage

TABLE 2 PROPERTIES OF FRESH CONCRETE

MIX #	SLUMP (in)		CONCRETE TEMP. (°F)	AIR CONTENT (%)	VEBE TIME (sec.)	INVERTED CONE TIME (sec.)
	INITIAL SLUMP	VEBE SLUMP				
NP4	9.25	6.75	71.4	5.2	0.7	---
NF1	8.25	4.88	70.2	9.0	2.0	---
NF7	6.25	3.50	79.9	4.4	2.0	7.8
NF3	5.25	2.06	70.9	5.4	3.5	23.0
NF5	3.75	2.75	77.7	3.2	3.7	23.7
NF2	0.13	0	70.0	4.4	10.0	90.0
NF6	0.13	0	77.2	3.2	9.5	62.0
G1	3.75	2.25	80.1	5.2	2.2	9.5
G2	1.25	1.06	79.3	3.5	5.5	15.3
G3B	3.13	1.88	80.2	6.9	3.7	56.0
G4	6.50	5.38	80.7	7.6	1.5	6.7
G5	6.25	3.5	81.0	4.3	1.6	6.1

- A 2-1/2 in. 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 upwards. 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 recorded. This was accomplished by counting the number of blows required to open the cracks sufficiently so that the pieces of the specimen were touching three positioning lugs on the base plate.

Flexural Fatigue Test

The main thrust of the investigation was to determine the endurance limit in flexural fatigue loading for various concretes. In this test, the endurance limit was defined as the maximum load at which the specimen could withstand 2,000,000 cycles of nonreversed fatigue loading. The 2,000,000-cycle limit was chosen to approximate the life span of a structure that may typically be subjected to fatigue loading, such as a bridge deck or highway pavement. The range of cyclic loading was expressed as a percentage of the average maximum load in static flexure for each mix. The lower limit for all tests was 10 percent of the maximum load. The upper limit varied depending on the particular mix—generally from 55 percent to 80 percent of the maximum load. The fatigue test was then run between these limits. If the beam failed before the 2,000,000-cycle limit, the upper limit was reduced for the next specimen. If the beam survived, the upper limit was raised, and a new beam was tested at the increased upper limit. All beams that survived the 2,000,000-cycle limit were later tested for flexure, and the maximum loads at which they failed were noted.

The frequency of loading used was 20 cycles/sec for all tests. The machine used for these tests was a Material Test System (MTS). The machine could be operated in any of three modes: load control (force applied to the specimen), strain control

(strain induced in the specimen), or deflection control (distance traveled by the ram or deflection of the specimen). Since this test was concerned with stress levels, load control was used for fatigue testing.

A choice of three waveforms could be used: sine wave, square wave, and triangular wave. The sine wave was selected because of its similarity to real-world behavior (2).

A built-in control unit kept track of the number of cycles to the nearest 100. When the beam failed, this reading was recorded.

TEST RESULTS AND DISCUSSION

Fresh Concrete Properties

The fibrillated polypropylene fibers used in this program performed very well. Although fibers, cement, and aggregates were added to the mixer simultaneously, no fiber balling occurred. The mixing action caused the bundles to open up and expand to fiber mesh form producing individual multifilament fibers uniformly distributed throughout the concrete. The fresh concrete with fibers had no surface bleeding and no segregation.

The results of the tests on fresh concrete are given in Table 2. To ensure that all the mixes were combined under approximately similar conditions, room temperature, humidity, and concrete temperature were recorded for each.

Workability

Three tests were performed to determine the workability of the mixes: slump, inverted cone time, and vebe time. The slump test results indicate that satisfactory workability can be maintained even with a relatively high fiber content. This was achieved by either adjusting the amount of superplasticizer used or adjusting the water and cement content (mix 3GB) to maintain relatively equal strengths and water/cement ratios.

Vebe time was used to measure workability based on the energy needed to compact the concrete. As the slump value decreased, the vebe time increased.

Inverted cone time is a new measurement that tests workability for fibrous concrete only. The inverted cone time

increased with a decrease in slump. Further, as vebe time increased, inverted cone time rose as well.

Finishability

A table vibrator was used to form a layer of mortar on the surface of the member; this made finishing easier. In general, the slump, air content, and concrete temperatures all varied slightly within the allowable variation normally obtained in concrete research. The variations in the fresh concrete properties did not significantly affect the hardened concrete properties.

Fiber Factor

Two higher quantities beyond the fiber manufacturer's recommended amount of 1.5 lb/yd³ (0.1 percent by volume) were selected: 7.5 lb/yd³ (0.5 percent by volume) and 15.0 lb/yd³ (1.0 percent by volume). For the NF series (mixes NF1 to NF7), the water/cement ratio and the mix proportions were maintained at a constant. Fibers in different quantities were added without considering the fiber factor. A higher volume of fibers reduced the slump because of the added surface area of the fibers. The compressive strength and the modulus of rupture values also decreased. Obviously, the same mix proportions could not be used for higher volumes of fibers; fiber factor adjustments are necessary to balance proportions for suitable workability, placeability, appearance, and strength. Optimum mixture proportions should be obtained by trial mixes when using higher fiber volumes.

HARDENED CONCRETE PROPERTIES

Compressive Strength

The results of the tests for compressive strength are given in Table 3. It was observed that compressive strength decreases

at high air contents. The coefficient of variation values calculated for all the mixes are below 2, which is the specified value for research work (7). The minor differences noticed are expected in experimental work.

An important asset of fiber concrete is the ductile mode of failure, which was demonstrated while testing for compressive strength. The plain concrete cylinder completely failed, shattering into pieces with a loud noise. The fiber concrete cylinders, however, continued to sustain the load and endured large deformations without totally breaking into pieces.

Static Modulus

The static modulus test results are given in Table 3. The average static modulus for all mixes was 4.92×10^6 psi, and its range was between 3.55×10^6 and 5.54×10^6 psi. The addition of fibers had no effect on static modulus.

Pulse Velocity

The pulse velocity test was used for quality control. Test results are given in Table 3. At 28 days, the average pulse velocity was 15,460 ft/sec, with a maximum of 15,920 ft/sec (2.9 percent) and a minimum of 14,600 ft/sec (-5.6 percent). The test results indicate a good degree of consistency and quality control. They also reveal that fiber content has little effect on pulse velocity.

Modulus of Rupture

The results of modulus of rupture are given in Table 3. Neither the fiber reinforcement nor the quantity of fibers had an appreciable effect on flexural strength.

There is always more scatter and sometimes one or two odd results in flexural testing of FRC. This is due to the fiber's

TABLE 3 HARDENED CONCRETE PROPERTIES AT AN AGE OF 28 DAYS

SP. #	f_c' (psi)	E_c (10^6 psi)	PULSE VELOCITY (ft/sec)	M.O.R (psi)
NP4	5905	4.94	15590	790
NF1	5940	4.63	15560	660
NF7	6720	5.33	15660	890
NF3	6975	5.29	15810	845
NF5	6780	5.33	15640	810
NF2	6415	5.36	15920	755
NF6	5570	5.07	15690	700
G1	5450	5.54	15380	760
G2	6020	5.33	15750	780
G3B	4970	3.55	14510	660
G4	4870	3.62	14600	670
G5	6450	5.03	15450	775

The values in the above table are the mean values of three to four specimens tested.

f_c' - Compressive Strength

E_c - Static modulus

M.O.R - Modulus of Rupture (Flexural Stress)

random orientation and possible nonuniform distribution of aggregate in small specimens, particularly in the tension zone.

Toughness Index

The results of the calculation for toughness index are given in Table 4. Typical load-deflection comparison curves for plain concrete and the concretes with three different fiber contents (0.1 percent, 0.5 percent, and 1.0 percent by volume) are given in Figures 1 and 2. The figures illustrate the improvement in elastic-plastic behavior of fiber concrete composite that occurs with the increase in fiber content from 0.1 percent to 1.0 percent.

The toughness index is defined as the area under the load-deflection curve up to a specified deflection, divided by the area under the curve up to the point where the concrete first cracks (first-crack toughness). The area under the curve represents the energy in inch-pounds required to cause the deflection of the beam. The toughness index measures the capacity of fracture energy absorption and the ductility of the specimen. Plain concrete fails immediately upon cracking, without further load-carrying capabilities. Since this is a brittle failure, I_5 , I_{10} , and I_{30} are always equal to 1.0. Concrete beams reinforced with polypropylene fibers, however, will continue to deflect in a ductile fashion and carry loads well past the point of first crack. In this case, the toughness index will be greater than 1.0. A straight line was used to connect the first crack point and the point immediately after crack.

The calculated values of toughness indexes (I_5 , I_{10} , and I_{30}) are given in Table 4. The beams with higher fiber content had higher energy absorption and ductility compared with beams with fewer fibers (see Figure 3).

The values equal to 2 and 3 for I_{10}/I_5 and I_{30}/I_{10} , respectively, illustrate perfect plastic behavior. The values of I_{10}/I_5 and I_{30}/I_{10} for all the mixes given in Table 4 indicate that they are less than 2 and 3, respectively. However, the obtained higher ratios indicate that, though a perfect plastic behavior is not achieved, a good measure of ductility and post-crack plastic behavior is obtained by adding a high volume (0.5 percent and 1.0 percent) of fibrillated polypropylene fibers.

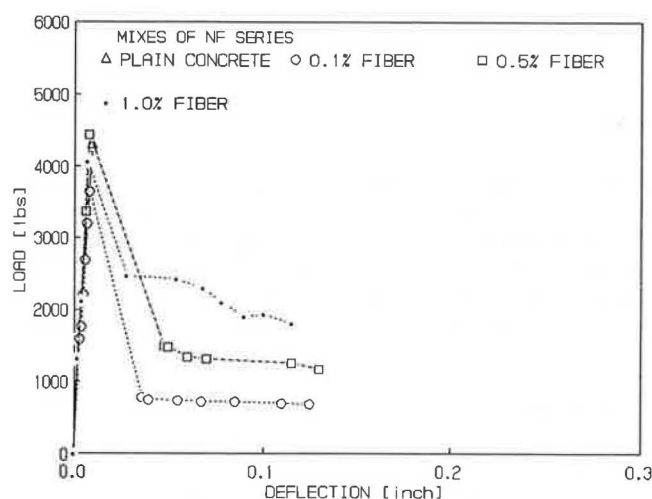


FIGURE 1 Load-deflection comparison curves for NF series.

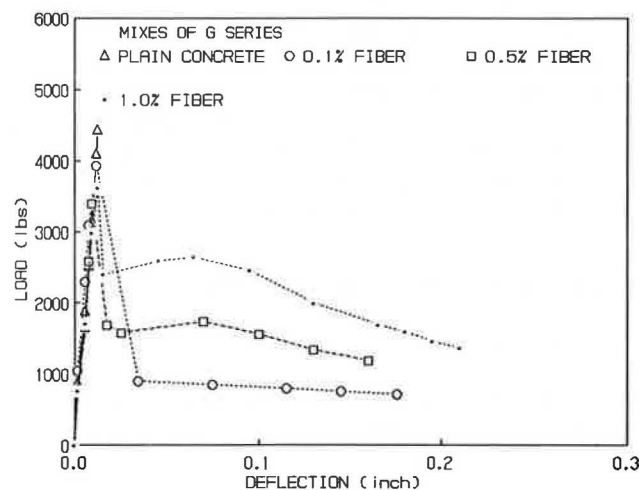


FIGURE 2 Load-deflection comparison curves for G series.

TABLE 4 TOUGHNESS INDEXES OF FIBER REINFORCED BEAMS

MIX #	FIRST CRACK TOUGHNESS (in-lbs)	I_5	I_{10}	I_{30}	I_{10}/I_5	I_{30}/I_{10}
NP4	----	1.000	1.000	1.00	1.00	1.00
NF1	17.28	3.519	5.110	9.00	1.47	1.76
NF7	----	1.000	1.000	1.00	1.00	1.00
NF3	24.65	3.330	5.320	11.99	1.60	2.30
NF5	19.22	4.650	7.330	14.37	1.58	1.96
NF2	19.79	3.510	6.530	16.49	1.87	2.53
NF6	13.57	4.810	8.360	21.98	1.75	2.62
G1	----	1.000	1.000	1.00	1.00	1.00
G2	23.39	4.120	5.590	9.13	1.35	1.64
G3B	17.08	4.020	7.690	21.12	1.91	2.73
G4	14.86	3.510	6.230	16.06	1.78	2.58
G5	----	1.000	1.000	1.00	1.00	1.00

The values in the above table are the mean values of three to four specimens tested.

Post-Crack Load Drop Phenomenon

Post-crack load drop is defined as the difference between the maximum load and the load recorded at a deflection equal to three times the deflection measured at first crack. The load drops expressed as a percentage of maximum loads are 45 percent, 27 percent, and 26 percent, respectively, for the beams of NF series with 0.1 percent, 0.5 percent, and 1.0 percent fiber contents. The load drops are 78 percent, 52 percent, and 30 percent for the beams of G series with 0.1 percent, 0.5 percent, and 1.0 percent fiber contents, respectively. The post-crack load drop generally decreases as the fiber content increases (Figures 1 and 2). Compared with polypropylene fibers, the straight steel fibers had higher post-crack load drops (8). The table below compares the load drops for typical load-deflection curves of two types of fibers.

Fiber Content (percent)	Types of Fibers	
	Polypropylene (percent)	Straight Steel (percent)
0.1	45	—
0.5	27	80
1.0	26	77

Impact Strength

The drop-weight test used in this investigation (6) is not completely scientific and is not expected to give accurate quantitative values for impact resistance. However, the test is simple and inexpensive and can be performed anywhere, including in the field.

The number of blows to failure for plain concrete specimens was very low; for specimens reinforced with polypropylene fibers the number of blows to failure increased tremendously. The comparison bar charts for first crack and full failure are shown in Figure 4. The figure shows that, for all fiber concrete mixes, the number of blows for first crack and final failure is higher than that for plain concrete. Also, the impact resistance increases with an increase in fiber content. These results prove that fiber concrete with fibrillated polypropylene fiber has excellent impact resistance.

FLEXURAL FATIGUE BEHAVIOR

Fatigue properties of fibrillated polypropylene FRC was the main objective of this investigation. Beams made with plain concrete and the concretes with 0.1 percent, 0.5 percent, and 1.0 percent fiber contents by volume were tested for flexural fatigue.

Results of fatigue tests are tabulated in Table 5, column 3, which shows maximum stress in psi. This was calculated using the actual dimensions of the beam at the failed cross section and the upper load limit used for the test. Similarly, column 6 shows the maximum fatigue stress of each specimen as a ratio of the average modulus of rupture for the same mix. Column 7 shows the number of cycles at failure. Figures 5 through 12 illustrate various relationships between the number of cycles (N), fatigue strength, and endurance limits. Based

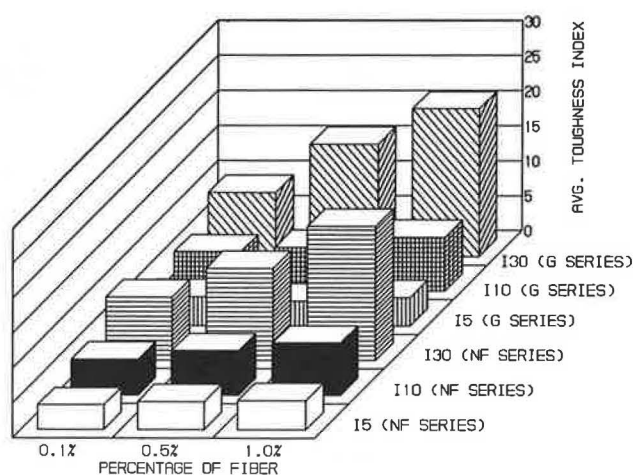


FIGURE 3 Toughness index bar chart.

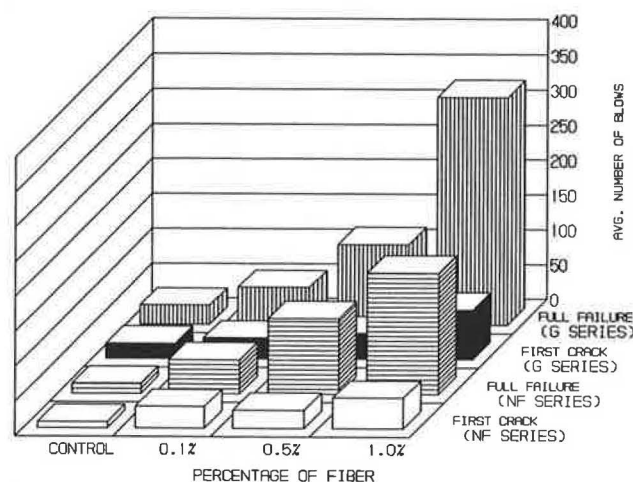


FIGURE 4 Impact test results.

on the figures and results given in the tables, fatigue strength and endurance limit were analyzed.

Fatigue Strength

Fatigue strength is defined as the maximum fatigue flexural stress at which the beam can withstand 2,000,000 cycles of nonreversed fatigue loading. Fatigue strength increased when fibrillated polypropylene fibers were added to the concrete. In the NF series, the fatigue strength was 395 psi for plain concrete; it was 386 psi, 500 psi, and 521 psi for 0.1 percent, 0.5 percent, and 1.0 percent fiber concrete mixes, respectively, showing a decrease of 2 percent for the 0.1 percent fiber concrete mix and an increase of 27 percent and 32 percent for the 0.5 and 1.0 percent fiber concrete mixes, respectively. Similarly, in the G series, there was an increase in fatigue strength of the fiber concrete mixes compared with plain concrete. Graphs were drawn for fatigue flexural stress versus the logarithm of the number of cycles for all mixes in the NF and G series. A linear relationship was found between fatigue stress and $\log N$. As seen in Figure 13, fatigue strength increases with fiber content.

TABLE 5 FATIGUE TEST RESULTS

SP. #	AGE (DAYS)	MAX. STRESS f_{max} (psi)	MIN. STRESS (psi)	STRESS RANGE (psi)	f_{max} f_r	CYCLES TO FAILURE
NP4-7	36	450	82	368	0.57	5660
NP4-8	34	383	77	306	0.48	2618700+
NP4-9	33	582	83	499	0.74	500
NP4-10	33	483	81	402	0.61	1860
NP4-11	33	477	80	397	0.60	75990
NP4-12	33	409	82	327	0.52	1951330
NF1-4	53	386	64	322	0.58	2190780+
NF1-5	54	521	65	456	0.79	993320
NF1-6	55	467	67	400	0.71	104380
NF1-7	55	483	69	414	0.73	2607340+
NF1-8	56	513	68	445	0.78	2580900+
NF1-9	30	330	66	264	0.50	2000150+
NF1-10	30	409	68	341	0.62	58560
NF1-11	30	481	69	412	0.73	1060
NF1-12	30	521	65	456	0.79	4280
NF7-1	119	749	88	661	0.84	23300
NF7-2	118	758	84	674	0.85	1104600
NF7-3	119	787	87	700	0.88	296000
NF7-4	117	749	88	661	0.84	2032290+
NF7-6	119	730	86	644	0.82	38500
NF7-7	119	659	88	571	0.74	2000000+
NF7-8	118	786	87	699	0.88	633100
NF7-9	119	648	86	562	0.73	2000000+
NF7-10	118	828	87	741	0.93	19200
NF7-11	118	823	87	736	0.92	1700
NF3-4	60	580	83	497	0.69	1058810
NF3-5	59	532	82	450	0.63	2390610+
NF3-6	59	614	88	526	0.73	121900
NF3-7	32	462	84	378	0.55	2818830+
NF3-8	31	405	81	324	0.48	2241100+
NF3-9	31	500	83	417	0.59	18510
NF3-10	31	514	86	428	0.61	8520
NF3-11	31	567	81	486	0.67	9940
NF5-5	79	712	79	633	0.88	23100
NF5-6	80	650	76	574	0.81	2002310+
NF5-7	81	668	79	589	0.83	2018780+
NF5-8	79	819	82	737	1.00	1170
NF5-9	80	716	80	636	0.89	24780
NF5-10	79	644	81	563	0.80	2030690+
NF5-11	79	759	80	679	0.94	2830
NF5-12	75	554	79	475	0.69	2011580+
NF5-13	78	696	77	619	0.86	2118020+
NF2-4	32	529	76	453	0.70	7830
NF2-5	30	375	75	300	0.50	2308100+
NF2-8	57	521	74	447	0.69	2001710+
NF2-9	58	580	77	503	0.77	372890
NF2-10	58	559	75	484	0.74	2032940+
NF2-11	59	590	74	516	0.78	116360
NF2-12	59	553	74	479	0.73	887210
NF6-5	84	583	65	518	0.83	859260
NF6-6	82	558	70	488	0.80	2382840+
NF6-7	85	548	69	479	0.78	2024730+
NF6-8	84	662	66	596	0.95	46550
NF6-9	84	612	70	542	0.87	11980
NF6-10	87	604	71	533	0.86	2076340+
NF6-11	86	560	66	494	0.80	2006900+
NF6-12	84	558	70	488	0.80	370240
NF6-13	88	578	68	510	0.83	2000000+

TABLE 5 (continued on next page)

TABLE 5 (continued)

SP. #	AGE (DAYS)	MAX. STRESS f_{max} (psi)	MIN. STRESS (psi)	STRESS RANGE (psi)	f_{max} f_r	CYCLES TO FAILURE
G1-2	90	488	81	407	0.60	2029550+
G1-3	89	560	80	480	0.70	1279610
G1-4	88	653	82	571	0.82	316320
G1-5	88	709	79	630	0.89	2020
G1-6	91	545	84	641	0.69	2009760+
G1-10	134	498	77	430	0.66	2013000+
G1-11	136	462	77	394	0.62	2011970+

+ - No failure

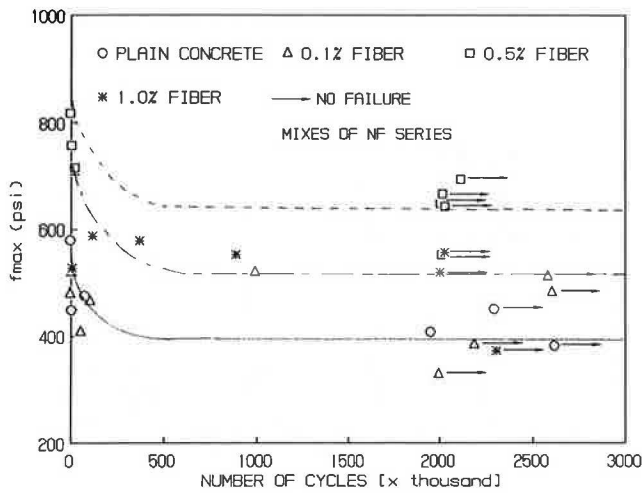
 f_r - Average Modulus of rupture of three to four specimens tested at 28 days

FIGURE 5 Fatigue stress versus number of cycles.

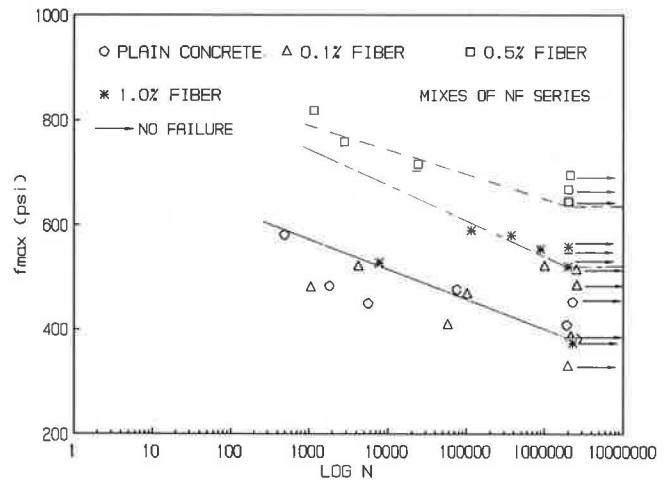


FIGURE 7 Fatigue stress versus log of number of cycles.

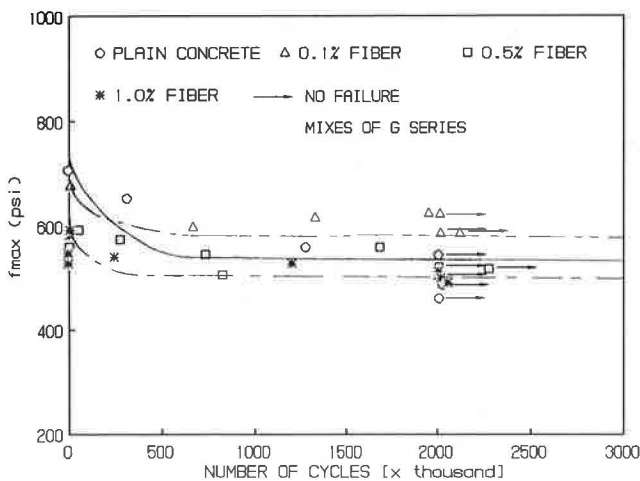


FIGURE 6 Fatigue stress versus number of cycles.

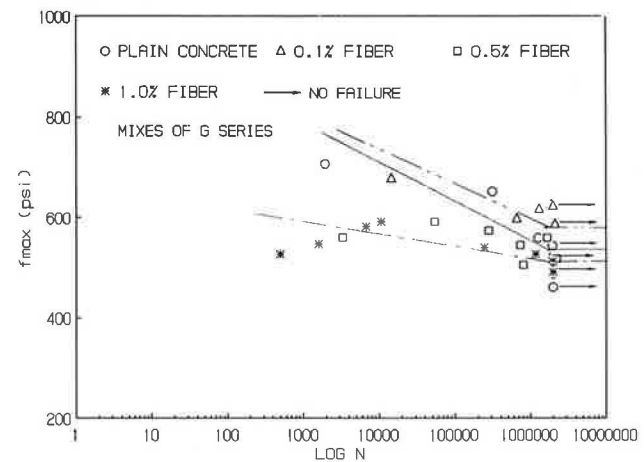


FIGURE 8 Fatigue stress versus log of number of cycles.

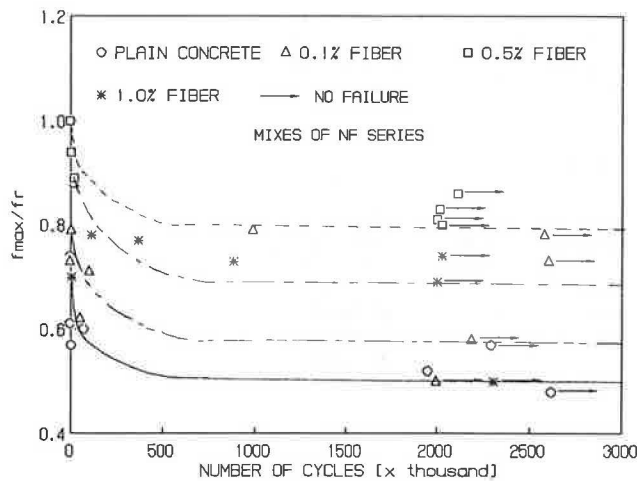


FIGURE 9 Number of cycles versus ratio of fatigue stress and flexural stress.

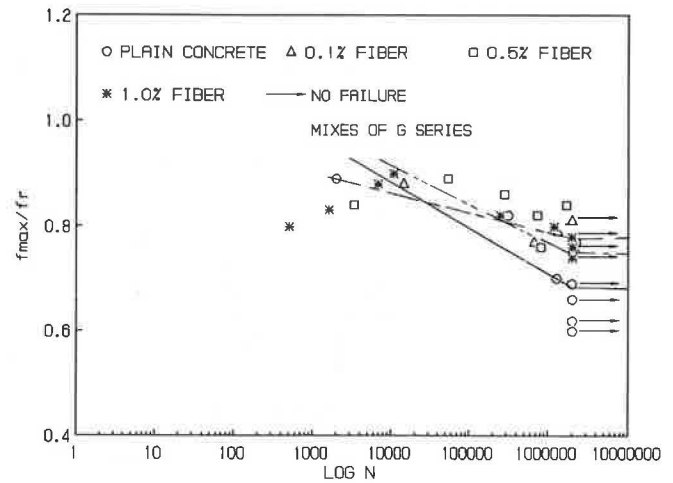


FIGURE 12 Log of number of cycles versus ratio of fatigue stress and flexural stress.

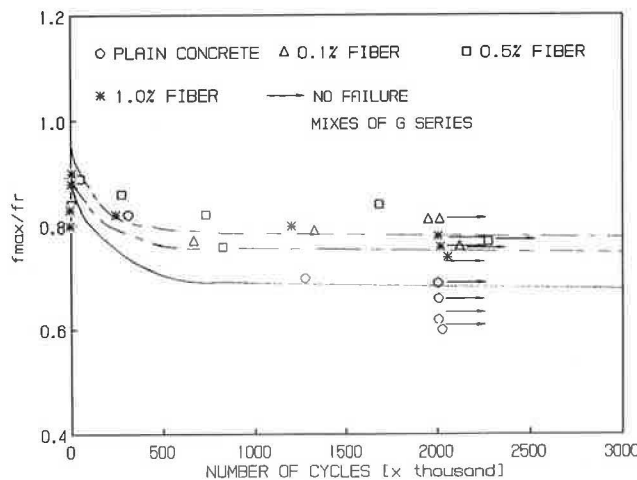


FIGURE 10 Number of cycles versus ratio of fatigue stress and flexural stress.

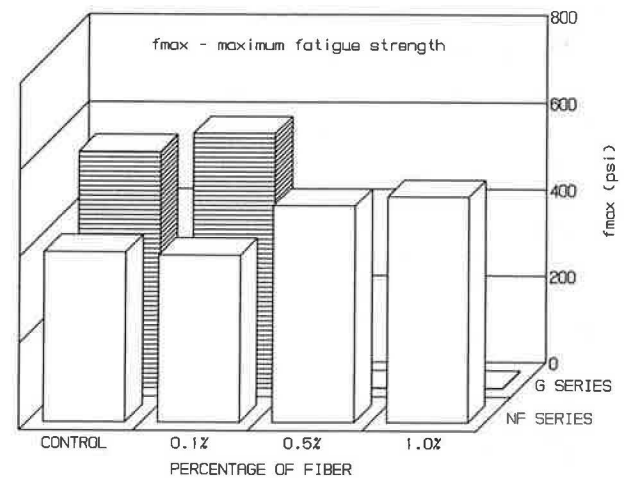


FIGURE 13 Fatigue strength bar chart.

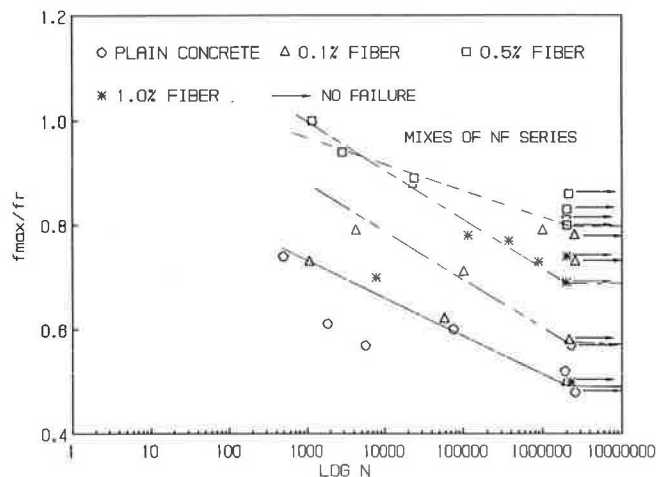


FIGURE 11 Log of number of cycles versus ratio of fatigue stress and flexural stress.

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

The endurance limit is defined as the maximum fatigue flexural stress at which the beam can withstand 2,000,000 cycles of nonreversed fatigue loading, expressed as a percentage of modulus of rupture of plain concrete.

Figure 14 indicates that, for the beams with 0.5 percent fiber content, the endurance limit increases when expressed as a percentage of modulus of rupture of plain concrete. In the mix with 0.5 percent fiber content in the NF series, the endurance limit was 63 percent when expressed as a percentage of modulus of rupture of plain concrete; it was 59 percent when expressed as a percentage of its modulus of rupture. However, in the NF series for the mixes with 0.1 percent fiber contents, the endurance limit expressed as a percentage of modulus of rupture of plain concrete was lower than that expressed as a percentage of its modulus of rupture.

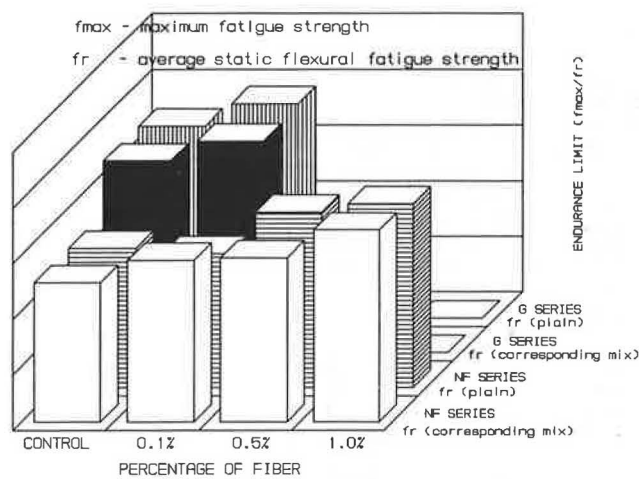


FIGURE 14 Endurance limit bar chart.

This is due to the lower compressive strength in these mixes compared with those of plain concrete. For the G series mixtures, the endurance limit expressed as a percentage of modulus of rupture of plain concrete was higher than that expressed as a percentage of its modulus of rupture.

Endurance Limit Expressed as a Percentage of Its Modulus of Rupture

The endurance limit of concrete can also be defined as the fatigue stress at which the beam can withstand 2,000,000 cycles of nonreversed fatigue loading, expressed as a percentage of its modulus of rupture.

The endurance limits for the mixes with 0.1 percent, 0.5 percent, and 1.0 percent fiber contents were 58 percent, 59 percent, and 69 percent, respectively. It was 50 percent for plain concrete, thus showing an improvement in the fatigue performance of FRC. Similarly, in the G series, the endurance limit increased with increases in fiber content. The endurance limit bar charts are shown in Figure 14.

Graphs of the ratio of fatigue flexural stress to modulus of rupture (f_{max}/f_r) versus the number of cycles are shown for all the mixes in Figures 9 and 10. The relationship is curvilinear until the fatigue strength of that particular mix is reached, then the line becomes parallel to the x-axis. Graphs were also drawn for f_{max}/f_r versus the logarithm of number of cycles for all the mixes (Figures 11 and 12). In this case, the relationship is linear.

The specimens that did not fail after more than 2,000,000 cycles in the flexural fatigue test were tested again in the static flexural test to determine if microcracks had developed or strength degradation had occurred in concrete because of the fatigue test at a fatigue loading below the endurance limit. The test results are shown in Table 6. The 2 million cycle fatigue loading below the endurance limit did not lead to a decrease in flexural strength. In most cases, the flexural strength increased slightly, especially when the fatigue stress to which the specimen was subjected earlier was lower.

The considerable amount of apparent scatter in the test

results can be attributed to time factors. Fatigue tests take a long time. The ages at which different specimens of the same mix were tested vary considerably; this age difference influenced the test results. The static flexure test was performed at 28 days, while the fatigue tests were performed at much later ages. Therefore, the ratio f_{max}/f_r , and hence the endurance limit, is not consistent. The endurance limit was determined by using the above referred factors.

Based on the test results, the addition of fibrillated polypropylene fiber improved the concrete's ability to withstand dynamic and fatigue loads. A significant advantage of polypropylene fiber under dynamic loads is its relatively low elastic modulus at slow rates of loading, which increases substantially because the effect of time-dependent viscoelastic behavior is eliminated. The polypropylene fiber reinforcement contributed to the improvement of fatigue strength of concrete.

CONCLUSIONS

Conclusions from the research are as follows:

- The addition of 0.5 and 1.0 percent by volume of fibrillated polypropylene fibers significantly improved the fatigue strength.
- The endurance limit (for 2,000,000 cycles) was considerably increased with the addition of fibrillated polypropylene fibers, which, when applied to pavement slabs, would substantially extend the service life of highways.
- The static flexural strength of the fiber concrete beams increased after the beams were subjected to fatigue loading.
- The toughness index values increased with increases in fiber contents. All concrete specimens reinforced with fibrillated polypropylene fibers exhibited an improved ductile behavior when compared with plain concrete.
- The concrete incorporating fibrillated polypropylene fiber had excellent impact resistance. The impact resistance increased with an increase in fiber content.
- The fiber reinforcement had no appreciable effect on the flexural strength when the same mix proportions for different quantities of fibers were used. However, when the fiber factor adjustment is made, the flexural strength may increase with increased fiber content. More research is needed to optimize fiber performance at higher fiber volumes.
- The fiber content in the concrete mix had no appreciable effect on the pulse velocity.
- The addition of fibrillated polypropylene fibers had no significant influence on the static modulus of concrete.
- Good workability can be maintained in polypropylene FRC by adding an appropriate quantity of superplasticizer. No balling or tangling of fibers occurred during mixing and placing even for concretes with 1 percent by volume of polypropylene fibers.
- When using high volumes (0.5 percent and 1.0 percent) of fibrillated polypropylene fibers, fiber factor adjustments are necessary for the mix proportions to balance the mix for workability, placeability, appearance, and strength.

TABLE 6 STATIC FLEXURAL TEST AFTER FATIGUE

SP. #	AGE	f_{max} f_r	MAXIMUM STRESS IN FATIGUE	FLEXURE STRESS BEFORE FATIGUE	FLEXURE STRESS AFTER FATIGUE	IN PERCENT
(1)	(DAYS) (2)	(3)	f_{max} (psi) (4)	f_r (psi) (5)	(MOR) (psi) (6)	(6)-(5)
NP4-6	119	0.57	453	790	925	17.08
NP4-8	46	0.48	383	790	730	-7.59
NF1-4	93	0.58	386	660	910	37.88
NF1-7	93	0.73	483	660	885	34.09
NF1-8	93	0.78	513	660	880	33.33
NF1-9	49	0.50	330	660	575	-12.88
NF7-4	174	0.84	749	890	1065	19.66
NF7-7	174	0.74	659	890	1045	17.42
NF7-9	174	0.73	648	890	995	11.80
NF3-5	91	0.63	532	845	945	11.83
NF3-7	47	0.55	462	845	680	-19.53
NF3-8	47	0.48	405	845	740	-12.43
NF5-6	89	0.81	650	810	925	14.20
NF5-7	89	0.83	668	810	910	12.35
NF5-10	89	0.80	644	810	990	22.22
NF5-12	89	0.69	554	810	895	10.49
NF5-13	89	0.86	696	810	910	12.35
NF2-5	48	0.50	375	755	815	7.95
NF2-8	92	0.69	521	755	985	30.46
NF2-10	92	0.74	559	755	905	19.87
NF6-6	89	0.80	558	700	875	25.00
NF6-7	89	0.78	548	700	885	26.43
NF6-10	89	0.86	604	700	850	21.43
NF6-11	89	0.80	560	700	835	19.29
NF6-13	181	0.83	578	700	770	10.00
G1-2	180	0.60	488	760	990	30.26
G1-6	180	0.69	545	760	715	-5.92
G1-10	180	0.66	498	760	850	11.84
G1-11	180	0.62	462	760	690	-9.21
G2-1	180	0.81	624	780	890	14.10
G2-4	180	0.76	587	780	945	21.15
G2-11	180	0.76	587	780	905	16.03
G3B-1	180	0.78	514	660	715	8.33
G3B-3	180	0.76	501	660	605	-8.33
G3B-6	180	0.74	491	660	650	-1.52
G4-5	180	0.77	518	670	750	11.94
G4-6	180	0.78	521	670	720	7.46
G5-2	174	0.82	636	775	920	18.71
G5-4	174	0.86	670	775	860	10.97
G5-5	174	0.88	686	775	840	8.39

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