Evaluation and Comparison of the Physical Properties of Fibrillated Polypropylene Fiber-Reinforced Concretes

R. C. ZELLERS AND V. RAMAKRISHNAN

A comparative evaluation of physical properties for plain concrete and concrete reinforced with collated fibrillated polypropylene fibers is presented. Three concentrations of fibers, 0.1, 0.2, and 0.3 percent by volume, were evaluated. Evaluation included concretes with the fiber dosages indicated and a plain or control mix in two series: (*a*) fresh concrete properties namely slump, unit weight, vebe time, air content, and concrete temperature and (*b*) hardened concrete properties, such as compressive strength, static modulus, modulus of rupture, and pulse velocity at 7 and 28 days—the second being the replicate. Toughness indexes based on ASTM C1018, as well as the flexural toughness factors, were calculated. In addition, an equivalent flexural strength based on the Japanese standard was obtained. Inspection of plastic mixes and failed test specimens showed that there was no balling of fibers during mixing and fabrication of test specimens. There was a slight increase in the flexural strength as the fiber content increased. Addition of fibers produced less than 5 percent difference in the static modulus, compressive strength, and pulse velocity. On the basis of I_5, I_{10}, and I_{20} toughness index data, the fiber concretes exhibited elasto-plastic behavior.

Concrete has two major deficiencies: low tensile strength and poor ductility. The tensile strength of concrete is very low because plain concrete normally contains numerous microcracks. It is the rapid propagation of these microcracks under applied stress that is responsible for the material's low tensile strength.

Those deficiencies have led to considerable research aimed at developing new approaches to modifying the brittle properties of concrete. Current research has developed a way to increase concrete ductility and energy absorption capacity, as well as to improve concrete's overall durability. The new technology uses discrete steel or synthetic fibers ranging from 19 to 63.5 mm (¾ to 2½ in.) long. The fibers are dispersed randomly throughout the concrete matrix; better distribution of internal and external stresses is provided by using a three-dimensional reinforcing network (*1–8*).

General requirements for fibers used as temperature/moisture shrinkage reinforcement include high tensile strength, high bond strength (typically mechanical), and ease of incorporation into the matrix to insure optimum distribution. The primary role of the fibers in hardened concrete at low volume is to modify the cracking mechanism. By modifying the cracking mechanism, the macrocracking becomes microcracking. The cracks are smaller in width, thus reducing the permeability of the concrete, and the ultimate cracking strain of the concrete is enhanced. Unreinforced concrete will separate at a crack, reducing the load carrying ability to zero across the crack. The fibers are capable of carrying a load across the crack, if all of the characteristics listed are met by the fiber (*1*).

R. Zellers, Forta Corporation, 100 Forta Dr., Grove City, Pa. 16127. V. Ramakrishnan, South Dakota School of Mines and Technology, 501 East St. Joseph Street, Rapid City, S.D. 57701–3995.

Fiber-reinforced concrete specimens, unlike plain concrete specimens that fail at the point of ultimate flexural strength or first crack, do not fail immediately after the initiation of the first crack. After first crack, the load is transferred from the concrete matrix to the fibers. Measuring this load carrying capability of the fibers after the first crack is determined per ASTM C1018.

A major advantage of using fiber reinforced concrete besides reducing permeability and increasing fatigue strength is that fiber addition improves the toughness or residual load carrying ability after the first crack. In addition, a number of studies have shown that the impact resistance of concrete can also increase dramatically with the addition of fibers. Low modulus fibers, like polypropylene, appear to be particularly effective in this regard (5). Combining the technical benefits and in-place costs, synthetic fiber reinforced concrete has been found to meet the prerequisites of value engineering in construction applications.

To demonstrate the validity of this statement, PennDOT had two projects in 1993 where synthetic fibers were specified. One project was a shotcrete application wherein the synthetic fiber reinforced shotcrete was used to protect the active-cathodic protection system on a bridge structure spanning the Lehigh River. The second project in Erie County enlisted the use of synthetic fiber reinforced concrete to replace the arch culvert invert slab. The engineer for both projects found the synthetic fibers filled both the engineering requirements and were cost effective when compared to alternate materials.

The fibers used in this investigation were collated fibrillated polypropylene fibers. These fibers have some unique properties that make them suitable for reinforcement in concrete mixes. The properties of polypropylene fibers are shown in the following:

- Melting point: 160°C–170°C (320°F–338°F),
- Ignition point: 590°C (1094°F),
- Tensile strength: 550–760 MPa (79750–110200 psi),
- Young's modulus: 3.5 GPa (507500 psi),
- Thermal conductivity: low,
- Electrical conductivity: low, and
- Acid and salt resistance: high.

Polypropylene fibers are chemically inert, noncorrosive, and have high resistance to acids, bases, and salts. The surface of the fibers is hydrophobic, which makes it nonabsorbent to water. These fibers have high tensile strength and are economical to use. The high magnitude elongation of these fibers is capable of imparting large energy absorption capacity to concrete, which also improves the ductility of the concrete. Fibrillated polypropylene fiber-reinforced concretes have higher fatigue strength and higher impact resistance.

Adding polypropylene fibers helps reduce early plastic shrinkage and cracking of concrete. The mortar matrix penetrates through the network pattern in the CFP fiber anchoring the fiber network like wire mesh. The mechanical anchorage is called "pegging."

RESEARCH OBJECTIVES

The primary objective of this research program is to study and compare the physical properties of plain concrete and concretes reinforced with collated fibrillated polypropylene fibers. The objective was achieved through determination of the following

1. Properties of the fresh concretes, plain and reinforced with CFP fibers;
2. Characteristics of hardened concrete, such as compressive strength, static modulus, static flexure strength, unit weight, and the pulse velocity;
3. Toughness indexes using the ASTM C1018 standard method and load deflection curves; and
4. Flexural toughness factor and equivalent flexural strength, using the Japanese standard method.

Values of 5.0, 10.0, 20.0 for I_5, I_{10}, I_{20}, respectively, correspond to linear elastic behavior up to the first crack and perfectly plastic behavior hereafter. A value of two for the ratios of I_{10}/I_5 and I_{20}/I_{10} indicates perfectly plastic material behavior between the deflections associated with these indexes.

The observed values of I_5, I_{10}, I_{20} are given in the in-text table.

Index	*Values of Toughness Indexes*		
	Plain concrete	*Elastic plastic material*	*Observed range for fibrous concrete*
I_5	1.0	5.0	1 to 6
I_{10}	1.0	10.0	1 to 12
I_{20}	1.0	20.0	1 to 25

MATERIALS, MIXES, AND TEST SPECIMENS

Materials

- Fiber: Collated fibrillated polypropylene (CFP) fibers produced by Forta Corporation were used. Fiber bundle length was 57 mm (2¼ in.), and the product designation was Type D-15.
- Cement: Type I normal portland cement, satisfying the requirements of ASTM C150, was used for all mixes. The cement was produced by a cement plant in Rapid City, South Dakota.
- Coarse Aggregate: The coarse aggregate used was crushed limestone aggregate obtained locally (Rapid City). The maximum size of the coarse aggregate was ¾ in. and met AASHTO #67 gradation requirements. Its absorption coefficient was 0.45 percent and its fineness modulus was 6.80.
- Fine Aggregate: The fine aggregate used was natural sand obtained locally; it had a water absorption coefficient of 1.64 percent and fineness modulus of 2.95. Both fine and coarse aggregates satisfied the grading requirements of ASTM C33.
- Water: The water used was tap water from the Rapid City, municipal water supply system.
- Superplasticizer: The superplasticizer used was Rheobuild 1000, which was manufactured by Master Builders and met ASTM C494 Type D specifications.

Mixing of Concrete

The basic mix proportions that were used for the research program were as follows:

- Coarse aggregate, 926 kg/m^3,
- Fine aggregate, 926 kg/m^3 Cement;
- Cement, 390 kg/m^3; and
- Water, 163.8 kg/m^3.
- Mix designations are given in Table 1. Three mixes were made using standard D-15 type polypropylene fibers containing 0.1, 0.2, and 0.3 percent by volume. Replicate mixes for the three mixes were also made, and one mix of plain concrete was made. Seven mixes were made for the program. The volume of each mix was 0.077 m^3 (2.75 ft^3). The water to cement ratio was maintained at 0.42. Mixing of concrete was done according to ASTM C192.

Test Specimens

The following specimens were cast from each mix, six 150 × 300 mm (6 × 12 in.) cylinders for the determination of the compressive strength and static modulus tests; six to eight 100 × 100 × 350 mm (4 × 4 × 14 in.) beams for the determination of the static flexural strength and toughness indexes.

The specimens were cast in steel molds immediately after mixing. The specimens were then covered with plastic sheets for 24 hr to prevent evaporation of water from the unhardened concrete. The specimens were then demolded and placed in lime-saturated water tanks in which the temperature of the water was maintained at 23°C (73°F). Specimens used for compressive strength tests and static flexural tests remained in water until they were tested at 7 and 28 days.

TABLE 1 Mix Designation and Properties of Fresh Concrete

Mix	Type of fiber	Percentage of fiber by volume	Superplasticizer Dosage (cc)	Room		Concrete Temp. (°C)	Unit Weight (kg/m^3)	Slump (mm)	Vebe Time (seconds)	Air Content (%)
				Temp. (°C)	Humidity (%)					
FP	No fiber	Plain concrete	150	21	40	22.7	2440	108	1.2	2.2
F1C	Forta D 15	0.10	260	17	65	19.0	2439	38	3.7	2.5
F2C	Forta D 15	0.20	250	21	40	22.4	2435	76	1.5	3.1
F3C	Forta D 15	0.30	380	17	65	19.6	2453	57	3.6	2.5
F1CR	Forta D 15	0.10	110	21	35	20.1	2412	57	1.1	2.4
F2CR	Forta D 15	0.20	140	18	30	20.9	2438	76	1.5	2.3
F3CR	Forta D 15	0.30	170	21	35	20.3	2428	38	3.3	2.2

TESTS FOR FRESH CONCRETE

The freshly mixed concrete was tested for slump (ASTM C143), air content (ASTM C231), fresh concrete unit weight (ASTM C138), as well as concrete temperature and vebe time.

TESTS FOR HARDENED CONCRETE

The cylinders were tested for compressive strength at 7 and 28 days, according to ASTM C39. They were also tested for the static modulus (ASTM C469), pulse velocity (ASTM C597), and unit weight.

Beams were tested for static flexural strength, third-point loading was applied to the beams per ASTM C1018. The span length was 150 mm (12 in.). Deflection was measured at midspan using a dial gauge accurate to 0.002 mm (0.0001 in.). The test was a deflection-controlled test, and the rate of deflection was kept in the range of 0.05 to 0.1 mm (0.002 to 0.004 in.)/min per ASTM C1018. Loads were recorded at every 0.05-mm (0.002-in.) increment in deflection until the first crack appeared, after which loads were recorded at regular intervals. The maximum load reached was called the "first crack load." From loads and deflections obtained from the tests, load deflection curves were drawn and toughness indexes were calculated from the load deflection curves.

The flexural toughness factor and equivalent flexural strength were calculated using the Japanese standard method.

TOUGHNESS

To measure the influence of fibers on flexural strength and the toughness, the United States and Japan prescribed similar bending tests in which the load was to be recorded at specified deflections of the specimen. Both countries used third-point loading configuration. However, the values obtained from these two countries' standards differed considerably. The two methods used were ASTM C1018 and Japanese standard JCI-SF4.

The ASTM method is dependent on the accurate determination of δ, where δ is the deflection up to the first crack. The value of δ is very small, usually in the order of 0.03 to 0.1 mm (0.0019 to 0.0039 in.). The toughness indexes I_5, I_{10}, and I_{20} were calculated using the ASTM method.

When using the Japanese method, the test should be continued until a deflection equal to 1/150 of the span is reached. That deflection is equal to 2 mm (0.08 in.) for a 150-mm (12-in.) span length. The deflection thus obtained is greater than what is measured by the ASTM standard method. The flexural toughness factor and equivalent flexural strength are calculated with the Japanese standard method.

If toughness calculations are made from midpoint deflections, the resultant energy value marginally overestimates the true energy absorbed by the specimen.

RESULTS AND DISCUSSION

Observed Fresh Concrete Properties

The CFP fiber used in the program performed well. Even though the fibers, cement, and water were added into the mixer all at once, no balling occurred. That was because of the low aspect ratio created by the collation of the fibers. The mixing action caused the bundles to open up and expand and form a fiber mesh of individual fibers, which spread uniformly throughout the concrete mix. The fresh concrete with fibers was observed to have very little surface bleeding and no segregation.

Workability

Slump and vebe time tests were conducted to determine the workability of the concrete mixes. Vebe time is used to measure the workability of concrete based on the energy needed to compact the concrete. Test results indicated that satisfactory workability can be maintained even with increased fiber content. Workability was maintained by adjusting the amount of superplasticizer without causing any change in the strength of the concrete. The following amounts of superplasticizer were added to the concrete mixes: 150 cc for plain concrete, 180 cc for 0.1 percent fiber content, 190 cc for 0.2 percent fiber content, and 270 cc for 0.3 percent fiber content. The water to cement ratio was maintained at 0.42. The test results for slump, unit weight, air content, and vebe time are given in Table 1.

The fiber-reinforced concrete was placed with relative ease and compacted using a vibrating table. The tests conducted on fresh fiber-reinforced concrete basically were aimed at determining the workability of each mix with different fiber contents. The room temperature, humidity, and the concrete temperature were noted to make sure that the mixing of the fiber-reinforced concrete mixes was done under similar conditions. The room temperature varied from 17°C to 21°C (64°F to 70°F), the humidity varied from 30 to 65 percent, and concrete temperature varied from 18°C to 22.8°C (64.4°F to 73.2°F).

Slump Versus Air Content

The relationship between the slump and air content is shown in Figure 1. The slump and air content are directly proportional, (i.e., as the slump increases the air content increases.) A linear regression analysis showing the relationship is illustrated in Figure 1.

Slump Versus Vebe Time

Figure 2 shows the relationship between slump and vebe time. The slump and vebe time are inversely proportional, (i.e., as the slump increases the vebe time decreases). A linear regression analysis showing the relationship is illustrated in Figure 2.

Fresh Concrete Unit Weight

The results of the fresh concrete unit weight are given in Table 1. The average unit weight of all mixes with fibers was 2408 kg/m^3 (150 lb/ft^3); whereas the unit weight of fresh concrete without fibers was 2416 kg/m^3 (150.52 lb/ft^3). The average values indicate that there was no significant difference in the unit weight as the fiber content increased from 0.1 to 0.3 percent by volume. It can be presumed that the superplasticizer enhanced consolidation of mixes with higher fiber content. The measured air contents were ranged from 2.2 to 3.1 percent.

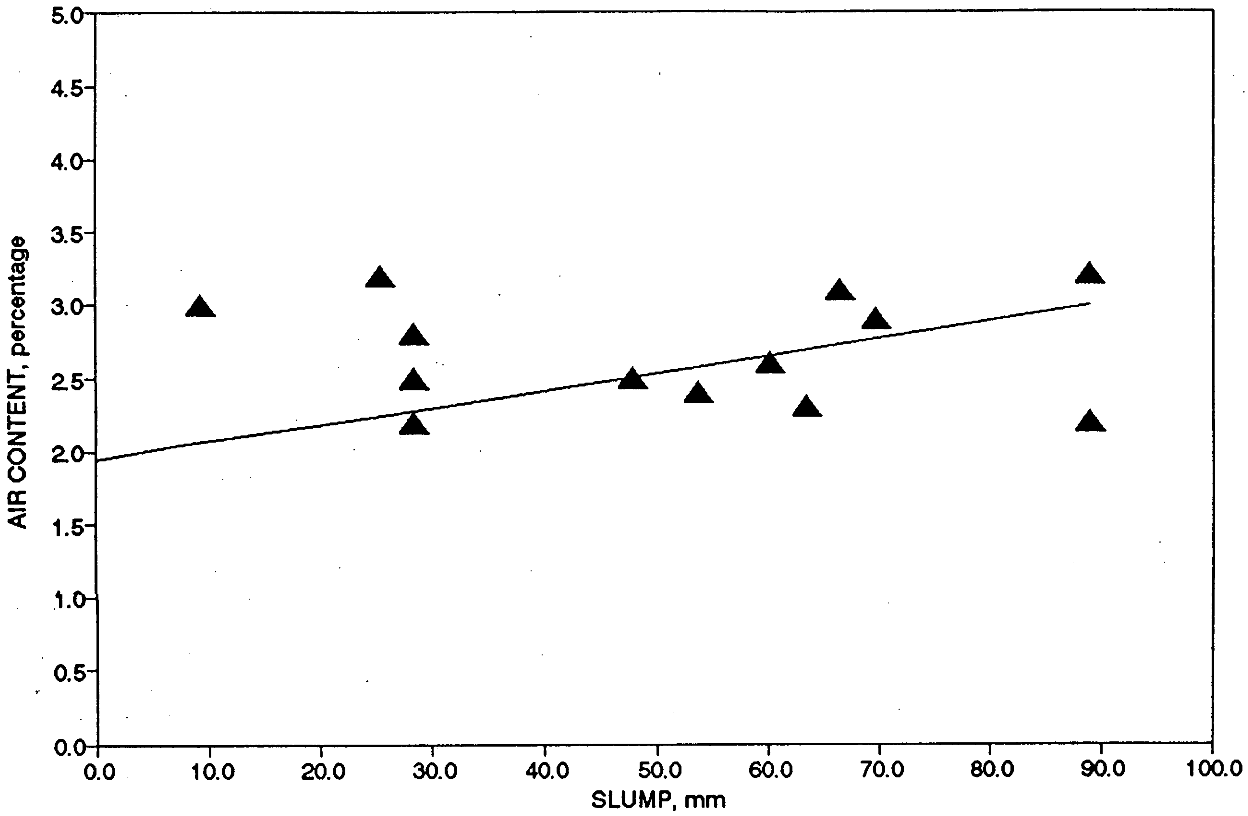

FIGURE 1 Slump versus air content for all mixes.

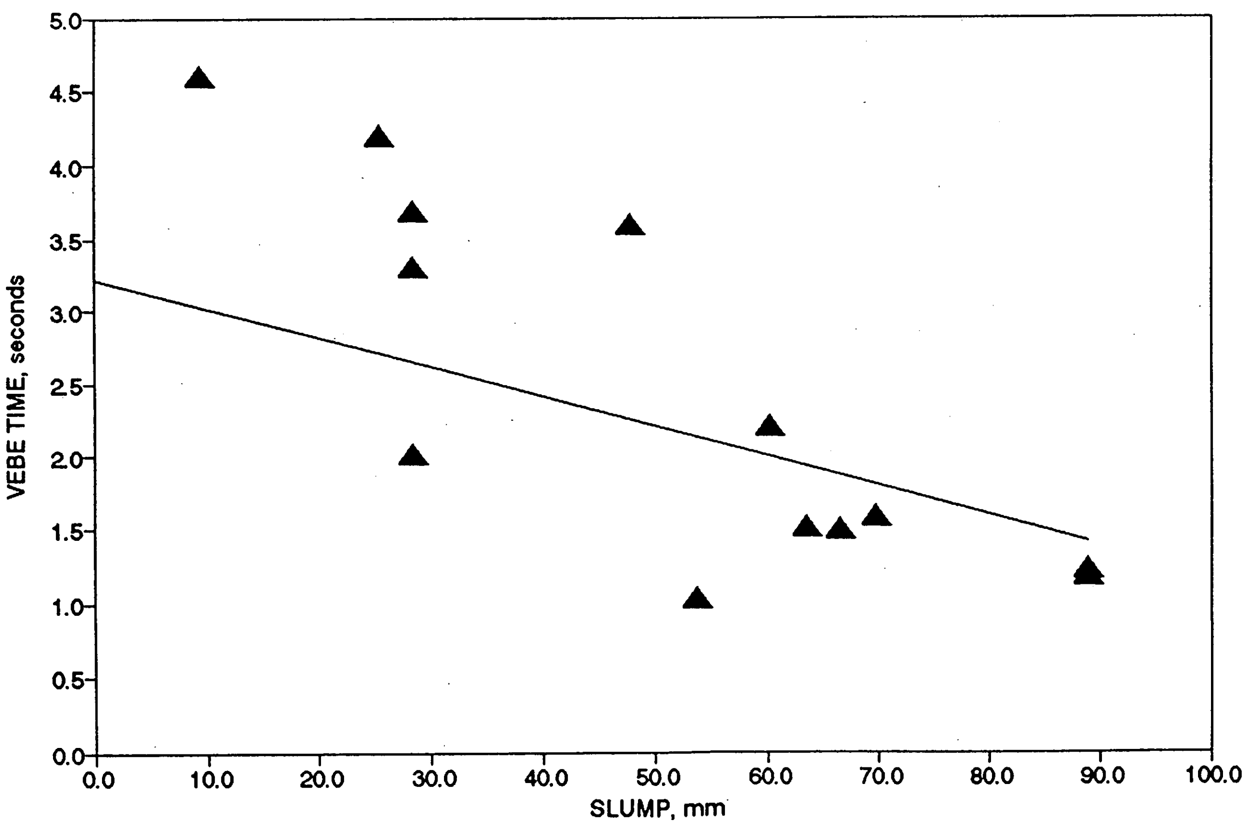

FIGURE 2 Slump versus vebe time for all mixes.

Finishability

Good finishability was obtained with collated fibrillated polypropylene fibers by suitably adjusting the amount of superplasticizer to get the required consistency. As observed, the fibers are coated with the mortar and cement paste. The more fibers introduced to the mix, the greater the mortar portion that is required. The factor does not come into play for the 0.3 percent by volume introduction rate. In fact, no change was required in the mixture proportions for the 0.3 percent by volume fibers.

HARDENED CONCRETE PROPERTIES

Compressive Strength

Compressive strength test results for the plain and fiber-reinforced cylinders are given in Table 2 and Figure 3. The test results indicate the polypropylene fiber-reinforced concrete has slightly higher values than plain concrete except for the 0.2 percent by volume mixes.

As the fiber content increased from 0.1 to 0.3 percent by volume, there was approximately a 5 percent increase in compressive strength. That range is within the experimental variation possible for concrete work. Hence, it can be stated that the addition of fibers did not influence the compressive strength of the concrete.

Flexural Strength

The 7- and 28-day flexural strength results are shown in Table 2 and Figure 3. The flexural strength was slightly higher for polypropylene fiber-reinforced mixes than for the plain concrete in all cases.

Results reported by others indicate there can be a slight reduction in flexural strength with the addition of fibers. The reduction may result from a number of factors, including improper compaction, inadequate mortar, or the lack of bond by fiber, either because of improper length or configuration. The latter would reduce the fibers' ability to modify the cracking and shrinkage.

Static Modulus

The static modulus test results are presented in Table 2 and Figure 3 and indicate that there was less than 5 percent difference between polypropylene fiber-reinforced concrete cylinders and the plain concrete cylinder. The static modulus of plain concrete was the same as that of the fiber reinforced concrete; addition of fibers did not cause any change in the static modulus.

Pulse Velocity

The pulse velocity test served as a good quality-control procedure and produced consistent results.

Pulse velocities are shown in Table 2 and Figure 4. Average pulse velocity for the polypropylene fiber-reinforced beams with 0.1 volume percent fibers was 4909 m/sec (16,096 ft/sec).

There was no difference in the propagation of compressional waves through the beams as the fiber contents were increased from 0.1 to 0.3 volume percent. The average pulse velocity for the plain concrete beams was 4808 m/sec (15,766 ft/sec).

TABLE 2 Hardened Concrete Properties

Mix	Compressive Strength, MPa		Flexural Strength, MPa		Static Modulus, MPa x 10^3		Pulse Velocity m/sec		Unit Weight kg/m^3	
	7- Day	28-Day	7- Day	28-Day	7- Day	28-Day	7- Day	28-Day	7- Day	28-Day
PL	39.13	48.23	3.75	4.06	42.72	36.58	4504.24	4815.03	2435.38	2427.27
	39.73	48.50	4.54	3.99	33.76	35.62	4725.67	4791.85	2437.00	2427.27
	40.65	49.26	4.40	4.61	36.31	36.86	4585.37	4850.72	2425.65	2437.00
Av.	39.89	48.66	4.07	4.51	37.62	36.37	4571.34	4808.63	2432.67	2430.51
F1C	43.46	52.86	4.89	4.87	37.13	36.86	4671.68	4895.86	2454.84	2456.46
	43.77	51.53	4.89	5.66	36.58	33.14	4772.64	4926.36	2466.19	2459.70
	44.11	53.22	5.16	5.37	36.79	36.86	4770.50	4925.14	2458.08	2456.46
Av	43.78	52.54	4.98	5.30	36.86	35.62	4738.17	4915.68	2459.70	2457.54
F2C	37.24	44.29	4.58	4.99	32.58	36.72	4692.73	4795.82	2461.32	2446.73
	36.62	48.91	4.48	5.23	32.86	33.55	4636.91	4908.67	2461.32	2445.11
	38.91	48.04	4.78	4.96	32.31	36.65	4785.75	4902.26	2467.81	2446.73
Av	37.59	47.08	4.61	5.05	32.58	35.62	4705.23	4869.02	2463.48	2446.19
F3C	44.27	52.35	4.92	5.81	35.62	36.03	4784.23	4939.78	2451.60	2456.46
	43.89	48.36	4.96	4.95	36.17	36.65	4718.65	4922.39	2454.84	2448.35
	44.27	51.50	5.13	5.80	36.93	36.79	4725.67	4947.10	2456.46	2461.32
Av	44.14	50.73	5.00	5.52	36.24	36.51	4742.75	5109.66	2454.30	2455.37

Note: The values given are the averages of original and replicate mixes.

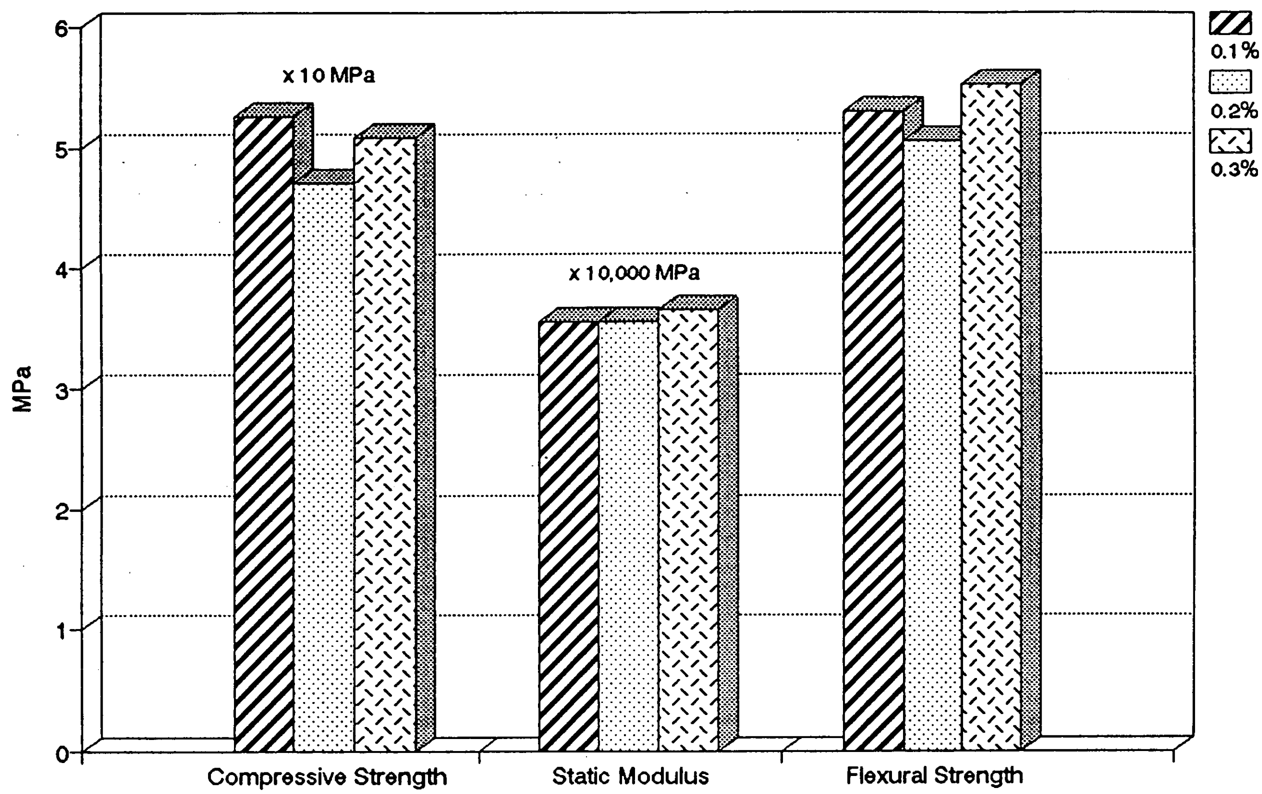

FIGURE 3 Comparison of compressive strength, static modulus, and flexural strength for different fiber contents.

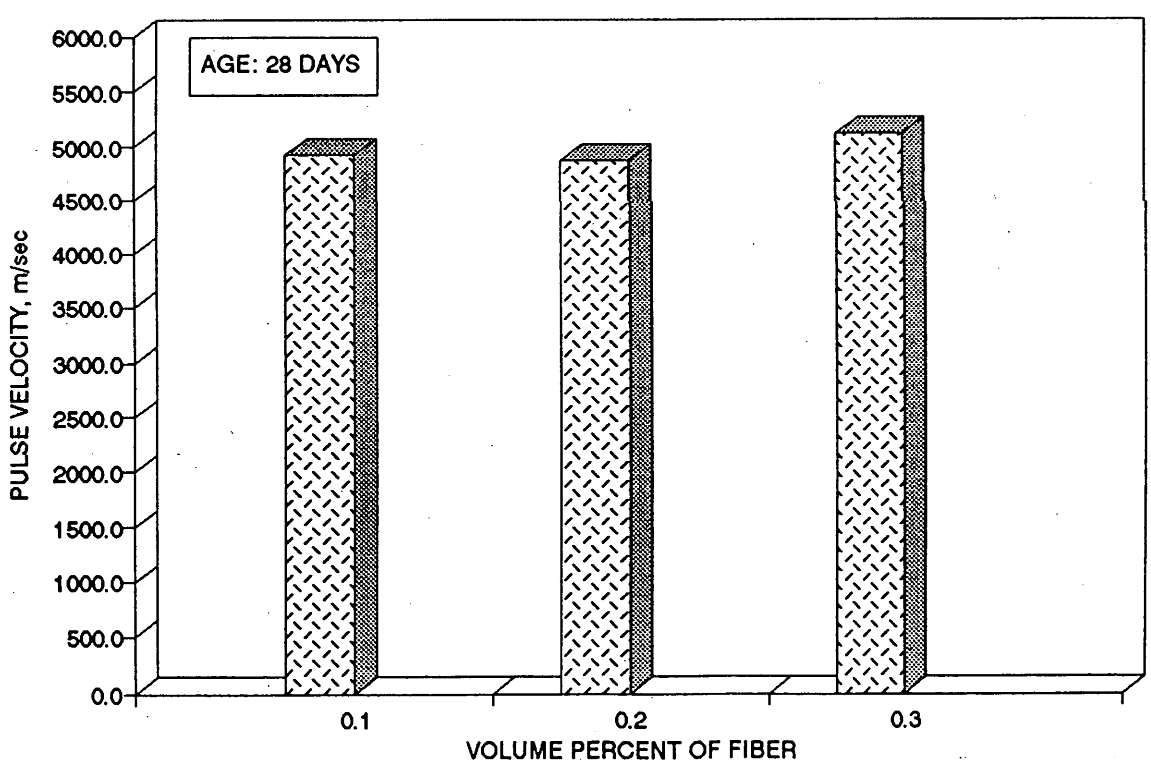

FIGURE 4 Pulse velocity versus fiber content.

Load-Deflection Behavior

Figure 5 shows the load deflection curves for the polypropylene fiber-reinforced concrete beams. The area under the load deflection curve represents the energy absorbed by the beam.

The load deflection curves indicate that elasto-plastic behavior improved as the fiber content was increased. All the plain concrete beams failed immediately after the first crack formed, as would be expected.

Another important observation is that the load deflection curves become nonlinear before any visible signs of material distress. However, the rate at which the moment of inertia deteriorated when the first crack appeared, was lessened by the fibers, because the fibers resisted the propagation of cracks. The crack widths were smaller as fiber content increased. That indicates the energy-carrying capacity or the toughness of the beams increased with an increase in fiber content.

Although only small quantities of fiber were used in this research project, test results and behavior of the load deflection curves indicate that the flexural strengths and toughness indices of fiber-reinforced concrete are approximately 18 percent greater than for plain concrete.

Toughness Indexes (ASTM C1018)

The calculated toughness indexes are given in Table 3 and Figure 6.

The I_{10}/I_5 and I_{20}/I_{10} ratio results (Figure 7) indicate that, even though the specimens were not perfectly elasto-plastic, the fiber reinforced beams achieved a good measure of ductility and post-crack plastic behavior. The results also indicate that there was no significant improvement in the behavior of the beams as the volume percent of fiber was increased from 0.1 to 0.3. That could be because only a small amount of fiber was used in the investigation.

Statistical analysis indicated that good quality control was maintained in the casting and testing operation.

JAPANESE STANDARD METHOD

Flexural Toughness Factor

The values of the flexural toughness factor are given in Table 3 and Figure 8. The Japanese standard method, unlike the ASTM method, specifies the deflection as equal to $^1/_{150}$ of its span. The span for beams used in this investigation was 150 mm (12 in.). The deflection measured using this method was much greater than what was measured using the ASTM method.

Equivalent Flexural Strength

The Japanese method provides a better comparison of toughness for concretes with different fiber contents than does the ASTM method. As the fiber content increased, the flexural toughness factor and the equivalent flexural strength values also increased (Figure 9).

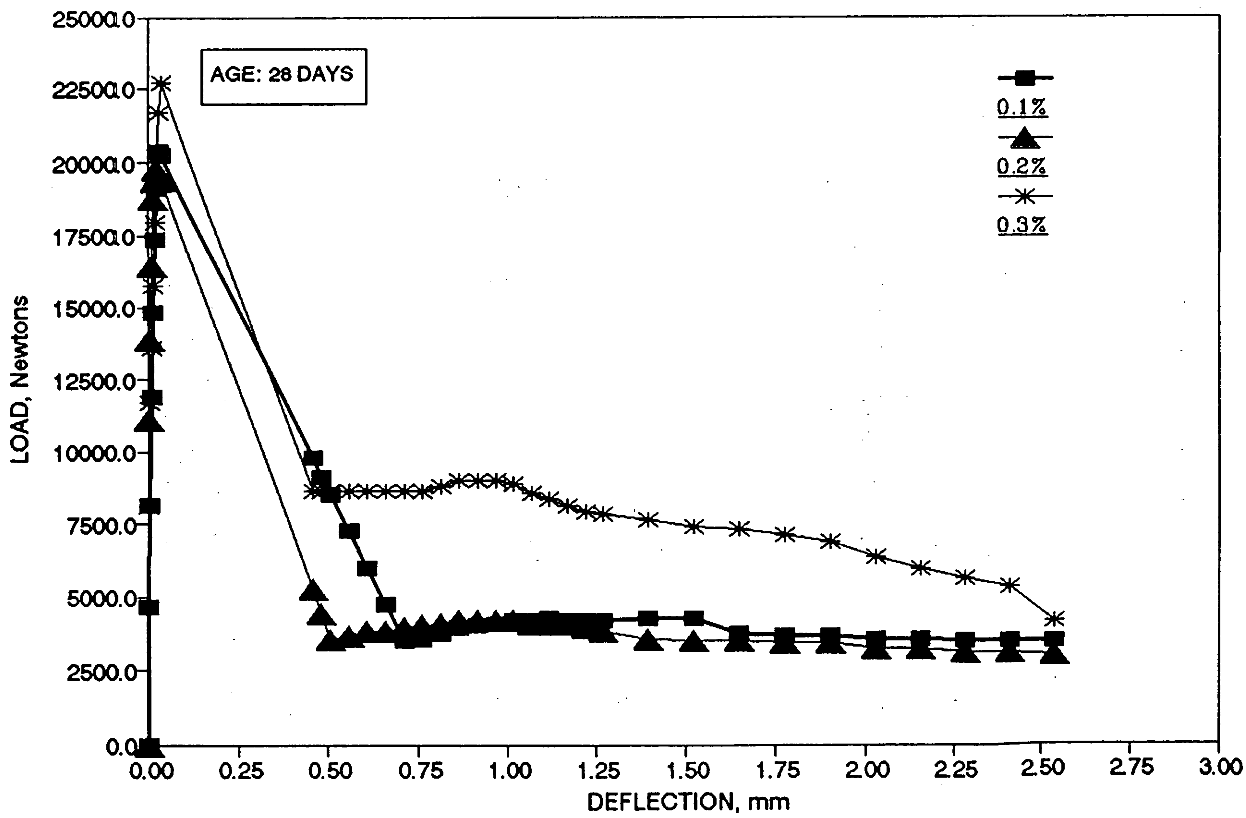

FIGURE 5 Load deflection curves versus fiber content.

TABLE 3 Toughness Indexes (ASTM) and Strength (Japanese Standard)

Mix	Toughness Indexes (ASTM)								Japanese Standard	
	I5		I10		I20		I10/I5	I20/I10	Flexural Toughness x 10³ N-mm	Equivalent Flexural Strength, MPa
	7-Day	28-Day	7-Day	28-Day	7-Day	28-Day	28-Day	28-Day	28 - Day	28 - Day
F1C	3.64	3.89	6.69	6.45	11.36	11.57	1.69	1.79	13.11	1.72
	3.05	4.38	5.00	8.02	8.48	13.38	1.84	1.68	13.45	1.80
	3.22	3.84	6.33	6.71	11.29	10.88	1.75	1.62	13.56	1.82
Av	3.30	4.04	6.01	7.06	10.38	11.94	1.76	1.70	13.37	1.78
F2C	3.48	4.13	6.17	7.26	9.82	12.26	1.77	1.69	17.40	2.35
	3.57	3.54	6.45	6.60	10.50	10.71	1.85	1.64	13.67	1.86
	3.60	3.71	5.89	7.12	9.74	11.79	1.92	1.65	17.29	2.34
Av	3.55	3.79	6.17	6.99	10.02	11.58	1.85	1.66	16.12	2.18
F3C	3.46	3.50	6.58	6.65	11.51	11.05	1.90	1.67	20.34	2.84
	3.68	3.20	6.88	5.97	11.34	10.47	1.87	1.77	20.23	2.80
	3.90	3.40	7.00	6.42	11.51	10.73	1.89	1.67	18.98	2.62
Av	3.68	3.36	6.82	6.34	11.45	10.75	1.89	1.70	19.85	2.75

CONCLUSIONS AND RECOMMENDATIONS

The workability of the fresh fiber-reinforced concrete mixes can be maintained by adding suitable amounts of superplasticizer. No balling of fibers occurred during mixing. There was no problem in placing and finishing the concrete. The mortar portion of the mix did not need to be increased to accommodate up to 0.3 percent by volume of the CFP fiber (FORTA CR Type D-15).

The compressive strength of the concrete was not significantly affected by the addition of fibers. The static modulus, pulse velocity and unit weight for the fiber-reinforced concrete was less than five percent above that of plain control concrete specimens.

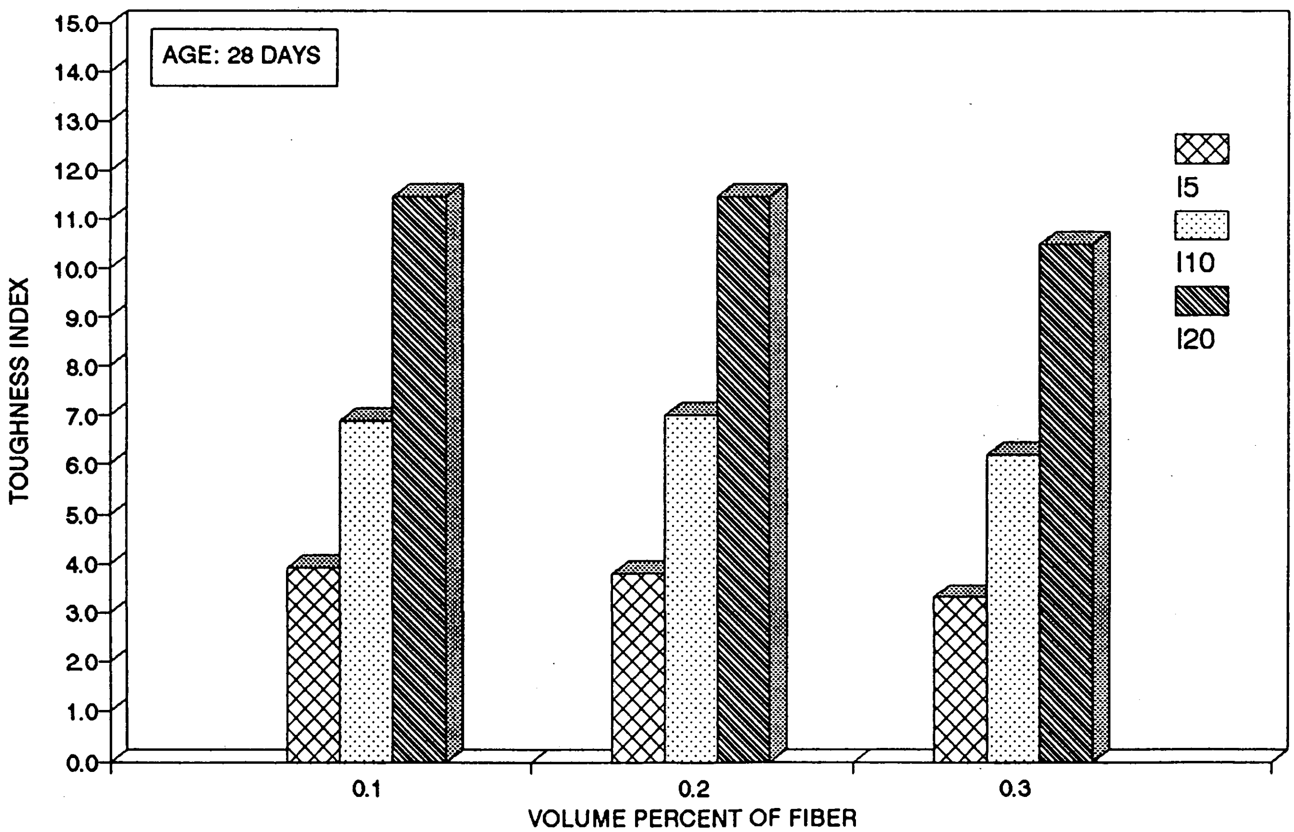

FIGURE 6 Toughness indexes versus fiber content.

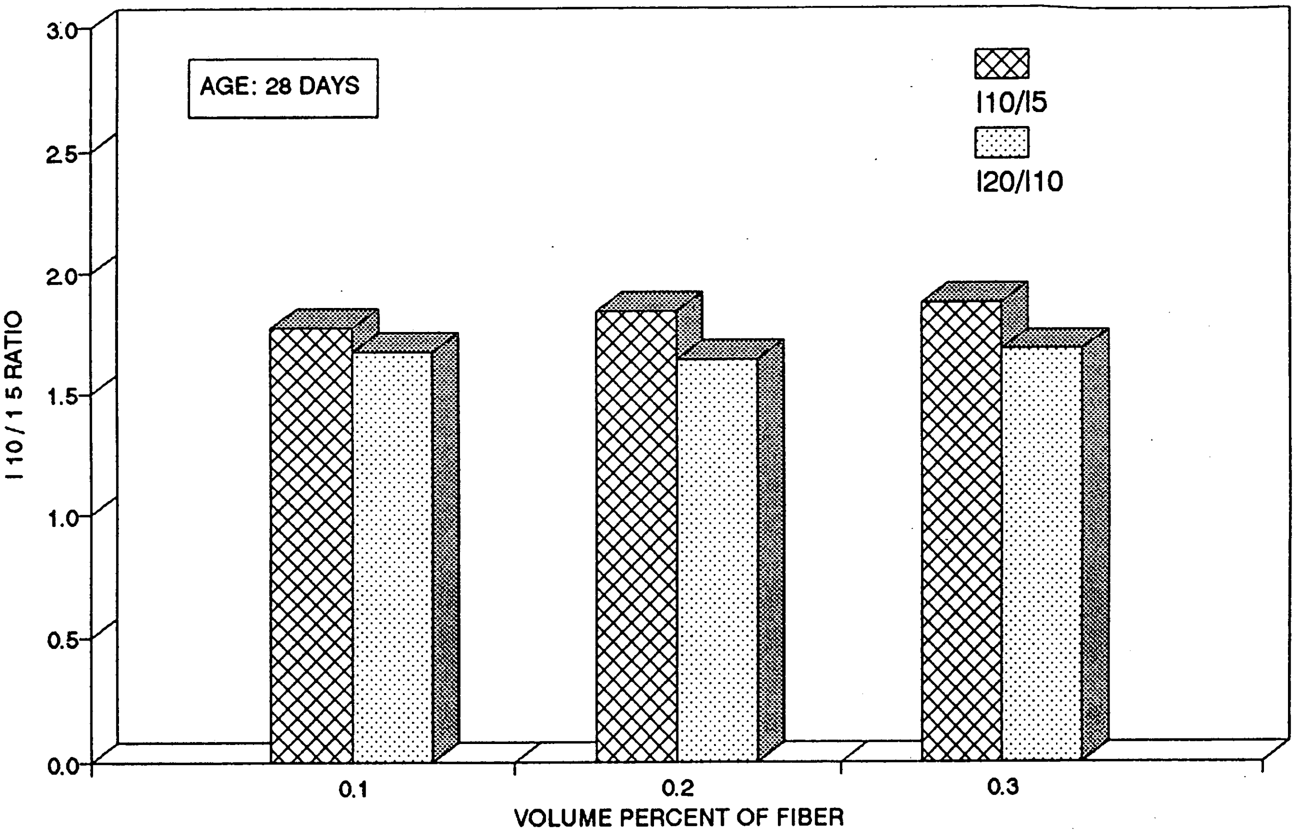

FIGURE 7 Toughness indexes ratios versus fiber content.

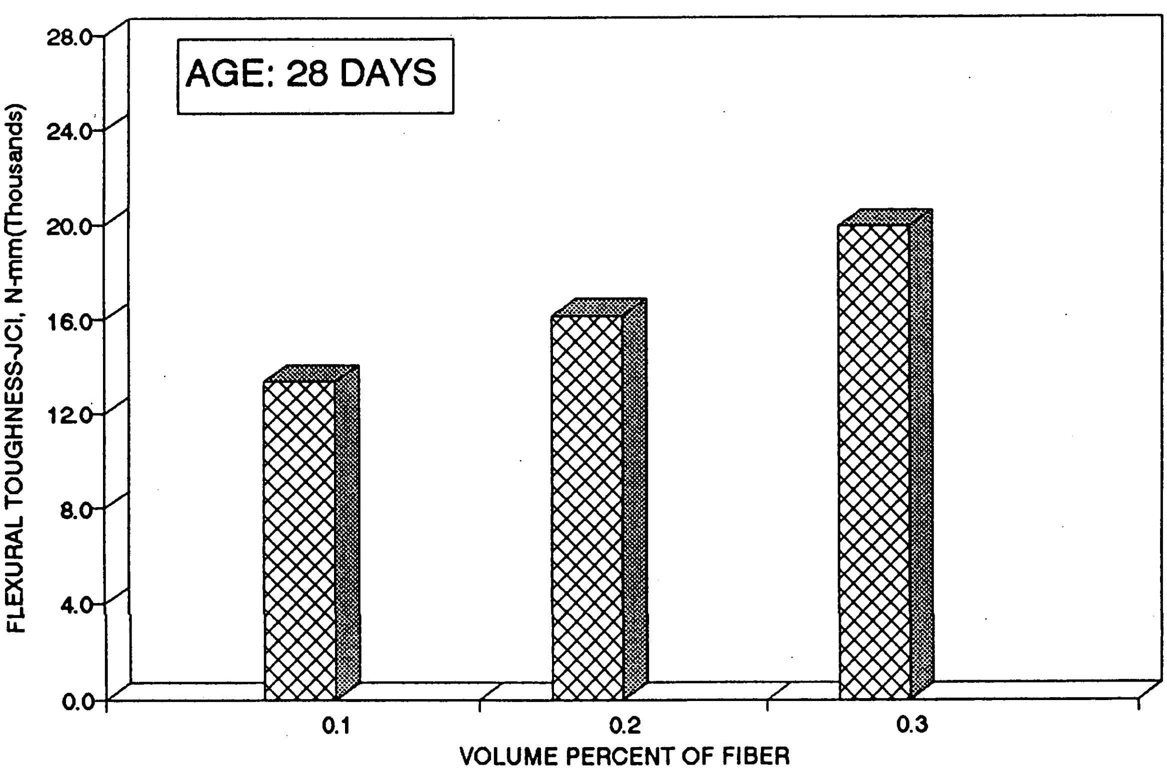

FIGURE 8 Flexural toughness factor (Japanese standard) versus fiber content.

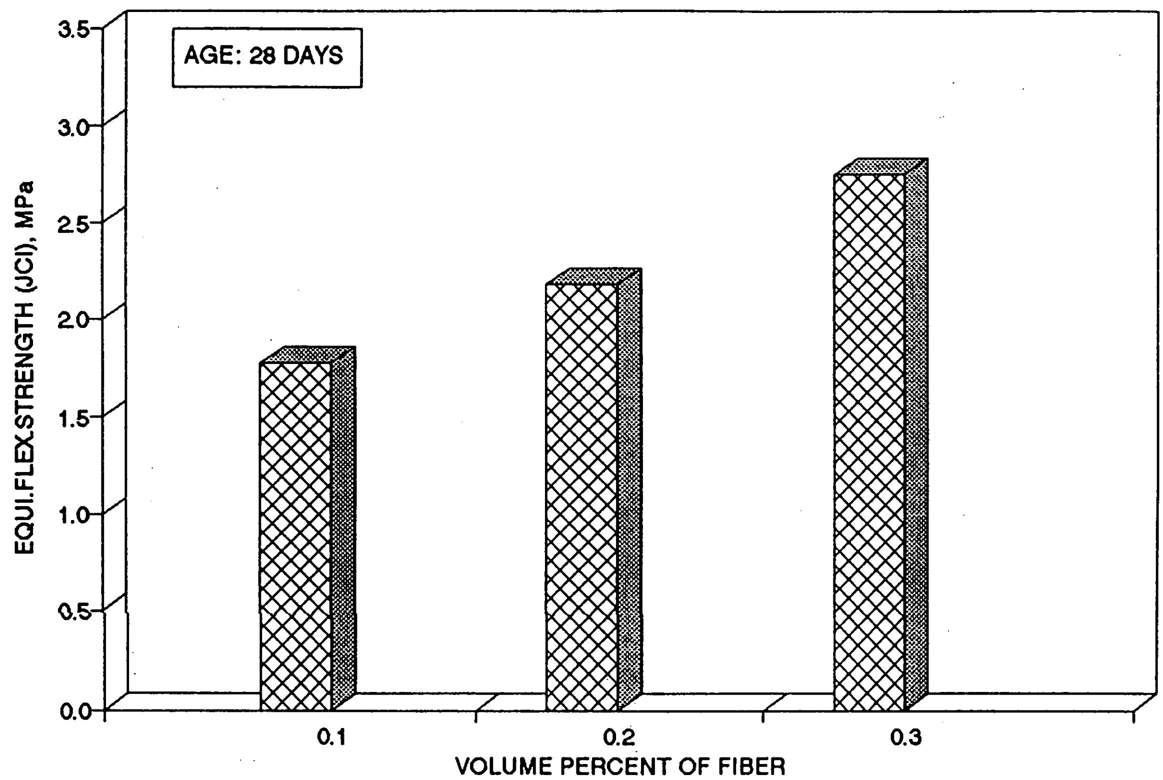

FIGURE 9 Equivalent flexural strength (Japanese standard) versus fiber content.

The ductility of the concrete was increased with the addition of fibrillated polypropylene fiber. The increase in ductility was proportional to the increase in dosage fiber.

The first crack strength and the static flexural strength increased slightly as the volume percent of the fiber was increased from 0.1 to 0.3. The ASTM toughness indexes, I_5, I_{10}, and I_{20}, showed that the fiber-reinforced concrete beams had an elasto-plastic behavior when subjected to flexural loading.

There is no doubt that improvements in the flexural strength and toughness of concrete with the addition of fiber will extend its application in structures such as bridge decks and highway pavements. Nevertheless, addition of fiber represents an additional cost. Therefore the optimum fiber content should be determined by future research.

Effects of fiber length on the performance characteristics of concrete reinforced with standard and modified polypropylene fibers at high fiber volumes merits additional study.

ACKNOWLEDGMENTS

The authors' research was conducted at the Civil Engineering Department of the South Dakota School of Mines and Technology and was partly funded by the Forta Corporation. The authors are grateful to Chowdhary S. Gondy for his help in the experimental work and to Sidhesh Kakodkar for his help in preparing the paper.

REFERENCES

1. Ramakrishnan, V. Materials and Properties of Fiber Reinforced Concrete. *Proc., International Symposium on Fiber Reinforced Concrete,* Madras, India, Dec. 16–19, 1987.
2. Ramakrishnan, V., W. V. Coyle, V. Kulandaiswamy, and E. K. Schrader. Performance Characteristics of Fiber Reinforced Concrete with Low Fiber Contents. *ACI Journal Proceedings,* Vol. 78, No. 5, Sept–Oct. 1981, pp. 384–394.
3. Ramakrishnan, V., S. Gollapudi, and R. Zellers. Performance Characteristics and Fatigue Strength of Polypropylene Fiber Reinforced Concrete. In *Fiber Reinforced Concrete; Properties and Applications,* Special Publication SP105, American Concrete Institute, Detroit, Mich. 1987, pp.159–177.
4. Ramakrishnan, V., G. Y. Wu, and G. Hosalli. Flexural Behavior and Toughness of Fiber Reinforced Concrete. Presented at 68th Annual Meeting of the Transportation Research Board, Washington D.C., Jan. 1989.
5. State of the Art Report on Fiber Reinforced Concrete. Special Publication SP44, American Concrete Institute, Detroit, Mich. 1974, 550 pp.
6. Ramakrishnan, V., G. L. Vandran, and N. Mulphuri. Fatigue Strength of Polypropylene Fiber Reinforced Concrete. In *Fiber Reinforced Cements and Concretes, Recent Developments,* R.N. Swamy, and B. Barr, eds. 1989, pp.533–541.
7. Mulphuri, N. Performance Evaluation of Fatigue Properties of Polypropylene Fiber Reinforced Concrete; An Experimental Investigation. M.S. thesis. South Dakota School of Mines and Technology, Rapid City, 1988.
8. Yongxin, L. Properties of Polypropylene Fiber Reinforced Concrete and Effects of Fiber Length, An Experimental Investigation. M.S. thesis. South Dakota School of Mines and Technology, Rapid City, 1988.

Publication of this paper sponsored by Committee on Mechanical Properties of Concrete.