SP 142-1

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

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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

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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 form 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.

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 recommend 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 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/m^3, and it was 908 kg/m^3 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 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 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 Proctor & Gamble Company are gratefully acknowledged.

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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.

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.