Effect of Fibrillated Polypropylene Fiber Reinforcement on Concrete Behavior

by

Ruinian Jiang
Assistant Professor
rjiang@nmsu.edu
Department of Engineering Technology and Surveying Engineering
New Mexico State University

Eric Lowe
Civil Engineer, Bridge Section
eric.lowe@state.nm.us
New Mexico Department of Transportation

Haihong Du
Civil Engineer
Chrisdu1977@yahoo.com

Abstract: *This paper introduces a comprehensive test on the behavior of polypropylene fiber reinforced concrete. Fibermesh 300 synthetic fibers produced by SI Concrete Systems was used in concrete strengthening and the effects of fibers on various concrete properties were explored by varying water/cement (w/c) ratios and volumetric fiber content. The results showed that polypropylene fibers have great potential in controlling plastic shrinkage and plastic settlement cracking and in the improvement of toughness and tensile strength of concrete.*

I. Introduction

Concrete cracking is a major concern of contractors and their clients. In order to improve the toughness and tensile strength of concrete, various types of fibers have been developed since the 1940s. Synthetic fibers have been found one of the most popular fibers commercially available (Brown, 2002). If cracking due to intrinsic stress is reduced or eliminated, problems due to water mitigation and chemical exposure may be avoided.

Many researches have been found on the behavior of fiber-reinforced concrete. Grzybowski and Shah (1990) conducted research to assess cracking of fiber reinforced concrete due to restrained shrinkage. They found that adding fiber reinforcement does not substantially control drying shrinkage. However, the steel fibers proved to be more effective than the polypropylene fiber in this aspect. The shrinkage cracks, on the other hand, may be reduced significantly with the addition of polypropylene or steel fibers. As the fiber content increases the shrinkage cracks decrease. Moreover, with a small amount of polypropylene fiber in volume equal to 0.1 percent, the influence of fiber was negligible.

Biddle (1991) discussed the use of fiber reinforcement in residential concrete. Since the first residential application in 1979, fiber reinforcement has gained acceptance for residential applications. Not only was the fiber concrete easy to work with, it also eliminated the need for welded wire mesh reinforcement. The author goes on to claim that the fibers control and inhibit plastic shrinkage cracking but, good concreting practices must be followed.

In research conducted by Gopalaratnam et al. (1991) flexural tests were conducted on concrete beams reinforced with steel and polypropylene fibers. According to Gopalaratnam et al., the fiber type and volume content influenced the toughness of concrete. The toughness data indicated that concrete reinforced with steel fibers resulted in toughness values similar to that of concrete reinforced with polypropylene fibers. The shape of fiber is also a factor that determined the toughness of concrete. At the same volume content of fiber, steel-hooked fiber reinforced concrete was more ductile than steel-crimped fiber reinforced concrete. Test results indicated that the modulus of elasticity increased with an increase in fiber content. It was concluded that ultimate strength and toughness increased with an increase in fiber content.

Ramakrishnan et al. (1994) conducted research to determine elastic and mechanical properties of concrete reinforced with monofilament polypropylene fibers. Variability was observed in strength with an increase in fiber content. Again, there was no clear correlation between strength and fiber content. Toughness, however, was always observed to increase with an increase in fiber content.

Taylor et al. (1996) conducted research on steel and polypropylene fiber reinforced high strength concrete. Tabulated data indicated that as the volume of polypropylene fiber increased the 28 day strength showed some variation. The strength tends to decrease with some fiber contents and increase with others. Taylor et al. found that there was an optimum amount of fiber content. The toughness of the concrete tested exhibited that same trend. The steel specimens tested always indicated an increase in strength and toughness with an increase in steel fiber.

Banthia and Dubey (2000) conducted research on concrete reinforced with steel and polypropylene fibers of various shapes and lengths. It was determined that the flexural toughness of concrete was dependant upon the type of fiber. For example, the crimped polypropylene fibers proved more beneficial than the straight fibers. When considering compressive strength of concrete containing various quantities of fibers, variability was seen in the results. The strength did not necessarily increase or decrease with an increase in polypropylene fiber content.

This research conducted a comprehensive test on the behavior of polypropylene fiber reinforced concrete. The tests intended to provide a general reference on how polypropylene fibers affect the major concrete properties under various fiber content and water/cement ratios. In this research, Fibermesh® 300 (formerly INFORCE) synthetic fiber produced by SI Concrete Systems (Propex, 2007) was used in strengthening concrete. Fibermesh 300 contains 100% virgin homopolymer polypropylene fibrillated fibers which conform to ASTM C 1116 Type III specifications. The effects of fibers on various concrete properties were explored by varying water/cement (w/c) ratios and volumetric fiber content. The results have shown the great potential of polypropylene fibers in controlling plastic shrinkage and plastic settlement cracking and in the improvement of toughness and tensile strength of concrete.

II. Test Procedure

Specimen Preparation

Concrete mixtures were designed in accordance with procedures outlined in the Portland Cement Association (PCA) manual (Kosmatka et al., 2002). A total of seven concrete mixtures were designed which were sufficient to show concrete property changes at a least cost. Six of the mixtures contained polypropylene fibers; the seventh served as a control mixture (no fiber reinforcement). Three water/cement ratios (w/c ratio, commonly used values) and two polypropylene fiber concentrations were used. The fiber was added to the concrete as a percentage of the total volume of concrete and the fiber contents were selected according to the specification of the synthetic fiber (Propex, 2007). The concrete mixtures are summarized in Table 1.

Table 1. Concrete mixtures

Mixture	1	2	3	4	5	6	7
W/C Ratio	0.50	0.55	0.60	0.50	0.55	0.60	0.50
Fiber Content	1%	1%	1%	2%	2%	2%	2%

Note: 1% fiber content is about 15 lb fibers per cubic yard of concrete.

For each of the six mixtures containing fiber reinforcement, the following specimens were made and tested:

- Four 6” (diameter) by 12” (height) cylinders
- Two 6” by 6” by 24” beams
- One 6” by 6” by 30” beam

For the control mixture, the following specimens were made:

- Four 6” (diameter) by 12” (height) cylinders
- One 6” by 6” by 30” beam

The slump of all the mixtures was controlled at 6 inches. The design of the seven mixtures is summarized in Table 2.

Table 2. Concrete mixture design

Constituent (lbs)	1	2	3	4	5	6	7
Water	26.17	31.27	27.32	29.74	29.37	29.06	19.39
Cement	59.26	64.65	59.26	73.33	66.67	61.11	48.89
Fiber	0.14	0.17	0.17	0.33	0.33	0.33	0
Coarse Aggregate	141.13	169.35	166.95	166.95	166.95	166.95	111.30
Fine Aggregate	117.47	146.19	156.78	137.00	142.61	147.30	97.96

Note: the batch quantity is 2 ft^3.

Test Methods

All concrete cylinders were tested in compression with a Tinius Olsen 400 kip Universal Testing Machine. The load was transferred to the cylinders through neoprene pads with steel caps. The cylinders were outfitted with a frame that allowed deflection to be measured in the vertical and horizontal directions as seen in Figure 1.

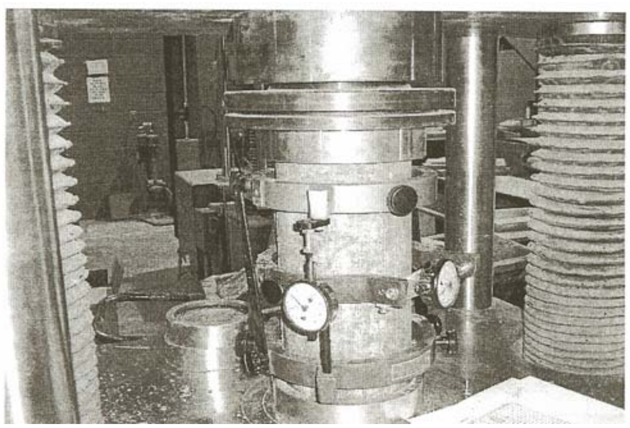

Figure 1: Test frame

The gages used were capable of measuring deflection in increments of 0.0001 in. The modulus of elasticity test was performed on the cylinders according to the procedure of ASTM C 469-94. The specimens were tested after 14 days of moisture curing. Load was applied to test the strength of the cylinders. Deflections were recorded at 5,000 lb. increments up to 50,000 lbs.; after that deflection was recorded every 2,000 lbs until the cylinder failed. Once the cylinder yielded the load readings were recorded at deformation increments that provided a reasonable amount of data points. The cylinders were loaded until failure. Occasionally some cylinders were loaded such that the cylinders failed suddenly not allowing adequate load deformation data to be recorded.

The beams were tested in flexure. Vertical deflection data at the center of the beams were collected by placing a gage under the bottom face of the beam. The gage used was capable of measuring deflection in increments of 0.01 mm. The modulus of rupture (MOR) test was performed as prescribed by ASTM C 78-00. The MOR test frame and beam are shown in Figures 2 and 3. Load was applied to the MOR test frame and deformation data was recorded at 200 lb. increments until the beam failed.

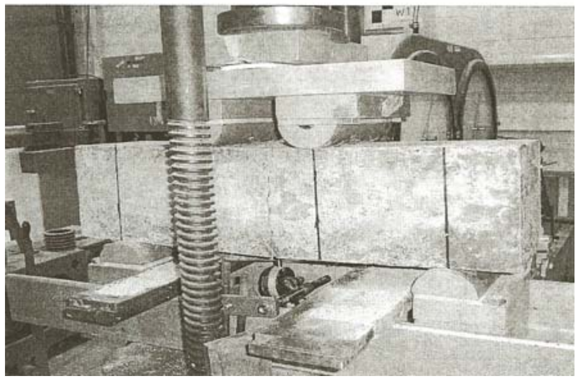

Figure 2: MOR test frame

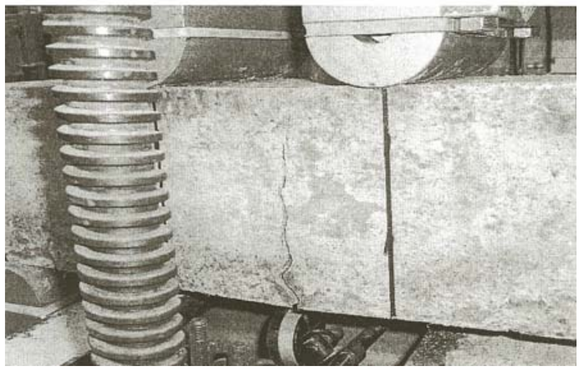

Figure 3: Beam failure in the MOR test

III. Test Results

Compressive Test

The cylinders were loaded in compression until failure. Data recorded was used to calculate ultimate strength (f'c), modulus of elasticity (E), ductility, and toughness of each specimen. The data recorded from the gage in horizontal direction was not used since the cylinders did not deform uniformly. The horizontal deformation reading was taken at mid-height of the cylinders and did not provide an accurate representation of cross sectional deformation. The results are shown in Table 3. In this table the ductility was measured as the maximum strain of the concrete and the toughness was the area under the stress-strain curve from the origin to the breaking point.

The test results plotted in Figure 4 indicated that compressive strength decreases with the increase of w/c ratio for all the concrete with different fiber content. For low w/c ratio (0.5), compressive strength decreased with the increase of fiber content, as shown in Figure 5. For higher w/c ratio (0.55 to 0.6), compressive strength increased slightly with the increase of fiber content.

When considering 1% fiber content, ductility decreased with the increase of w/c ratio from 0.5 to 0.55, then increased from 0.55 to 0.6, as seen in Figure 6. When taking into account the 2% fiber content, ductility increased with the increase of w/c ratio (from 0.5 to 0.6). The trend for the 2% fiber-reinforced concrete was expected. The trend of 1% fiber concrete was not as expected.

Table 3. Properties of cylinders

Mixture	Cylinder #	f'c (psi)	E (10^6 psi)	Ductility (in/in)	Toughness (psi)
1	1	4565	3.87	0.0075	23.31
	2	4707	3.80	0.0023	7.23
	3	4123	4.06	0.0025	7.28
	4	4560	4.07	0.0034	10.50
	Average	4489	3.95	0.0039	12.08
2	1	3915	3.86	0.0014	3.48
	2	4065	3.74	0.0013	7.97
	3	4049	3.67	0.0026	6.55
	4	4211	3.94	0.0016	4.37
	Average	4060	3.80	0.0017	5.59
3	1	3488	3.45	0.0014	2.99
	2	3731	3.39	0.0044	11.18
	3	3635	3.74	0.0063	14.37
	4	3447	3.51	0.0013	2.73
	Average	3575	3.52	0.0033	7.82
4	1	4211	4.01	0.0051	15.27
	2	4351	3.57	0.0018	4.72
	3	4272	3.86	0.0048	14.70
	4	4412	3.73	0.0043	12.74
	Average	4312	3.79	0.0040	11.86
5	1	4057	4.00	0.0019	5.78
	2	4112	3.78	0.0077	22.51
	3	4171	3.94	0.0049	13.20
	4	4269	3.85	0.0020	6.02
	Average	4152	3.89	0.0041	11.88
6	1	3416	3.35	0.0036	9.43
	2	3785	3.46	0.0072	18.43
	3	3641	3.41	0.0106	27.25
	4	3493	3.41	0.0025	6.37
	Average	3584	3.41	0.0060	15.37
7	1	4911	4.47	0.0023	7.94
	2	4804	4.39	0.0018	5.89
	3	4998	4.39	0.0019	6.33
	4	5119	4.00	0.0021	7.56
	Average	4958	4.31	0.0020	6.93

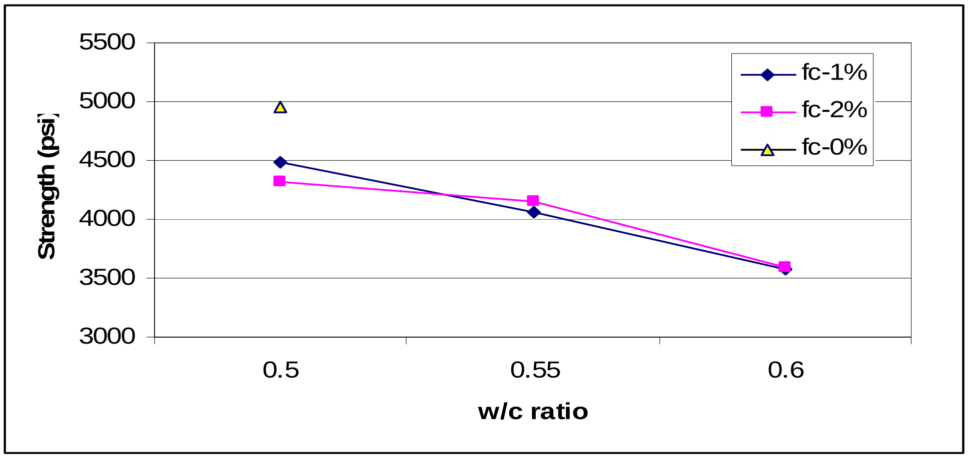

Figure 4: Compressive strength versus w/c ratio

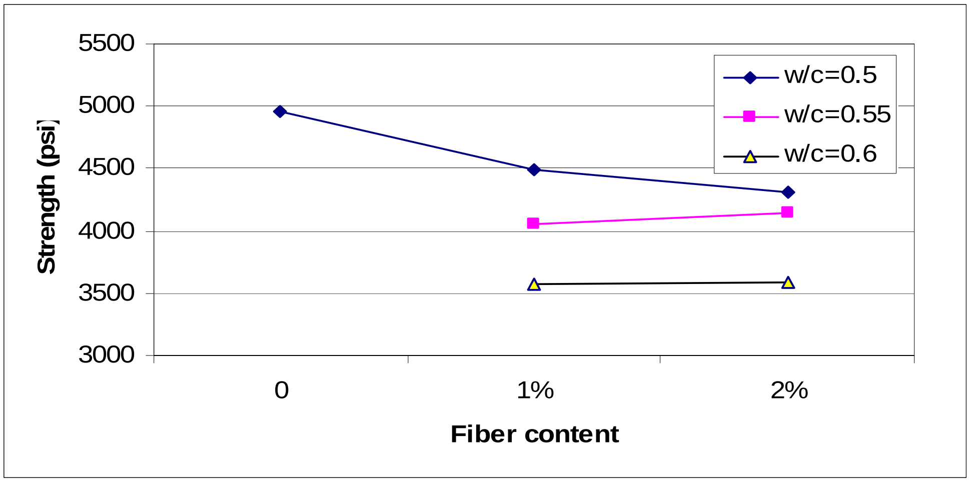

Figure 5: Compressive strength versus fiber content

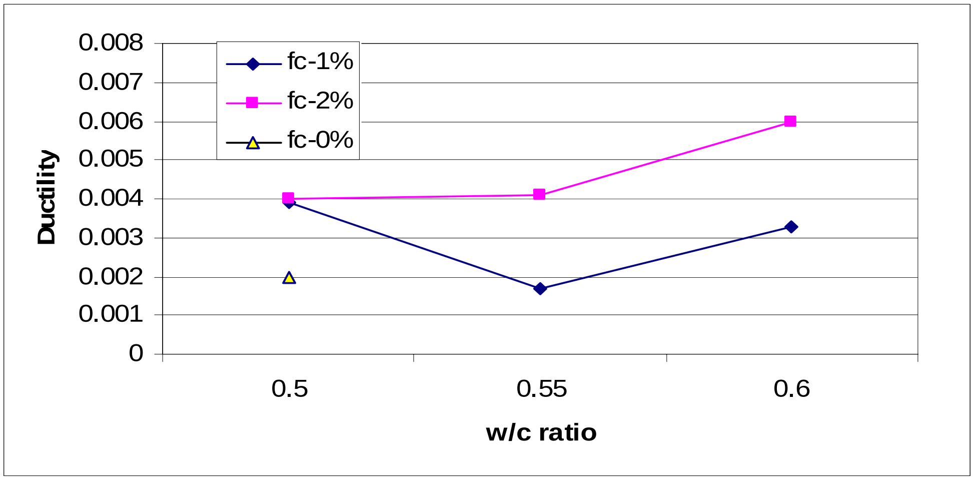

Figure 6: Ductility versus w/c ratio

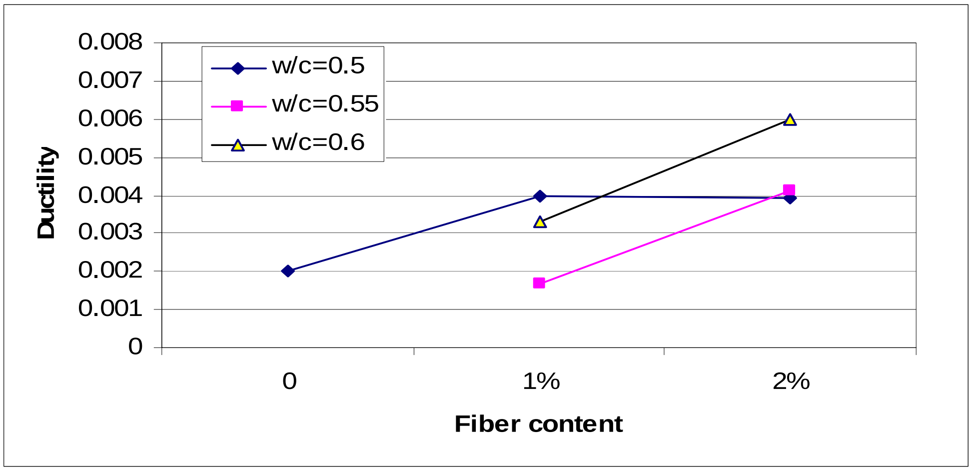

Figure 7: Ductility versus fiber content

The increasing trends seen in Figure 7 indicate that ductility increased with an increase in fiber content for all w/c ratios. It was expected that the fiber would result in greater ductility.

When considering the 2% fiber concrete the toughness increased with an increase in w/c ratio. The opposite was observed in the 1% fiber reinforced concrete when w/c changed from 0.5 to 0.55, as shown in Figure 8. The toughness increased for all the fiber contents when w/c ratio changed from 0.55 to 0.6.

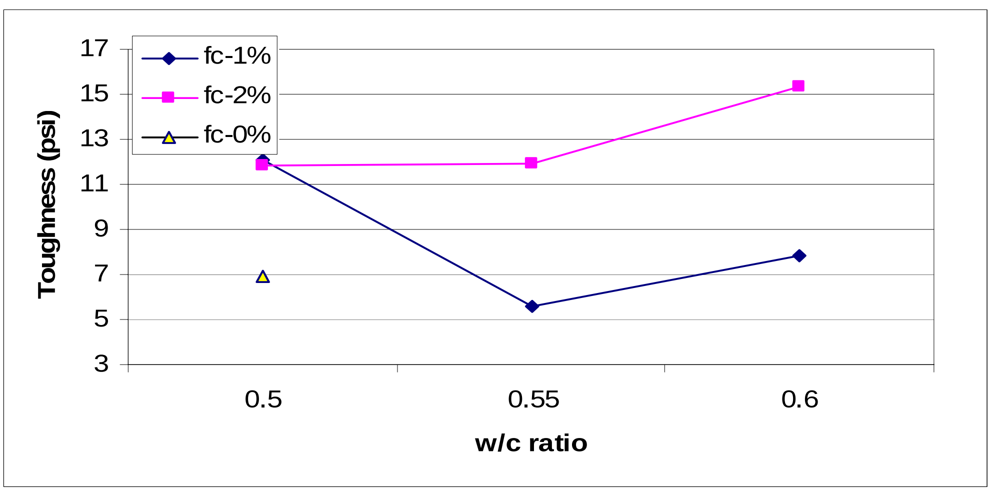

Figure 8: Toughness versus w/c ratio

For all w/c ratios the toughness increased with an increase in fiber content as seen in Figure 9. This is in agreement with research conducted by Gopalaratnam et al (1991) and Ramakrishnan et al. (1994). From the test it was found that the loading rate had an affect on the toughness. If a specimen was loaded too quickly deformation data could not be recorded. The limit of dial gages might create another problem at times. If the dial gage was not set properly it was possible that the deformation would exceed the range of the gage.

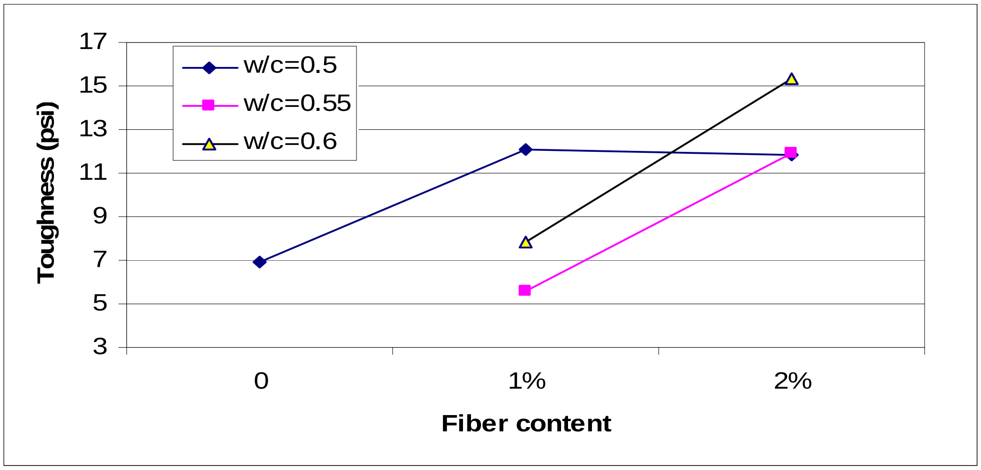

Figure 9: Toughness versus fiber content

When considering the effect of w/c ratio on modulus of elasticity, it is seen in Figure 10 that for all fiber contents the modulus of elasticity changed very slightly with w/c ratio changes from 0.5 to 0.55, but the modulus of elasticity decreased significantly with the increase in w/c ratio from 0.55 to 0.6. It was expected as in the case of strength that the modulus of elasticity would decrease with an increasing of w/c ratio since the modulus of elasticity is dependant of strength.

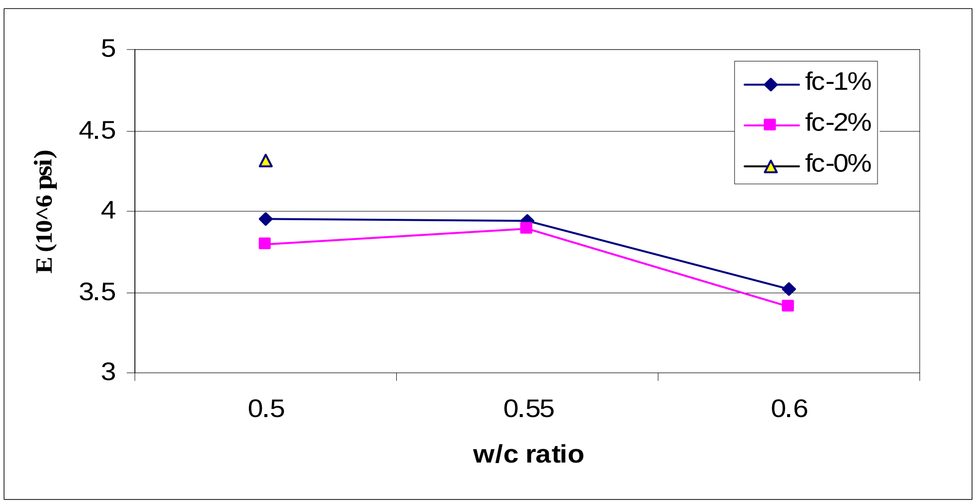

Figure 10: Modulus of elasticity versus w/c ratio

In Figure 11 it can be seen that the modulus of elasticity decreased with the increase of fiber contents for all w/c ratios.

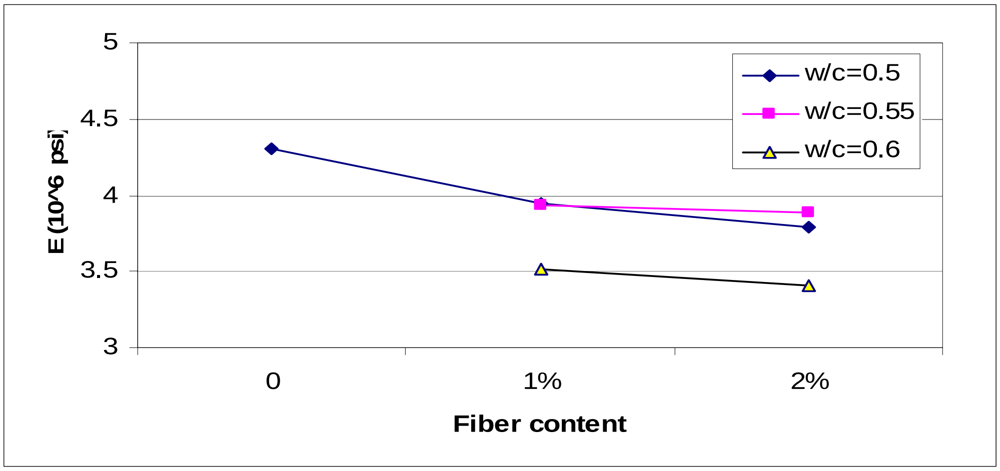

Figure 11: Modulus of elasticity versus fiber content

Beam Test

The beams were loaded in a MOR frame until failure. It was expected that upon first cracking the fiber-reinforced beams would continue to deform while remaining in one piece. However, all of the beams containing 1% fiber came apart in two pieces when they first cracked. The beams containing 2% fiber cracked but remained partially connected. Yet, the deflection upon first cracking was so large that data could no longer be collected. A higher resolution gage and slower loading rate might have resulted in more desired outcome.

When comparing fiber reinforced mixtures of different fiber contents, it was observed that the bending strength of the beam increased from 0 fiber content to 1% only for beam 1, the bending strength decreased with the increase of fiber content for all other cases, as shown in Table 4 below.

Table 4: Ultimate load (lbs.)

Mixture	Beam 1	Beam 2	Beam 3	Mean
1	9200	7000	6400	7500
2	6800	7200	7000	6800
3	7000	6600	6400	6700
4	7600	7600	6800	7300
5	6800	6400	6600	6600
6	6000	6400	6200	6200
7	8000			8000

Table 5 gives the change of curvature of various mixtures at the ultimate load. It was expected that the fiber would increase the ductility of the beams and that the curvature would increase with an increase in fiber content. However, the curvature increase was not observed. No clear correlation between fiber content and curvature was observed during the testing.

Table 5: Curvature at Ultimate load

Mixture	Beam 1 (x 10^{-8} in^{-1})	Beam 2 (x 10^{-8} in^{-1})	Beam 3 (x 10^{-8} in^{-1})	Mean (x 10^{-8} in^{-1})
1	5.69	4.33	3.96	4.66
2	4.65	4.93	4.79	4.79
3	5.44	5.13	4.97	5.18
4	4.90	4.90	4.38	4.73
5	4.55	4.28	4.41	4.41
6	4.65	4.96	4.81	4.81
7	4.48	N/A	N/A	4.48

There was a clear trend in the relationship between the mean tensile strength and w/c ratio of the beam specimens. As the w/c ratio decreases the strength increases. For the same w/c ratio, as the fiber content increases, the strength decreases in most of cases.

IV. CONCLUSIONS

The following conclusions were obtained from the tests:

- The addition and increase of fiber to concrete had variable affects on ultimate compressive strength; for flexural strength it was observed that as fiber content increases, the flexural strength decreases in most cases;
- As the w/c ratio increases fiber reinforcement slightly helps to control the loss of strength;
- Ductility and toughness increase with an increase in fiber content; and
- Modulus of elasticity decreases with the increase of fiber content.

References

Banthis, N., Dubey, A. (2000). Measurements of flexural toughness of fiber-reinforced concrete using a novel technique – part 2: performance of various composites. *ACI Materials Journal*, 97(1), 3-11.

Biddle, D.T. (1991). Fiber reinforcement in residential concrete. *Concrete International*, 13(2), 46-47.

Brown, R., Shukla, A., Natarajan, K.R. (2002). Fiber Reinforcement of Concrete Structures, technical report for the URITC PROJECT NO. 536101, University of Rhode Island, p55.

Gopalaratnam, S.V., Shah, P.S., Batson, B.G., Criswell, E.M., Ramakrishnan, V., Wecharatana, M. (1991). Fracture toughness of fiber reinforced concrete. *ACI Materials Journal*, 88(4), 339-353.

Grzybowski, M., Shah, P.S. (1990). Shrinkage cracking of fiber reinforced concrete. *ACI Materials Journal*, 87(2), 138-148.

Kosmatka, S.H., Kerkhoff, B., Panareses, C. (2002). *Design and Control of Concrete Mixtures*. Skokie, IL, Portland Cement Association.

Propex (2007). Synthetic fibers. http://www.fibermesh.com/product.aspx?ID=2184, accessed August 2007.

Ramakrishnan, V., Speakman, J., Kakodkar, S., Sure, R.V. (1994). Performance characteristics of monofilament polypropylene fiber-reinforced concrete. *Transportation Research Record*, No 1458, 48-56.

Tayor, M.R., Lydon, F.D., Barr, B.I.G. (1996). Toughness characteristics of fiber-reinforced concrete. *The Indian Concrete Journal*, 70(10), 525-531.