

Fiber Reinforced Concrete Developments and Innovations



James I. Daniel
Surendra P. Shah
Editors



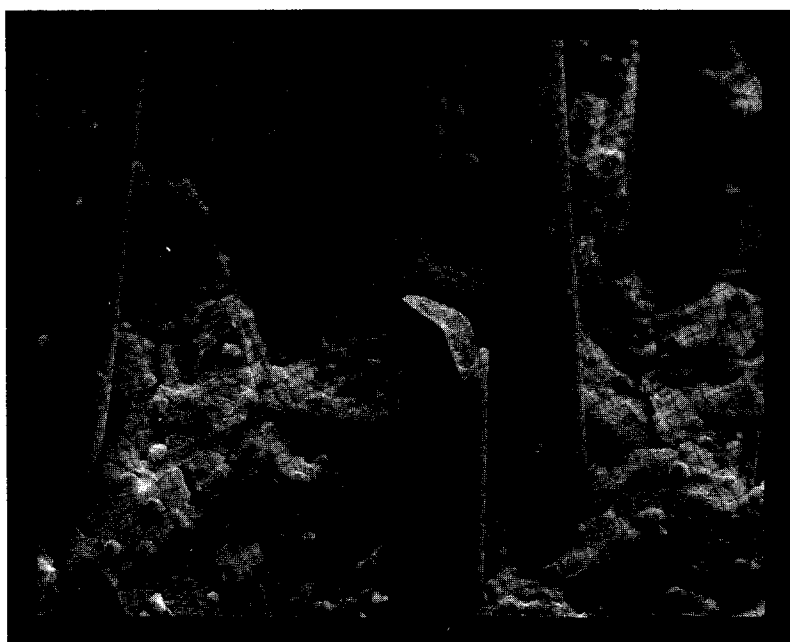
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Printed in the United States of America

Editorial production Victoria Wieczorek

Library of Congress catalog card number 93-73071

PREFACE

These proceedings are a result of the collective efforts of Committee 544 on Fiber Reinforced Concrete and Committee 549 on Ferrocement and Other Thin Reinforced Products. By ACI Committee 544 definition, fiber reinforced concrete is concrete made primarily of hydraulic cements, aggregates, and discrete reinforcing fibers. This definition does not include a provision for concretes reinforced with continuous meshes, woven fabrics, or continuous fiber networks.

Therefore, to address all potential types of fiber reinforced concrete, both ACI Committees 544 and 549 cosponsored a technical symposium. Original papers for this symposium were presented at the ACI Conventions in Boston, March 1991, and in Dallas, November 1991. The papers were reviewed by members of both ACI committees as well as members of the international community of experts on fiber reinforced concrete. These original, reviewed, and revised papers constitute this ACI Special Publication.

The editors gratefully acknowledge ACI Committees 544 and 549, the reviewers, the authors, Dr. Gordon B. Batson (symposium co-chairman and then Chairman of ACI Committee 549), and the staff of ACI who have made this volume a timely contribution to the awareness and growth of fiber reinforced concrete.

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CONTENTS

PREFACE	iii
COMPARISON OF SHRINKAGE CRACKING PERFORMANCE OF DIFFERENT TYPES OF FIBERS AND WIREMESH by S.P. Shah, M. Sarigaphuti, and M.E. Karaguler	1
THE EFFECT OF LOW ADDITION RATES OF POLY- PROPYLENE FIBERS ON PLASTIC SHRINKAGE CRACKING AND MECHANICAL PROPERTIES OF CONCRETE by N.S. Berke and M.P. Dallaire	19
TOUGHNESS OF SLURRY INFILTRATED FIBROUS CONCRETE (SIFCON) by V.S. Parameswaran, K. Balasubramanian, V. Ramakrishnan, and T.S. Krishnamoorthy	43
TENSILE AND COMPRESSIVE STRENGTHS OF POLYPROPYLENE FIBER REINFORCED CONCRETE by M. Tavakoli	61
DURABILITY CHARACTERISTICS OF CELLULOSE FIBER REINFORCED CEMENT COMPOSITES by P. Soroushian and S. Marikunte	73
CARBON FIBER REINFORCED CEMENTS: STRUCTURE, PERFORMANCE, APPLICATIONS AND RESEARCH NEEDS by N. Banthia	91
FLEXURAL BEHAVIOR OF CARBON FIBER REINFORCED CEMENT COMPOSITE by H. Sakai, K. Takahashi, Y. Mitsui, T. Ando, M. Awata, and T. Hoshijima	121

SHEAR CAPACITY OF FIBER REINFORCED CONCRETE BASED ON PLASTICITY OF CONCRETES: A REVIEW by G.B. Batson and A.G. Youssef	141
INFLUENCE OF TEST CONTROL ON THE LOAD- DEFLECTION BEHAVIOR OF FRC by A. Khajuria, Z. El-Shakra, S. Gopalaratnam, and P. Balaguru ...	167
SHEAR BEHAVIOR OF LABORATORY-SIZED HIGH STRENGTH CONCRETE BEAMS REINFORCED WITH BARS AND STEEL FIBERS by S.W. Shin, J.G. Oh, and S.K. Ghosh	181
BEHAVIOR OF FIBER REINFORCED HIGH STRENGTH CONCRETE UNDER DIRECT SHEAR by M. Valle, and O. Buyukozturk	201
ULTRA HIGH PERFORMANCE REINFORCED CONCRETE by L.E. Hackman, M.B. Farrell, and O.O. Dunham	235
CONSTITUTIVE MODELING OF FIBER REINFORCED CONCRETE by D.J. Stevens and D. Liu	249
ANALYTICAL DEFLECTION EVALUATION OF PARTIALLY PRESTRESSED FIBER REINFORCED CONCRETE BEAMS by A.S. Ezeldin	269
DYNAMIC TENSION FATIGUE PERFORMANCE OF FIBROUS CONCRETE COMPOSITES by N.L. Lovata and P.B. Morrill	295
SI (Metric) TABLES	315
INDEX	317

SP 142-1

Comparison of Shrinkage Cracking Performance of Different Types of Fibers and Wiremesh

by S.P. Shah, M. Sarigaphuti,
and M.E. Karaguler

Synopsis: Concrete structures shrink when they are subjected to a drying environment. If this shrinkage is restrained, then tensile stresses develop and concrete may crack. One of the methods to reduce the adverse effects of shrinkage cracking is to reinforce concrete with short randomly distributed fibers. Another possibility is the use of wiremesh. The efficiencies of fibers and wiremesh to arrest cracks in cementitious composites were studied. Different types of fiber (steel, polypropylene, and cellulose) with fiber content of 0.25% and 0.5% by volume of concrete were examined. Ring-type specimens were used for restrained shrinkage cracking test. These fibers and wiremesh show significant reduction in crack width. Steel fiber reinforced concrete (0.5% addition) showed 80% reduction in maximum crack width and up to 90% reduction in average crack width. Concrete reinforced with 0.5% polypropylene or cellulose fibers was as effective as 0.25% steel fibers or wiremesh reinforced concrete (about 70% reduction in maximum and average crack width). Other properties such as free (unrestrained) shrinkage and compressive strength were also investigated.

Keywords: Compressive strength; cracking (fracturing); drying shrinkage; fiber reinforced concretes; fibers; shrinkage; tensile stress; welded wire fabric

2 Shah, Sarigaphuti, and Karaguler

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INTRODUCTION

One of the disadvantages of concrete is that it tends to shrink and crack if the shrinkage is restrained. This shrinkage cracking is a major concern for concrete structures especially for walls, slabs, and pavements. The possibility of shrinkage cracking for a given environment may depend on the properties of concrete such as free (unrestrained) shrinkage, creep, the tensile strength, and the degree of restraint.

One way to reduce the adverse effects of shrinkage cracking is to reinforce concrete with short, randomly distributed fiber. This will not change the properties of concrete mentioned above but it will prevent cracks from widening. Uniformly dispersed fibers can prevent microcracks from opening further and becoming macrocracks [1,2]. It is known that the addition of fiber will considerably reduce the crack width resulting from restrained shrinkage [1,3,4,5]. To evaluate the efficiency of different types and amounts of fibers in controlling shrinkage cracking, tests were conducted using a ring-type specimen. Three different types of fiber (steel, polypropylene, and cellulose) were studied. In addition, for cellulose fiber, three different types were investigated. The results of different fibers were compared with the conventional mesh reinforced concrete (wiremesh). The effect on other properties such as free shrinkage and compressive strength were also examined.

RESEARCH SIGNIFICANCE

It is shown that a relatively small content of cellulose fibers, polypropylene fibers, and steel fibers can significantly reduce crack widths resulting from restrained shrinkage. Specimens reinforced by steel fibers with a volume fraction of 0.25% showed a comparable reduction in crack widths as that shown by 6 x 6 inch welded wire mesh fabric, as well as cellulose and polypropylene fibers with a volume fraction of 0.5%. Since slabs and pavements in practice are considerably thicker than the ring specimens used in the laboratory, a single wire mesh layer is likely to be considerably less effective in the field than was observed for the ring specimens.

Fiber Reinforced Concrete 3

TEST SPECIMENS

There is no standard test method available to evaluate shrinkage cracking potential of concrete. The free shrinkage test as recommended by ASTM C157 does indicate the potential shrinkage of a given concrete. However, the possibility of cracking depends on other factors in addition to the free shrinkage characteristics of concrete. One possibility of simulating shrinkage cracking of slabs is to cast slab-type specimens and subject them to a controlled drying environment. Such a specimen will be subjected to a biaxial state of stress. The extent of biaxiality will depend on the dimensions of the slab. The number of cracks and crack width will also be a function of the size of the test specimen. A better specimen to evaluate shrinkage cracking would be a long specimen with cross-sectional dimensions such that the drying shrinkage is essentially one-dimensional and the uniaxial tensile stresses are produced as a result of restraint. Such uniaxial tests are difficult to perform. In this study, an axisymmetric ring-type of test specimen was used which is relatively easy to conduct and which approximates the desirable uniaxial condition. Because of the axial symmetry, the specimen can be considered very long and the cracking response may be regarded as size independent. A detailed analysis of the stresses in the ring test as well as a theoretical model developed to predict restrained cracking from the knowledge of free shrinkage, creep, and other material properties is described in Reference 2. Using this theoretical model and the data from the ring specimen, accurate predictions of the cracking response of slab-type specimens can be made [2].

The dimensions of the ring specimen are given in Fig. 1. The concrete annulus was cast around the steel ring. As a result of drying, the concrete ring would want to shrink but will be prevented by the steel ring. This would create an internal uniform pressure: hoop tensile stress and radial compressive stress. The calculation based on the theory of elasticity shows that the difference between the hoop tensile stress on the outer and the inner surface is 10%. In addition to hoop stress, the concrete ring is also subjected to radial compressive stresses. However, the maximum value of the radial stress is only 20% of the hoop stress. Thus, one can assume that the concrete is subjected to essentially uniform, uniaxial tensile stress when it is internally restrained by the steel ring, provided the effects of non-uniform drying are negligible.

Drying was only allowed from the outer, circumferential surface of the concrete specimen. Furthermore, since the width of the specimen (140 mm) (5.5") is greater than the thickness (35 mm) (1.38") of the specimen, uniform shrinkage along the width of the specimen can be assumed.

The free shrinkage specimen was 285 mm (11 1/4") long and had a 100 mm (4") square cross-section. This prismatic specimen is recommended by ASTM C157. It is assumed that if the length of the specimen is greater than the cross-sectional dimensions, the shrinkage takes place only in the length direction. The measurement of change in the length with time can then provide a measure of one-dimensional shrinkage of concrete.

TEST PROGRAM

For every batch of concrete the following tests were conducted: 1) restrained shrinkage cracking, 2) free shrinkage and weight loss, and 3) seven and twenty-eight days compressive strengths. For polypropylene fiber reinforced

4 Shah, Sarigaphuti, and Karaguler

concretes, the results of restrained shrinkage and free shrinkage are taken from the study done earlier by Grzybowski and Shah [1,2]. They used the identical ring-type specimen and free shrinkage prism with similar curing conditions. Each test series was accompanied by a control specimen (unreinforced concrete with the same water:cement ratio).

DETAILS OF COMPOSITION AND FABRICATION

Matrix

The mix-proportions by weight for the matrix were 1:2:2:0.5 or 1:2:2:0.55 (cement:coarse aggregate:sand:water). Maximum aggregate size of 9 mm was used. The sand was dried natural river sand of a maximum grain size of 3mm. Type I portland cement was used in all batches.

The w/c (water:cement) ratio of 0.5 was used for concrete reinforced with steel, polypropylene fiber, or wiremesh. For cellulose fiber reinforced concrete, the w/c was 0.55 in order to obtain a comparable workability without using any admixture.

Steel and Polypropylene Fibers

The fiber content of steel and polypropylene fibers varied from 0.25% to 0.5% by volume of concrete. Hooked-end steel fibers with 30 mm (1.2") long and diameter of 0.5 mm (0.02") were tested. The aspect ratio of steel fibers was 60. The polypropylene fibers used were collated, fibrillated fibers which were 19 mm (3/4") long. The density of steel fiber was approximately 7800 kg/m³, and it was 908 kg/m³ for polypropylene fibers.

Cellulose Fibers

The cellulose fiber content was 0.5% by volume or about 1% by weight of cement. Three different cellulose fibers were tested: type 1, type 2, and type 3 respectively. The fibers contained varying amounts of hardwood, softwood springwood, and softwood summerwood fibers. Depending on the species, softwood pulps have varying amounts of springwood and summerwood fibers. Springwood enriched pulps offer high unrefined strength and low porosity. Summerwood enriched pulps offer bulk and high tear strength. All of the cellulose fibers were provided by the Procter & Gamble Cellulose Company. The fibers were supplied in a dry fluffed form.

Conventional Mesh Reinforcement (Wiremesh)

Welded wiremesh fabric is often used to control cracking due to the shrinkage and temperature induced strain. The dimension of the commonly used wiremesh are: 150 mm x 150 mm (6"x6") with its diameter of 4.76 mm (3/16"). Welded wiremesh with the same dimensions were used in this study. In addition, 75 mm x 150 mm (3"x6") wiremesh was also used to examine whether a decrease in spacing would have any beneficial effect. It should be noted that since the thickness of the specimen used in this study was considerably less than the slabs, walls, and pavements used in the field, the results overestimate the efficiency of the welded wiremesh fabric.

Mixing Procedure

Every concrete batch was mixed in a regular vertical mixer. First, coarse aggregate and sand were mixed with half of the total amount of water for one minute. Then cement was added to the mixture and mixed for another minute. Finally, the rest of the water with or without fibers was added and mixed for another four minutes. All specimens were also subjected to vibration for two minutes.

MEASUREMENT

Specimens were subjected to a drying environment after 4 hours of moist curing. This relatively short curing time was selected to increase the potential of shrinkage cracking. Cracking in restrained specimens was investigated between four hours and forty-two days. To measure crack width, a special microscope set-up was designed (Fig. 2). The microscope was fixed to an adjustable and scaled locator which is connected to the round steel plate installed on the top of the specimen. The ball-bearing on the top of the plate enabled the microscope to move around the specimen, whereas the locator, which is connected to a horizontal bar, permitted up-and-down movement so that the whole circumferential surface of the specimen could be observed with the microscope. The crack width reported here is an average of three measurements: one at the center of the ring and the other two at the centers of the top and bottom half of the ring (Fig. 2). The surface of the specimens was examined for new crack and the measurements of the widths of already existing cracks every 24 hours during the first few days after cracking, and then every 48 hours.

Free shrinkage measurements were performed with a dial-gage extensometer. Values of the free shrinkage were recorded every 24 hours. At the same time using the same specimens, weight loss measurements were also conducted.

Specimens both for restrained shrinkage ring and free shrinkage prism were cured for four hours at 20°C (68°F), 100% RH, then after demolding exposed to drying in the humidity room at 20°C (68°F), 40% RH for 42 days.

In addition, the 3"x6" cylindrical specimens were tested for compressive strength. The specimens were cured in water for 7 days then subjected to a drying environment at 20°C, 40% RH.

RESULTS AND DISCUSSION

In order to see the effectiveness of reinforcement, all results of reinforced specimens are compared with the control specimen (plain concrete) of the same w/c ratio. The following results will be discussed: restrained shrinkage cracking, free shrinkage, and compressive strength.

Restrained Shrinkage Cracking

The development of restrained shrinkage cracking for different specimens is shown in Figs. 3-13. The effectiveness of different types and amount of fibers and wiremesh in controlling shrinkage cracking can also be seen in Table 1. Addition of all type of fibers shows significant reduction in crack width. The

6 Shah, Sarigaphuti, and Karaguler

higher the amount of fiber (steel/polypropylene) added, the lower in maximum and average crack width.

For comparison, the weight of reinforcement for specimen reinforced with wiremesh 1 (6"x6") and 0.25% steel fiber were almost identical (275 grams and 245 grams respectively). These two sets of specimens showed a similarity in maximum crack width (about 70% reduction). However, if only one mesh is used in the field, then its effectiveness will be considerably less in the field than that observed in this study.

In the case of wiremesh 2, one additional vertical reinforcement (3"x6") did not reduce either the maximum or the average crack width as compared to that of wiremesh 1.

The results of 0.5% cellulose fiber reinforced concretes were also very satisfactory. Type 1 cellulose fiber gave results comparable to 0.25% steel fiber, wiremesh, and 0.5% polypropylene fiber (approximately 70% reduction in maximum and average crack width). Types 2 and 3 cellulose fibers were also very effective. The maximum crack width was reduced by 55%, and the average crack width was reduced by 60%.

When subjected to drying, the concrete ring will shrink and tensile stress will develop if its shrinkage is restrained (in this case by the steel ring). If the cumulative value of this tensile stress reaches the tensile strength of the concrete, crack will occur. After cracking, the uncracked portion of the concrete will continue to shrink and the crack will widen. In the case of reinforced concrete, the widening of a crack is prevented due to the fiber bridging at the crack surface. The tensile stress will transfer through the uncracked matrix by shear deformation at the fiber-matrix interface. If these development stresses exceed the tensile strength, then another crack may form. Conventionally reinforced concrete (wiremesh) also acts in a very similar way. The ability of the reinforcement to control shrinkage cracking may depend on the distribution as well as on its properties such as strength, length, aspect ratio, density, and fiber-matrix bond.

Furthermore, the value of the crack widths on the outer surface, exposed to drying, and on the inner surface sealed off by the steel ring, were found to be very close. This proves the assumption of uniform stresses in the cross-section of the concrete ring.

Free Shrinkage

Results of free shrinkage of steel and cellulose fiber reinforced concretes can be seen in Figs. 14-15. The addition of steel or cellulose fibers does not substantially alter the drying free shrinkage. For steel fiber reinforced concrete, this confirmed other test data [1,6,11]. The work by Grzybowski and Shah [1,2] also reported that polypropylene fiber reinforcement has no significant effect on the free shrinkage behavior of concrete.

Weight Loss

Table 2 shows the percentage weight loss of different concrete at 42 days. The measurement is on the free shrinkage specimen. The weight loss of specimen is due to loss of water as the specimen is dried. Addition of steel fiber has little

Fiber Reinforced Concrete 7

effect on the water loss of concrete. Since cellulose fiber has the ability to retain water, weight loss of this specimen was somewhat lower than that of the plain concrete specimen.

Compressive Strength

Table 3 shows the results of 1 day, 7 days, and 28 days compressive strength of different specimens. There is no influence on strength caused by an addition of 0.25% steel fibers. However, there is a 16% increase in 28 days compressive strength for 0.5% steel fiber reinforced concrete. In contrast, there is a reduction in strength due to an addition of cellulose fibers. This reduction is relatively small (approximately 10% for 7 days and 1-8% for 28 days compressive strength). A small reduction in compressive strength for cellulose fiber reinforced concrete is also reported by Soroushian and Marikunte [7]. The reason why strength decreases is still unclear, but may be related to the increasing amount of entrapped air voids due to the fiber addition.

It should be noted that, many references [8,9,10] also report a strength reduction for polypropylene fiber reinforced concrete. The reduction varied between 5% and 30%, depending primary on the length and amount of polypropylene used.

Heat of Hydration

In order to find out the possible effects of thermal expansion, the temperature in the middle of the free shrinkage specimen was recorded using K-type thermocouple, digital thermometer and chart recorder. The temperature was recorded immediately after casting up to 24 hours while specimens were kept at 20°C and 50% relative humidity. Maximum temperature increases of 1°C was observed. This result shows that temperature rise due to heat of hydration was not a factor in this type of experimental set-up.

CONCLUSION

The ring test seems to be an appropriate test to measure the influence of fibers on cracking of concrete due to restrained shrinkage. The addition of fibers does not alter the free shrinkage behavior of concrete. Thus, the ability of fibers to control cracks depends on how well they prevent crack from widening. Wiremesh also acts in the same manner. Small amounts of fiber (steel, polypropylene, and cellulose) show the ability to reduce crack width significantly. For comparison purposes, concrete reinforced with 0.25% steel fiber, 0.5% polypropylene fiber, 0.5% cellulose fiber (type 1), or wiremesh show equally good performance (about 70% reduction in maximum crack width). The influence on compressive strength of fiber addition is minimal. It should be mentioned that the current study overestimates the effectiveness of the wiremesh since the thickness of the specimen used was considerably less than that used in the field.

ACKNOWLEDGMENT

The support of Procter & Gamble Cellulose Company and the National Science for Advanced Cement-Based Materials (ACBM) at Northwestern University is gratefully appreciated. The useful comments of Ken Vinson and Wendy Arbuckle of Procter & Gamble Company are gratefully acknowledged.

8 Shah, Sarigaphuti, and Karaguler

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Fiber Reinforced Concrete 9

TABLE 1 — THE RESULTS OF RESTRAINED SHRINKAGE CRACKING AT 42 DAYS

Concrete Code	First Visible Crack (days after casting)	Number of Cracks	Maximum Crack Width (mm)	Average Crack Width (mm)
Plain (w/c=0.5)	6-7	1	0.72 (1.00)	0.72 (1.00)
S0.25*	7	2	0.24 (0.33)***	0.23 (0.32)
S0.5	14	4	0.12 (0.17)	0.08 (0.11)
P0.25*	6	1	0.48 (0.67)	0.48 (0.67)
P0.5	17	1	0.23 (0.32)	0.23 (0.32)
Wiremesh1**	9	3	0.22 (0.30)	0.174 (0.21)
Wiremesh2	6	3	0.22 (0.30)	0.176 (0.24)
Plain (w/c=0.55)	8	1	0.90 (1.00)	0.90 (1.00)
C1-0.5*	9	2	0.32 (0.35)***	0.284 (0.32)
C2-0.5	9	2	0.48 (0.53)	0.395 (0.44)
C3-0.5	8	2	0.53 (0.59)	0.383 (0.42)

*S0.25 and S0.5 refer to concretes reinforced with 0.25 and 0.5% by volume of steel fibers.

*P0.25 and P0.5 refer to concretes reinforced with 0.25 and 0.5% by volume of polypropylene fibers.

*C1-0.5, C2-0.5, and C3-0.5 refer to concretes reinforced with 0.5% by volume of type 1, type 2, and type 3 respectively of cellulose fibers.

**Wiremesh1 is 6"x6" reinforcement.

Wiremesh2 is 3"x6" reinforcement.

***The values in parenthesis show the relative values comparatively to plain concrete of the same w/c ratio.

10 Shah, Sarigaphuti, and Karaguler

TABLE 2 — WEIGHT LOSS OF DIFFERENT CONCRETES AT 42 DAYS

Concrete Code	Weight Loss (%)	Relative Weight Loss (%)
Plain (w/c=0.5)	3.20	100
S0.25	3.15	100
S0.5	3.46	108
Plain (w/c=0.55)	4.57	100
C1-0.5	4.07	89
C2-0.5	3.93	86
C3-0.5	4.33	95

TABLE 3 — COMPRESSIVE STRENGTH OF DIFFERENT CONCRETES

Concrete Code	1-day Comp. Strength (psi)	7-days Comp. Strength (psi)	28-days Comp. Strength (psi)
Plain (w/c=0.5)	754 (1.00)	3271 (1.00)	5157 (1.00)
S0.25	790 (1.05)	3385 (1.03)*	5404 (1.04)
S0.5	-	-	5500 (1.06)
Plain (w/c=0.55)	580 (1.00)	3062 (1.00)	4795 (1.00)
C1-0.5	-	2760 (0.90)*	4950 (1.03)
C2-0.5	555 (0.96)	2803 (0.92)	4624 (0.96)
C3-0.5	-	2883 (0.94)	4702 (0.98)

* The values in parenthesis show the relative values comparatively to plain concrete of the same w/c ratio.

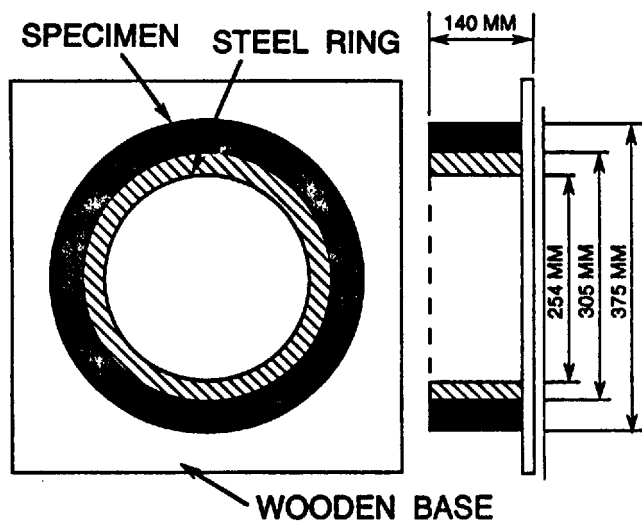
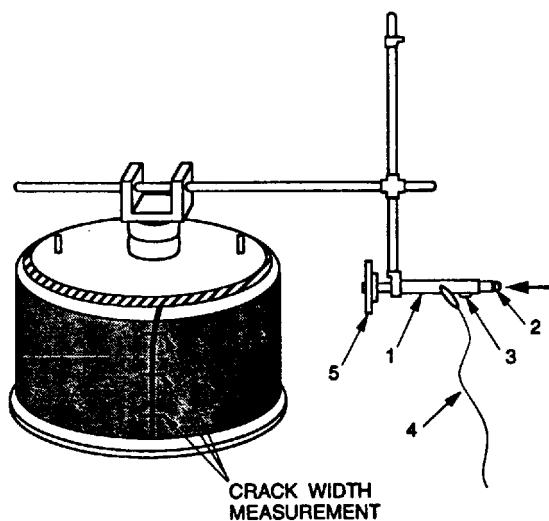


Fig. 1—Dimension of the test specimen



1. MICROSCOPE
2. FILAR EYEPIECE
3. FOCUS KNOB
4. INTERNAL ILLUMINATION
5. FLUORESCENT LAMP

Fig. 2—Test set-up to measure crack width with a microscope

12 Shah, Sarigaphuti, and Karaguler

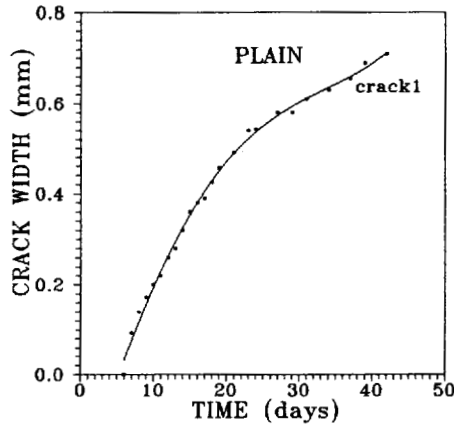


Fig. 3—Crack width measurements of plain concrete ($w/c = 0.5$)

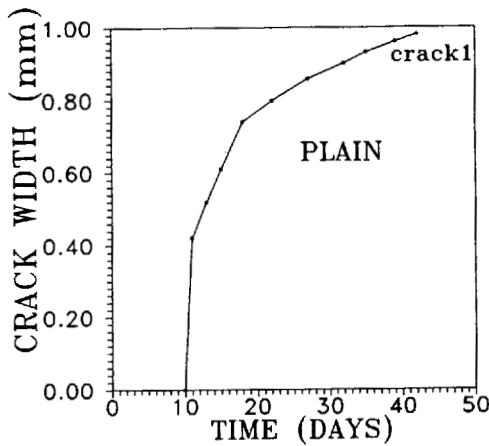


Fig. 4—Crack width measurements of plain concrete ($w/c = 0.55$)

Fiber Reinforced Concrete 13

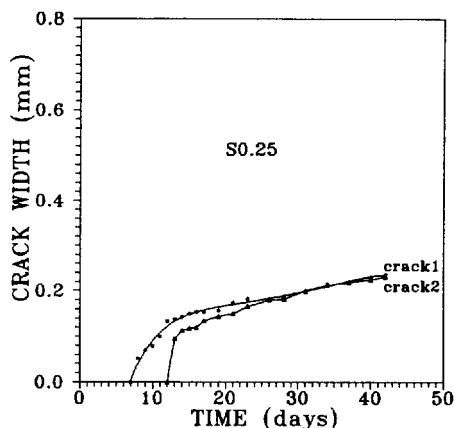


Fig. 5—Crack width measurements of 0.25 percent steel fiber reinforced concrete ($w/c = 0.5$)

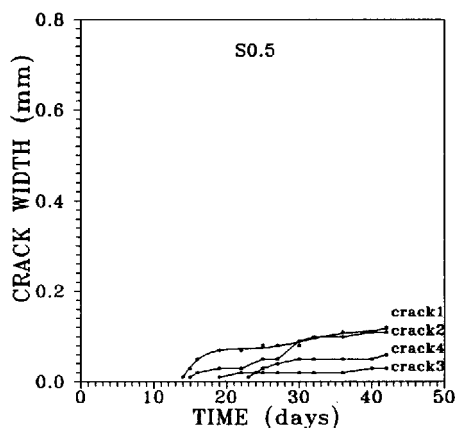


Fig. 6—Crack width measurements of 0.5 percent steel fiber reinforced concrete ($w/c = 0.5$)

14 Shah, Sarigaphuti, and Karaguler

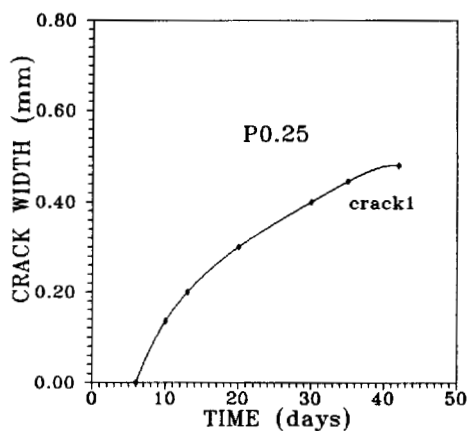


Fig. 7—Crack width measurements of 0.25 percent polypropylene fiber reinforced concrete ($w/c = 0.5$)

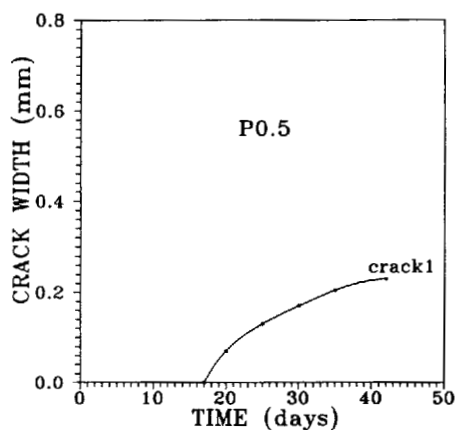


Fig. 8—Crack width measurements of 0.5 percent polypropylene fiber reinforced concrete ($w/c = 0.5$)

Fiber Reinforced Concrete 15

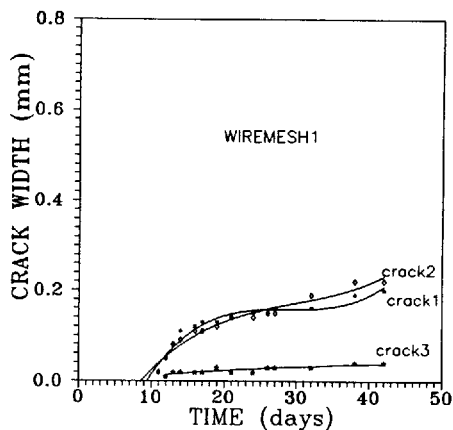


Fig. 9—Crack width measurements of wiremesh (6 in. x 6 in.) reinforced concrete ($w/c = 0.5$)

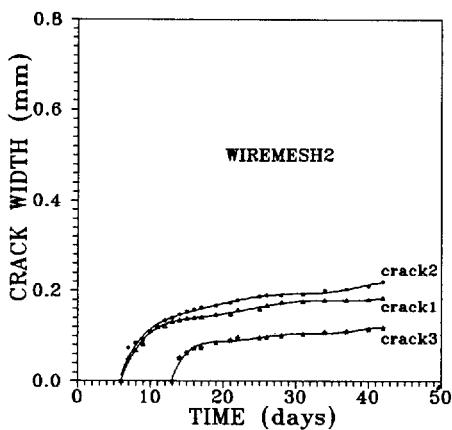


Fig. 10—Crack width measurements of wiremesh (3 in. x 6 in.) reinforced concrete ($w/c = 0.5$)

16 Shah, Sarigaphuti, and Karaguler

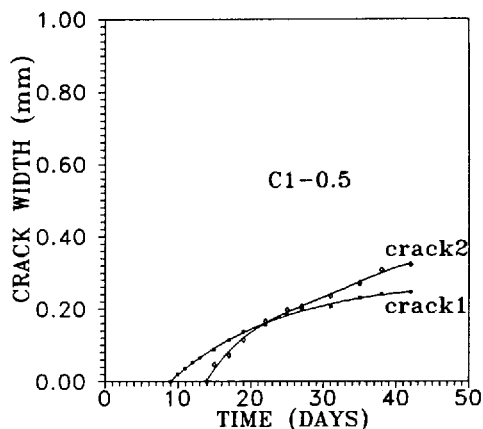


Fig. 11—Crack width measurements of 0.5 percent type 1 cellulose fiber reinforced concrete ($w/c = 0.55$)

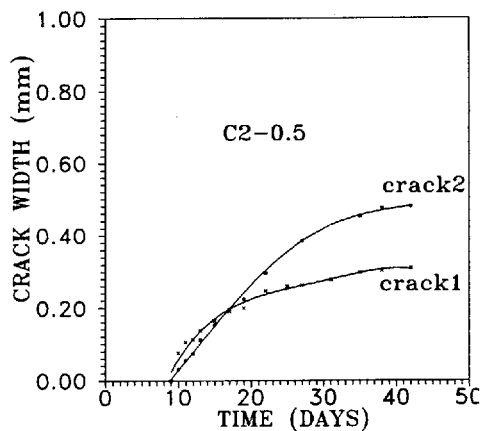


Fig. 12—Crack width measurements of 0.5 percent type 2 cellulose fiber reinforced concrete ($w/c = 0.55$)

Fiber Reinforced Concrete 17

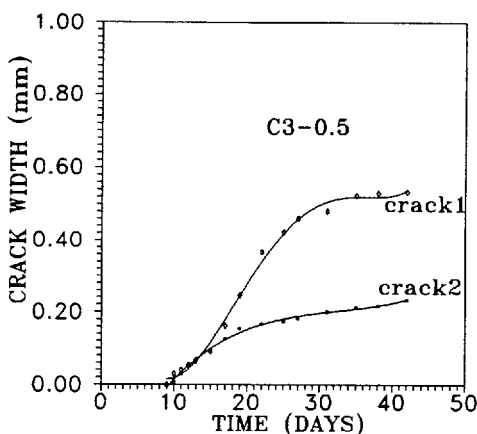


Fig. 13—Crack width measurements of 0.5 percent type 3 cellulose fiber reinforced concrete ($w/c = 0.55$)

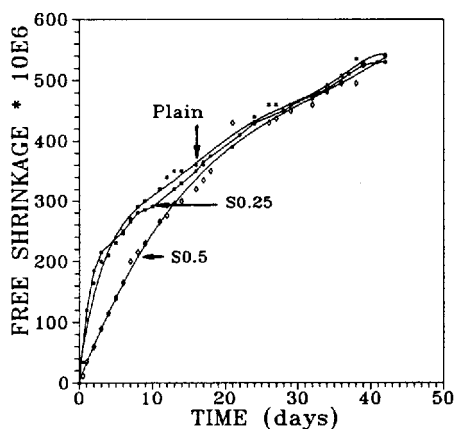


Fig. 14—Free shrinkage test results of 0.25 percent and 0.5 percent steel fiber reinforced concrete and plain ($w/c = 0.5$)

18 Shah, Sarigaphuti, and Karaguler

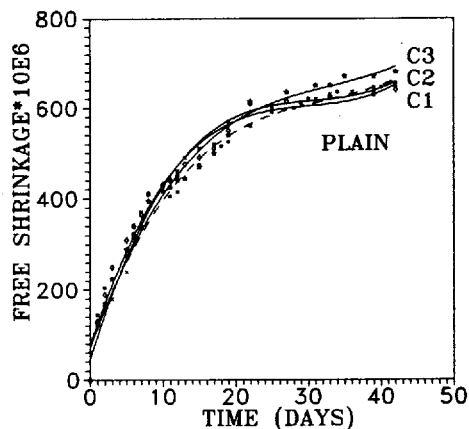


Fig. 15—Free shrinkage of different type of cellulose fiber reinforced concretes ($w/c = 0.55$, fiber content = 0.5 percent volume) and plain concrete ($w/c = 0.55$)

SP 142-2

The Effect of Low Addition Rates of Polypropylene Fibers on Plastic Shrinkage Cracking and Mechanical Properties of Concrete

by N.S. Berke and M.P. Dallaire

Synopsis: The results of a study of the effects of low addition rates of polypropylene fibers on plastic shrinkage cracking and mechanical properties of concrete are discussed. Addition rates of 0.75 lb/cubic yard, 1.5 lb/cubic yard, and 3.0 lb/cubic yard (0.05 to 0.2 volume percent) were used, with fiber lengths that varied between 0.5 inches and 2 inches. Relatively low addition rates are shown to significantly reduce plastic shrinkage cracking. Freezing and thawing durability was not affected by the addition of fibers. Modulus of elasticity, flexural strength, and compressive strength were not changed by the addition rates of polypropylene fibers studied. At the addition rates of polypropylene fibers studied, ASTM Method C1116 Level II I_5 toughness index values were satisfied. The drop weight hammer test as described in ACI Committee 544's report, "ACI 544.2R-89, Measurement of Properties of Fiber Reinforced Concrete" was utilized for determining the impact resistance of fiber reinforced concrete. Drop weight hammer impact results for fiber reinforced concrete at the fiber addition rate of 3.0 lb/cubic yard demonstrated a significant improvement.

Keywords: Compressive strength; cracking (fracturing); fiber reinforced concretes; flexural strength; freeze thaw durability; impact strength; mechanical properties; modulus of elasticity; polypropylene fibers; shrinkage

20 Berke and Dallaire

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INTRODUCTION

A wide range of tests were performed to investigate the properties of concrete having polypropylene fibers at low addition rates (up to 0.2 volume percent). Low addition rates of fibers have been utilized for some time by the industry to reduce plastic shrinkage cracking of concrete. One purpose of the paper was to document the effectiveness of fibers in reducing plastic shrinkage cracking and to develop a test method to illustrate this. Additionally, there is little published data showing the effect of low addition rates of polypropylene fibers on mechanical properties. The purpose of the mechanical testing was to show the effects and the benefits of low fiber addition rates on specific mechanical properties of concrete. The results of this diverse testing program are presented.

EXPERIMENTAL PROGRAM

Materials, Specimen Fabrication and Test Procedures

The coarse aggregate utilized for the study met ASTM Method C33 specifications. A rounded gravel meeting ASTM Method C33 size 67 was used for the majority of the testing. A crushed quartz diorite was utilized for the remainder of the testing, with three sizes 3/4 inch, 1/2 inch and 3/8 inch blended to meet size 67 specifications. An expanded shale coarse aggregate was used for lightweight coarse aggregate-normal weight fine aggregate concrete. A fine aggregate meeting ASTM

Fiber Reinforced Concrete 21

Method C33 specifications and a Type I cement were utilized throughout the program. Specimens were fabricated according to ASTM Method C192. The admixtures used were an air entraining agent, a water reducing agent, a high range water reducing agent, and a retarder. Material properties are found in Table 1.

Plastic Shrinkage

A series of tests were performed to ascertain the influence of collated, fibrillated polypropylene fibers in reducing plastic shrinkage of concrete. Several fiber addition rates and fiber lengths were studied. Fiber loading rates ranged from 0.75 pcy to 3.0 pcy. Fiber length ranged from 1/2 inch to 2 inches. The cement factor for the study was 517 pcy with a w/c ratio of 0.48. Standard doses of retarding admixture and air entraining agent was utilized. The mix design used for the study along with a summary of fiber addition rates, type, and length can be found in Table 2. Concrete was mixed according to ASTM Method C192, with the fibers being added 1 minute after the addition of the cement. Standard ASTM test methods for slump, unit weight, air content by the pressure method, and compressive strength were measured. Plastic shrinkage specimens were fabricated using a plyform mold with a surface area to volume ratio of 3:1. Specimen dimensions were 14.5 inches in width x 22 inches in length x 4 inches in depth. A metal insert in the bottom of the mold was oiled to allow for debonding of the plastic concrete. End restraint was provided by risers at each end of the mold. A center stress riser promoted the formation of cracks. A schematic drawing of the mold can be found in Figure 1.

Specimens were vibrated for a total of 15 seconds. The shrinkage slabs were moved to the environmental room and maintained at an average temperature of 95 °F and 40 % relative humidity. The specimens were then placed on a fan table to increase the severity of the test. A schematic drawing of the fan table is found in Figure 2. After placing the specimen on the fan table, the specimen was floated with a magnesium float for a total of 20 passes. The drying fans were turned on and the air velocity was measured with a hand held anemometer. The average wind velocity over the specimens was 17 mph.

22 Berke and Dallaire

After a period of 24 hours, the specimens were removed from the environmental room. The specimens were carefully gridded into 2 inch x 2 inch squares and the surface was inspected for cracks. Any crack found was marked by tracing along the length of the crack. A crack comparator with a minimum crack width of 0.002 inch was used to measure average crack width at 1/2 inch intervals. The length of cracks and the average width for each grid square was recorded. These values were then summed up to obtain the total crack length and total crack area of the specimen. The crack areas of concrete specimens with fiber additions were compared to crack area of the control concrete specimen(s) fabricated the same day. The reduction of crack area of the fiber addition concretes was expressed as:

$$\text{PERCENT OF CONTROL CRACK AREA} = \frac{\text{Crack Area of Fiber Concrete}}{\text{Crack Area of Control Concrete}} \times 100\%$$

Freezing and Thawing Durability

The performance of polypropylene fiber reinforced concrete in freezing and thawing durability tests was investigated. Normal weight concrete was tested with 1.5 pcy of fibrillated fiber. Two fiber lengths of 1/2 inch and 3/4 inch were investigated. The cement factor for the study was 517 pcy, with a w/c ratio of 0.55. Concrete mix design data can be found in Table 3. Testing for slump, unit weight, air content by the pressure method, and compressive strength were measured. Specimens were cured and removed from curing according to ASTM Method C666.

The freezing and thawing specimens were run according to ASTM Method C666, Procedure A. Initial dynamic modulus readings and beam weights were recorded after curing 14 days in limewater. Dynamic modulus readings were then taken according to ASTM Method specifications throughout the duration of the test. For each reading, Relative Dynamic Modulus (RDME) was calculated and the specimen weight recorded. Scaling of the specimens was also evaluated qualitatively and mass loss of the specimens was calculated.

Flexural Strength

concrete having addition rates of 0.75 pcy and 1.5 pcy of fibrillated fiber were tested. Fiber lengths of 1/2 inch and 3/4 inch were investigated for normal weight concrete and lightweight coarse aggregate-normal weight fine aggregate concrete. The cement factor for both normal weight concrete and coarse aggregate lightweight concrete was 517 pcy. W/c ratio for the normal weight concrete was 0.62 and 0.51 for lightweight coarse aggregate-normal weight fine aggregate concrete. Specimen dimensions were 3 inches in width x 4 inches in depth x 16 inches in length. Slump, unit weight, air content by the pressure method, and compressive strength were also performed for normal weight concrete. Air content for sand- lightweight concrete was determined by the volumetric method as specified by ASTM Method C173. Concrete mix data can be found in Table 4.

The flexural strength of the concrete was determined by ASTM Method C78, Flexural Strength of Concrete by the Third Point Method. The apparent ductility of the specimen (ie did the specimen remain in one piece after ultimate load) at failure was noted.

Modulus of Elasticity

Concretes made with addition rates of 0.75 pcy, 1.5 pcy, and 3.0 pcy of 3/4 inch fibrillated fiber were tested. The cement factor was 500 pcy, identical to the concrete utilized for plastic shrinkage cracking. Slump, unit weight, and air content by the pressure method were measured and compressive strength cylinders were also made and tested. Concrete mix design data can be found in Table 5.

The Modulus of Elasticity of the concrete was determined according to ASTM Method C469, Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression. Deflection of the specimens during compression was recorded using a comparator equipped with an LVDT. The output from the LVDT was directly tied to an X-Y plotter. Load was also recorded on the X-Y plotter.

24 Berke and Dallaire

Toughness

The addition rates studied for the determination of toughness by ASTM Method C1018 were a control mix, and mixes with 0.75 pcy, 1.5 pcy, and 3.0 pcy addition rates of polypropylene fibers. Fiber lengths investigated were 1/2 inch and 3/4 inch length. The cement factor was 517, with a w/c ratio of 0.62. Mix design data can be found in Table 6. Specimen dimensions were 3 inches in width x 4 inches in depth x 16 inches in length. Slump, unit weight, air content by the pressure method were measured, and compressive strength cylinders were also made and tested.

The toughness of the concrete was determined according to ASTM Method C1018. An MTS position control hydraulic testing machine was used to provide the 0.003 in/min deflection rate. The system was a closed loop system with deflection rate control feedback provided by an LVDT. The LVDT was positioned at the mid-span and mid-width of the specimen to calculate nonminal mid-span deflections. An X-Y plotter plotted the toughness curve. A typical load deflection curve is presented in Figure 3. The area under the curve was determined by the use of a planimeter.

Drop Weight Hammer Impact

The drop weight hammer test as described in ACI Committee 544's report, "ACI 544.2R-89, Measurement of Properties of Fiber Reinforced Concrete" was utilized for determining the impact resistance of fiber reinforced concrete. An illustration of the test apparatus can be found in Figure 4. The test apparatus was anchored to a concrete base with a mass of 100 lbs to eliminate rebounding of the test apparatus. Cement factors in the concrete tested were 400 pcy and 517 pcy. Mix design data can be found in Table 7. Specimens were fabricated as a 6 inch diameter x 12 inch cylinder in accordance to ASTM Method C192. The cylinders were then cut into the appropriate thickness, 2 1/2 inches thick, for the test method.

Foam shims were placed between the four supports and the specimens. The number of blows to the first visible crack was recorded. The shims were then removed and the

Fiber Reinforced Concrete 25

number of blows required for the specimen to come in contact with three of the four supports was recorded.

Compressive Strength

Compressive strength data was generated as part of the testing for flexural strength, freezing and thawing, toughness, and Modulus of Elasticity. Since a wide range of data was generated from various portions of the research, compressive strength data from the plastic shrinkage study is analyzed. The plastic shrinkage study encompassed a broad cross section of fiber lengths and addition rates. Mix design data is shown in Table 8. The specimen size chosen for the study was 4 inch diameter x 8 inch cylinders. Specimens were tested according to ASTM Method C39 specifications.

Specimens were tested according to ASTM Method C39, Compressive Strength of Cylindrical Concrete Specimens. Specimens were cured in a fog room, sulphur capped the day of testing and kept moist until tested.

RESULTS AND DISCUSSION

Plastic Shrinkage

Results of plastic shrinkage cracking are presented in Figure 5. All fiber addition rates and fiber lengths tested resulted in significant reductions in plastic shrinkage cracking. Similar reduction in plastic shrinkage cracking was noted by Vondron. (1) At a fiber addition rate of 1.5 pcy, the Percent of Control Crack Area of the combined average of the three fiber lengths was reduced to under 40 percent. An increase of the fiber addition rate to 3.0 pcy reduced the combined average of the Percent of Control Crack Area to under 20 percent. The increase in length from 1/2 inch to 3/4 inch shows a marked decrease in crack area at low addition rates due to the increase in efficiency of the fibrillation. There is little difference between the performance of the 3/4 inch length fiber and the 2 inch length fiber.

26 Berke and Dallaire

Freezing and Thawing

Results of testing are found in Table 9. RDME values are close to or exceed 100%. RDME values indicate that the addition of fibers at the rates utilized in this study does not affect the freezing and thawing durability of properly air entrained concrete. The weight loss of the specimens was minimal. These results agree with work presented by Vondron.(1)

Flexural Strength

Results of flexural strength testing are found in Table 10. At 95% confidence, the control concrete and the fiber reinforced concrete at the low fiber volume percents studied had the same flexural strengths. Results are similar to those reported by Romauldi.(2)

Modulus of Elasticity

Results of Modulus of Elasticity testing are found in Table 11. Results at the various ages and mix designs indicate that there was little difference in the Modulus of Elasticity of the control concrete and the fiber reinforced concrete.

Toughness

Results of Toughness testing are found in Table 12. All mixes including the control mix achieved toughness values greater than 4.0. All concrete mixes meet ASTM Method C1116 specifications for Level II performance at I5 toughness levels. The average toughness values were slightly larger for specimens containing fibers, but the 95% confidence intervals indicated that the results were not significantly different.

Drop Hammer Impact

Results of Drop Hammer Impact testing are found in Table 13. The test results indicate that good repeatability is achievable utilizing this test method based on pooled standard deviations and 95% confidence intervals.

Fiber Reinforced Concrete 27

Results from both mix designs indicate that there is a definite improvement at the fiber loading rate of three pounds per cubic yard. The data indicate that the fiber loading rate of 1.5 pounds per cubic yard does not provide an increase in impact resistance.

Compressive Strength

Results of Compressive strength testing are found in Table 14. Overall, pooled standard deviation of the data set was 143 psi. Average Coefficient of Variation was 2.4%. Compressive strength at 28 days averaged 5,290 psi. Average air content of the concrete was 5.3%. Table 14 gives the 95% confidence intervals for the compressive strengths. Since these tests were performed over a long period of time, a comparison of mixes performed on the same day is a good indicator of how fibers affect the compressive strength of concrete. The confidence interval values have been normalized by dividing the average compressive strength of the control mix for a given mix day into the 95% upper confidence intervals, 95% lower confidence intervals, and averages of the fiber mixes tested the same day.

To summarize the results of the compressive strength testing, a graph which averages the normalized confidence intervals is presented in Figure 6. The average normalized values for each fiber length and addition rate is plotted against the average of the control mixes for each fiber length and addition rate. The results indicate that there is no significant difference between the control mixes and the fiber addition mixes. ACI 544.1R reports similar findings.

(3)

CONCLUSIONS

Plastic shrinkage cracking is significantly reduced with the addition of low volume percentages of fiber.

Mechanical properties of compressive strength, flexural strength, and Modulus of Elasticity are not affected by the low volume addition rate of fibers in this study.

28 Berke and Dallaire

Freezing and thawing durability of concrete is not affected by the low volume addition rate of fibers in this study. This confirms work by Vondron.

ASTM Method C1116 Level II Toughness for I5 is met by the low volume percent fiber addition rates in this study, but it is not clear that fiber concrete is different from the reference.

Impact resistance as measured by the drop weight hammer test method of ACI Committee 544's report "ACI 544.2R-89, Measurement of Properties of Fiber Reinforced Concrete" is significantly improved at 0.2% volume percent (3 lbs/yd³) fiber addition rate.

1. Vondron, G. , "Making More Durable Concrete with Polymeric Fibers", ACI SP-100, Concrete Durability, Katherine and Bryant Mather International Conference, 1987, pp 377-396.
2. Romauldi, J. P., "The Effect of Polypropylene Fibers in the Early Curing Stages of Concrete", Department of Civil Engineering, Carnegie Mellon University, October 1988.
3. ACI 544.1R, "State-of-the Art Report on Fiber Reinforced Concrete", ACI Manual of Concrete Practice, Vol. 5, 1990.

Fiber Reinforced Concrete 29

TABLE 1 — FIBER REINFORCED CONCRETE STUDY
MATERIAL PROPERTIES

Material	Specific Gravity	Percent Absorption
Lab Fine Aggregate	2.62	0.9
Lab Gravel	2.63	0.9
Lab Trap Rock	2.95	0.5
Lightweight CA	1.25	14% for 24 hours of soaking
Air Entraining Agent	1.05	---
Retarder (ASTM C494 Type D)	1.21	---
Water Reducer (ASTM C494 Type A)	1.22	---

TABLE 2 — PLASTIC SHRINKAGE CRACKING MIX DESIGN DATA

Cement Factor	500 pcy	
Coarse Aggregate	1750 pcy	Gravel
Fine Aggregate	1370 pcy	
Unit Weight	143 pcy	
W/C Ratio	0.48	
Air Content	6-8%	
0.75 oz/cwt AEA		
4 oz/cwt Retarder		

Fiber Length and Addition Rate Data

Fiber Length (Inches)	Fiber Addition (pcy)
0.5	0.75
0.5	1.5
0.5	3
0.75	0.75
0.75	1.5
0.75	3
2	0.75
2	1.5
2	3

TABLE 3 — FREEZE THAW MIX DESIGN DATA

Normal Weight Concrete		
Cement Factor	517 pcy	
Coarse Aggregate	1800 pcy	
Fine Aggregate	1180 pcy	
Unit Weight	140 pcf	
W/C Ratio	0.55	
Air Content	5.5-7%	
Fiber Length (Inches)	Fiber Addition (PCY)	
0.5	1.5	
0.75	1.5	
Lightweight Concrete		
Cement Factor	517 pcy	
Coarse Aggregate	750 pcy	Expanded Shale Lightweight
Fine Aggregate	1400 pcy	
Unit Weight	116 pcf	
W/C Ratio	0.55	
Air Content	5.1 - 6.6%	
Fiber Length (Inches)	Fiber Addition (pcy)	
0.5	0.75	
0.75	0.75	
0.5	1.5	
0.75	1.5	

TABLE 4 — FLEXURAL STRENGTH MIX DESIGN DATA

Normal Weight Concrete		
Cement Factor	517 pcy	
Coarse Aggregate	1700 pcy	Trap Rock
Fine Aggregate	1180 pcy	
Unit Weight	140 pcf	
W/C Ratio	0.62	
Air Content	2-3%	
Fiber Length (Inches)	Fiber Addition (pcy)	
0.5	0.75	
0.75	0.75	
0.5	1.5	
0.75	1.5	
0.75	3	
Lightweight Concrete		
Cement Factor	517 pcy	
Coarse Aggregate	750 pcy	Expanded Shale Lightweight
Fine Aggregate	1400 pcy	
Design W/c	0.55	
Actual W/c	0.51	
Air Content	6-7%	
Unit Weight	113 pcf	
Fiber Length (Inches)	Fiber Addition (PCY)	
0.5	0.75	
0.5	1.5	
0.75	1.5	

Fiber Reinforced Concrete 31

TABLE 5 — MODULUS OF ELASTICITY MIX DESIGN DATA

Cement Factor	500 pcy	650 pcy	
Coarse Aggregate	1750 pcy Gravel	1750 pcy	Trap Rock
Fine Aggregate	1370 pcy	1370 pcy	
Unit Weight	143 pcf	150 pcf	
W/C Ratio	0.48	0.48	
Air Content	3-6%	3-6%	
4 oz/cwt Retarder			
0.75 oz/cwt AEA			
Fiber Length	Fiber Addition		
(Inches)	(PCY)		
0.75	0.75		
0.75	1.5		
0.5	3		

TABLE 6 — TOUGHNESS MIX DESIGN DATA

Normal Weight Concrete			
Cement Factor	517 pcy		
Coarse Aggregate	1700 pcy		Trap Rock
Fine Aggregate	1580 pcy		
Unit Weight	151 pcf		
W/C Ratio	0.62		
Air Content	2-3%		
Fiber Length	Fiber Addition		
(Inches)	(PCY)		
0.5	0.75		
0.75	0.75		
0.5	1.5		
0.75	1.5		
0.75	3		

32 Berke and Dallaire

TABLE 7 — DROP WEIGHT HAMMER IMPACT MIX DESIGN DATA

Normal Weight Concrete		
Cement Factors	400 - 517	pcy
Coarse Aggregate	1750	Gravel
Coarse Aggregate	1700	Trap Rock
Fine Aggregate	1650-1380	pcy
Unit Weight	141-150	pcf
W/C Ratio	0.56- 0.78	
Air Content	2-3%	
Fiber Length (Inches)	Fiber Addition (PCY)	
0.75	0.75	
0.75	1.5	
0.75	2.25	
0.75	3	
0.75	4.5	
2	0.75	
2	1.5	

TABLE 8 — COMPRESSIVE STRENGTH MIX DESIGN DATA

Normal Weight Concrete		
Cement Factor	500	pcy
Coarse Aggregate	1750	pcy
Fine Aggregate	1370	pcy
Unit Weight	143	pcf
W/C Ratio	0.48	
Air Content	6-8%	
Fiber Length (Inches)	Fiber Addition (PCY)	
0.5	0.75	
0.5	1.5	
0.5	3	
0.75	0.75	
0.75	1.5	
0.75	3	
2	0.75	
2	1.5	
2	3	
Lightweight Concrete		
Cement Factor	517	pcy
Coarse Aggregate	750	pcy
Fine Aggregate	1400	pcy
Unit Weight	116	pcf
W/C Ratio	0.55	
Air Content	5.1 - 6.6%	
Fiber Length (Inches)	Fiber Addition (PCY)	
0.5	0.75	
0.75	0.75	
0.5	1.5	
0.75	1.5	

Fiber Reinforced Concrete 33

TABLE 9 — FREEZING AND THAWING DURABILITY DATA

Normal Weight Concrete						
Cement Factor (PCY)	W/C	Air Content %	Fiber Length (IN)	Fiber Addition (PCY)	RDME Value @ 302 Cycles	% Weight Loss
517	0.55	6.8	0	0	100	1.4
517	0.55	6.2	0.5	1.5	103	0.6
517	0.55	6.8	0.75	1.5	105	0.9
517	0.55	7	0.75	1.5	104	0.8
517	0.55	6.75	0.75	1.5	102	1

RDME 95% Confidence Interval= ± 5 Weight Loss 95% Confidence Interval= $\pm 1\%$

Lightweight Concrete						
Cement Factor (PCY)	W/C	Air Content %	Fiber Length (IN)	Fiber Addition (PCY)	RDME Value @ 311 Cycles	% Weight Loss
517	0.51	6	0	0	96	0.1
517	0.51	6.6	0.75	1.5	90	0.2
517	0.51	6.4	0.5	1.5	99	0
517	0.51	5.1	0.75	0.75	98	0
517	0.51	6.1	0.5	0.75	100	0

RDME 95% Confidence Interval= ± 4 TABLE 10 — FLEXURAL STRENGTH DATA —
NORMAL WEIGHT CONCRETE

Normal Weight Concrete				Flexural Strength 7 Day (psi)	Flexural Strength 28 DAY (psi)
Cement Factor (pcy)	W/C	Fiber Length (in)	Fiber Addition (pcy)		
517	0.62	0	0	615	760
517	0.62	0.5	0.75	570	690
517	0.62	0.75	0.75	585	710
517	0.62	0.5	1.5	540	705
517	0.62	0.75	1.5	590	780
517	0.62	0.75	3	600	750

7 Day 95% Confidence Interval= ± 44 psi28 Day 95% Confidence Interval= ± 100 psi

Lightweight Concrete				Flexural Strength 7 Day (psi)	Flexural Strength 28 DAY (psi)
Cement Factor (pcy)	W/C	Fiber Length (in)	Fiber Addition (pcy)		
517	0.51	0	0	590	670
517	0.51	0.75	1.5	520	680
517	0.51	0.5	1.5	585	645
517	0.51	0.75	0.75	580	675

7 Day 95% Confidence Interval= ± 106 psi28 Day 95% Confidence Interval= ± 30 psi

34 Berke and Dallaire

TABLE 11 — MODULUS OF ELASTICITY DATA FOR FIBER CONCRETE

Mix #	Cement Factor (pcy)	Micro-Silica (pcy)	Fiber Length (in)	Fiber Addition (pcy)	w/c ratio	Slump (in)	Air Content%	Compressive Strength 28 Day (psi)
1	500	0	0.00	0.00	0.47	5.75	6.1	4900
2	500	0	0.75	0.75	0.47	5.75	5.4	5455
3	500	0	0.75	1.50	0.47	4.75	3.8	5470
4	500	0	0.75	3.00	0.47	4.00	3.2	5533
5	650	65	0.00	0.00	0.40	5.50	5.0	9570
6	650	65	0.75	3.00	0.40	5.00	5.3	9720
7	517	0	0.00	0.00	0.58	6.25	7.6	4460
8	517	0	0.75	3.00	0.58	3	6.2	4040

Table 11 Continued
Modulus of Elasticity Data

(x 10 psi) (Average)					
Mix #	1 Day	7 Day	14 Day	28 Day	9 Months
1	2.09		2.52		3.50
2	2.22		3.12		3.60
3	2.11		2.95		4.01
4	1.97		2.89		4.19
5	3.97	4.90		5.57	
6	3.40	4.95		5.55	
7	1.96	3.55		4.45	
8	1.97	3.65		4.05	

TABLE 12 — ASTM METHOD C 1018 TOUGHNESS DATA

Cement Factor (pcy)	Fiber Length (in)	Fiber Addition (pcy)	W/C	I 5 Toughness Values
517	0.00	0.00	0.62	4.031
517	0.50	1.50	0.62	4.407
517	0.50	0.75	0.62	4.694
517	0.75	0.75	0.62	4.444
517	0.75	1.50	0.62	4.256
517	0.75	3.00	0.62	4.425

95% Confidence Interval= ± 0.52

Fiber Reinforced Concrete 35

TABLE 13 — DROP WEIGHT HAMMER IMPACT DATA

Cement Factor (pcy)	Fiber Length (in)	Fiber Addition (pcy)	W/C	Average Number of Drops To Test Comple- tion	Statist- cally Signif- icant Difference
=====	=====	=====	=====	=====	=====
400	0.00	0.00	0.76	3.8	not applicable
400	0.75	0.75	0.76	6.8	no
400	0.75	1.50	0.76	6.2	no
400	0.75	2.25	0.76	7.7	yes
400	0.75	3.00	0.76	8.8	yes
400	0.75	4.50	0.76	8.4	yes
95% Confidence Interval= ± 1.8					
400	0.00	0.00	0.78	4.40	not applicable
400	0.75	0.75	0.78	5.20	no
400	0.75	1.50	0.78	6.20	no
400	0.75	3.00	0.78	9.00	yes
95% Confidence Interval= ± 1.7					
517	0.00	0.00	0.56	3.8	not applicable
517	2	0.75	0.56	3.2	no
517	2	1.5	0.56	3.4	no
517	2	3.00	0.56	13.20	yes
517	0.75	0.75	0.56	3.20	no
517	0.75	1.50	0.56	3.20	no
517	0.75	3.00	0.56	12.60	yes
95% Confidence Interval= ± 2.8					

36 Berke and Dallaire

TABLE 14 — FIBER CONCRETE COMPRESSIVE STRENGTH SUMMARY

MIX DAY	Fiber Addition (pcy)	Fiber Length (in.)	Air Content (%)	Compressive Strength Avg. (psi)	Standard Deviation (psi)	Compressive Strength		95 % Confidence Intervals		Normalized Strength Fiber Avg		Control Avg.	
						UPPER	LOWER	CONFIDENCE INTERVAL	Avg.	UPPER	LOWER	CONFIDENCE INTERVAL	Avg.
1	0.00	0.00	6.40	4435	80	4599	4435	4271	103.5	100.0	96.2		
1	0.75	0.50	6.40	4260	65	4424	4260	4096	99.9	96.1	92.3		
1	0.75	0.75	5.80	4687	170	4851	4687	4523	109.5	105.7	101.9		
1	0.75	0.75	6.20	4811	50	4975	4811	4647	112.3	108.5	104.7		
2	0.00	0.00	6.00	4825	295	4989	4825	4661	103.3	100.0	96.5		
2	0.75	0.75	6.60	4662	122	4826	4662	4498	100.1	96.6	93.0		
3	0.00	0.00	6.10	4746	94	4910	4746	4582	103.3	100.0	96.4		
3	0.75	0.50	6.40	4600	228	4764	4600	4436	100.5	96.9	93.3		
3	0.75	0.75	6.60	4374	120	4538	4374	4210	95.9	92.3	88.7		
4	0.00	0.00	7.10	4342	38	4809	4645	4481	103.9	100.0	96.1		
4	0.75	0.75	8.00	4226	116	4506	4342	4178	101.2	97.3	93.4		
5	0.75	0.50	6.90	5381	86	5545	5381	5217	103.0	94.7	91.7		
5	0.00	0.00	6.60	5683	73	5847	5683	5519	103.0	100.0	97.0		
5	0.75	0.75	6.60	5443	40	5607	5443	5279	98.8	95.8	93.8		
6	0.00	0.00	3.40	6005	141	6169	6005	5841	102.8	100.0	97.2		
6	0.75	2.00	3.50	5993	48	6157	5993	5829	102.6	99.8	97.0		
6	1.50	2.00	4.00	5573	105	5737	5573	5409	95.6	92.8	90.0		
7	0.00	0.00	5.90	5159	120	5323	5159	4995	103.3	100.0	96.7		
7	0.75	0.75	6.00	5232	208	5433	5232	5031	104.7	101.4	98.1		
7	1.50	0.75	6.20	5468	98	5632	5468	5304	109.3	106.0	102.7		
8	0.00	0.00	4.30	5972	37	6136	5972	5808	102.8	100.0	97.2		
8	1.50	2.00	3.50	6480	221	6644	6480	6316	111.3	108.5	105.7		
9	0.00	0.00	1.80	5392	58	5593	5392	5191	103.1	100.0	96.9		
9	0.75	2.00	2.10	6215	124	6416	6215	6014	118.3	115.2	112.1		
9	1.50	2.00	2.20	5956	294	6157	5956	5755	113.5	110.4	107.3		
9	3.00	2.00	2.20	5686	31	5887	5686	5485	108.6	105.5	102.4		
10	0.00	0.00	7.60	5211	224	5375	5211	5047	103.2	100.0	96.8		
10	0.75	2.00	7.10	5741	98	5905	5741	5577	113.4	110.2	107.0		
11	0.00	0.00	4.30	5210	224	5374	5210	5046	103.2	100.0	96.8		
11	1.50	2.00	4.80	5739	98	5903	5739	5575	116.9	113.7	110.5		
11	3.00	2.00	5.00	6210	20	6374	6210	6046	122.4	119.2	116.0		
12	0.00	0.00	3.60	4973	188	5137	4973	4809	103.4	100.0	96.6		
12	3.00	2.00	4.30	5385	90	5549	5385	5221	111.5	108.3	105.1		
12	3.00	2.00	4.60	5182	163	5346	5182	5018	107.6	104.2	100.8		
13	0.00	0.00	3.70	5440	79	5604	5440	5276	103.1	100.0	96.9		
13	1.50	0.50	3.80	5517	49	5681	5517	5353	104.4	101.4	98.3		
13	1.50	0.50	3.90	5014	53	5178	5014	4850	95.3	92.2	89.1		
14	0.00	0.00	3.40	5517	60	5681	5517	5353	103.0	100.0	97.0		
14	1.50	0.50	3.90	5446	115	5610	5446	5282	101.7	98.7	95.7		
15	0.00	0.00	2.80	5820	80	5984	5820	5656	102.9	100.0	97.1		
15	1.50	0.50	3.00	5647	43	5811	5647	5483	99.9	97.0	95.1		
15	3.00	0.50	3.00	5483	53	5683	5483	5282	97.1	94.2	91.3		
16	0.00	0.00	7.90	4095	242	4259	4095	3931	104.1	100.0	95.9		
16	1.50	0.75	7.40	4105	233	4269	4105	3941	104.3	100.2	96.1		
17	0.00	0.00	9.80	4258	161	4422	4258	4094	104.0	100.0	96.0		
17	1.50	0.50	9.00	4144	29	4308	4144	3980	101.3	97.3	94.3		
18	0.00	0.00	6.50	5022	85	5186	5022	4858	103.4	100.0	96.6		
18	1.50	0.75	6.00	5262	121	5426	5262	5098	108.2	104.8	101.4		
19	0.00	0.00	4.90	5202	130	5366	5202	5038	103.2	100.0	96.8		
19	3.00	0.75	5.40	5368	145	5568	5368	5167	106.4	103.2	100.0		

Pooled Standard Deviation= 143 psi

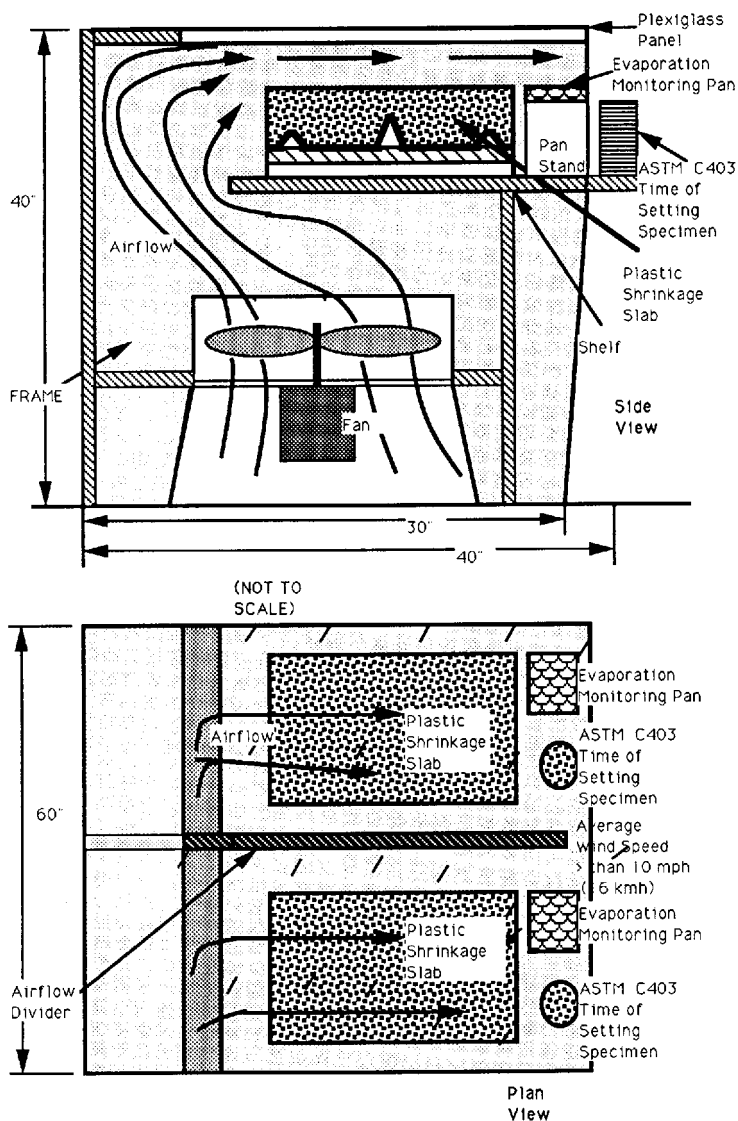


Fig. 1—Schematic drawing of fan box used to evaluate plastic shrinkage cracking

38 Berke and Dallaire

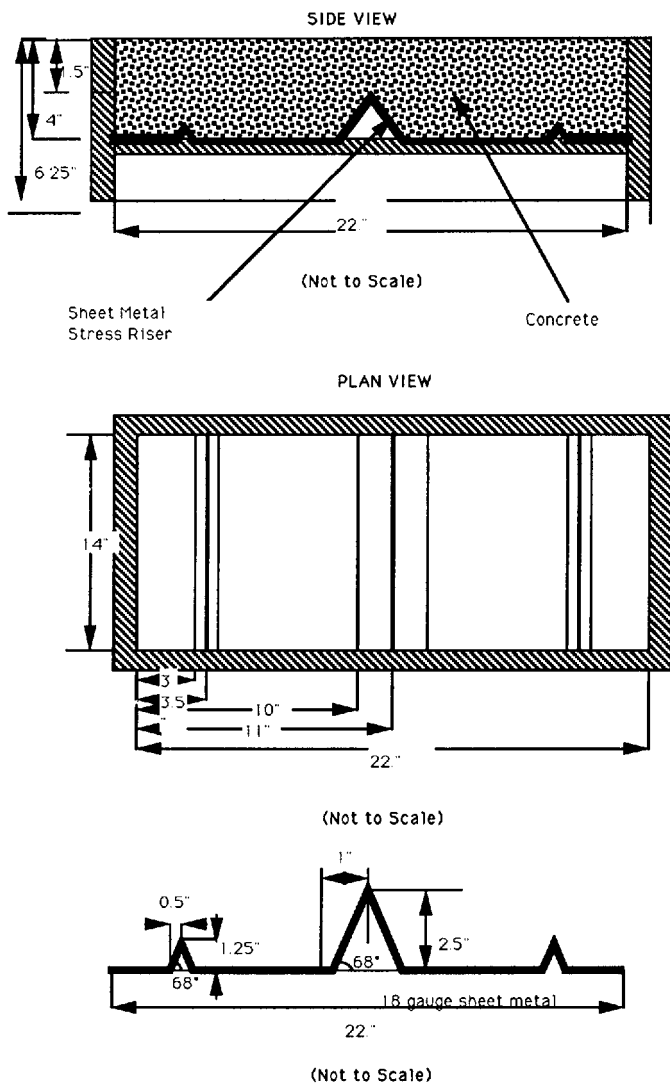


Fig. 2—Schematic of mold

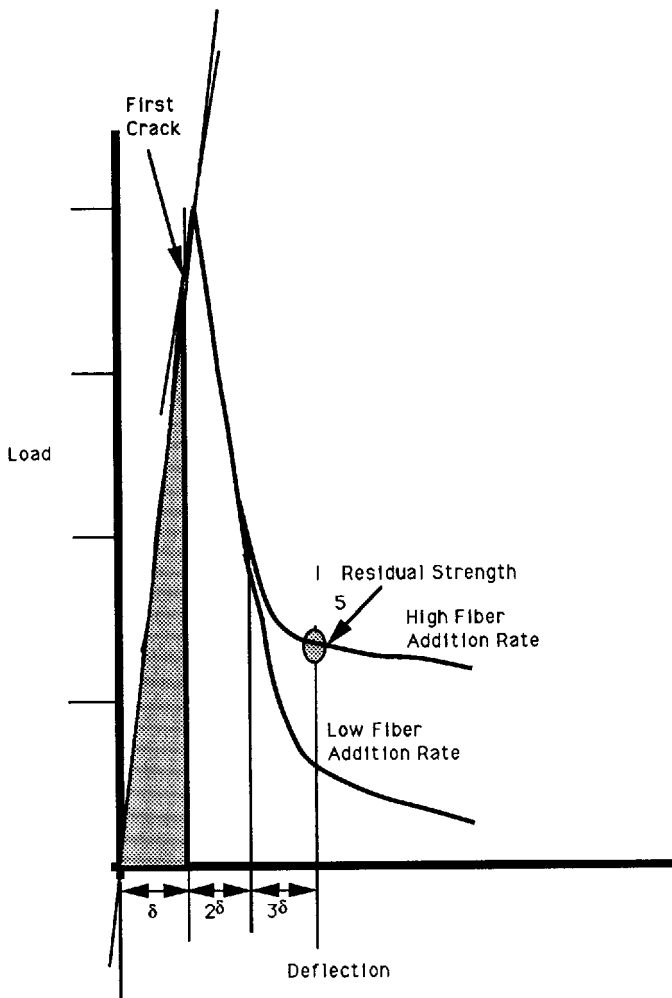


Fig. 3—I₅ toughness curve

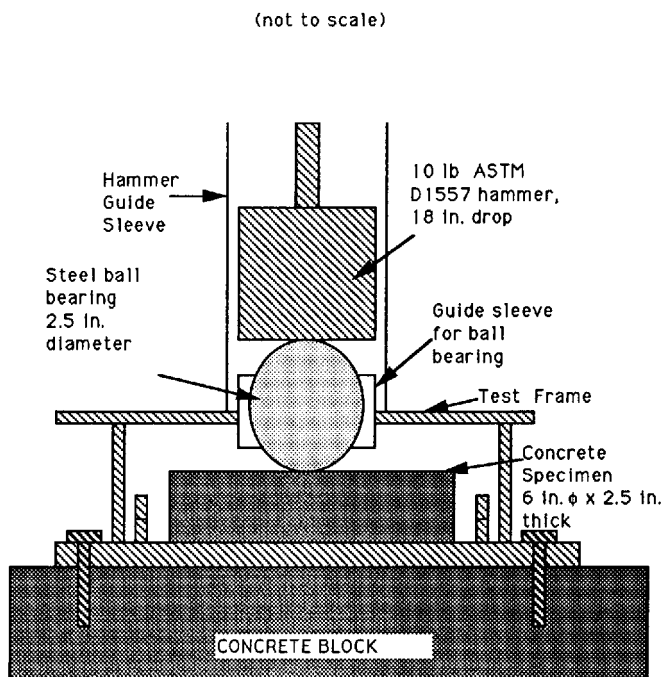


Fig. 4—Drop weight hammer impact test

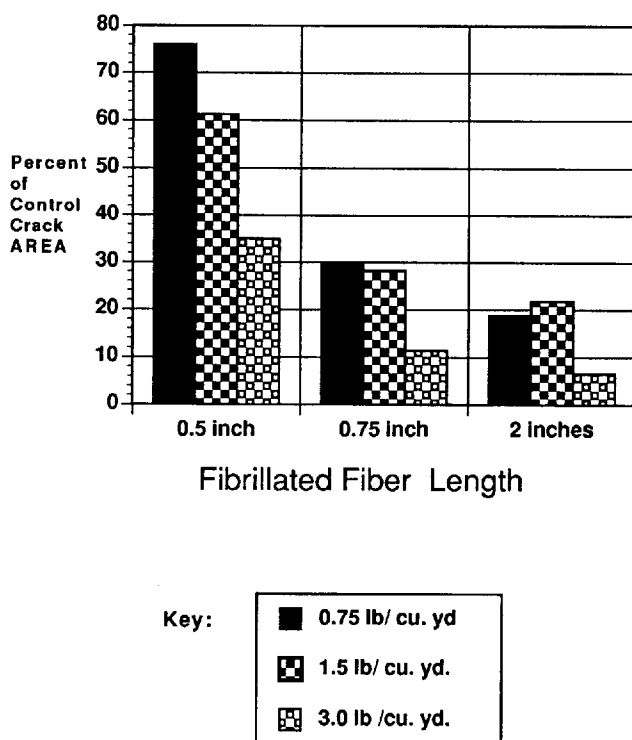


Fig. 5—Summary of crack reduction properties fiber lengths and loading

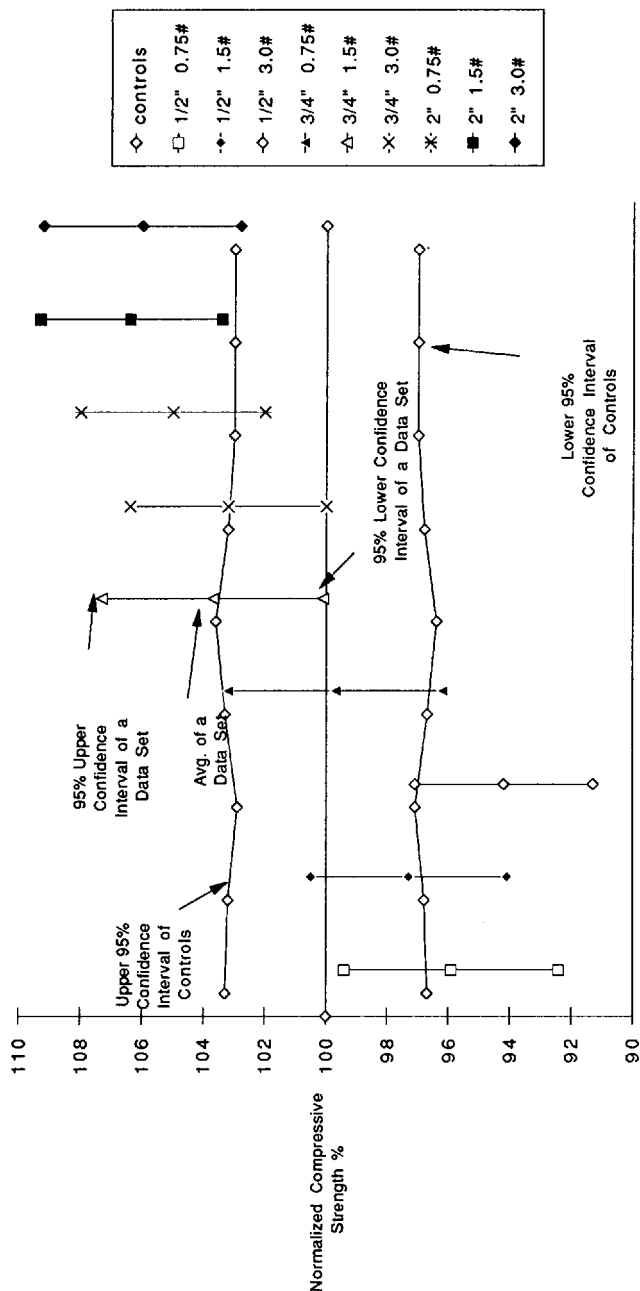


Fig. 6—Normalized compressive strength data