Plastic Shrinkage Cracking of Restrained Fiber-Reinforced Concrete

ANTONIO NANNI, DENNIS A. LUDWIG, AND MICHAEL T. MCGILLIS

It is well established that the low-volume addition of fibers (synthetic or steel) to concrete can significantly reduce cracking due to plastic shrinkage. However, as of today, there is no consensus standard test method available to measure this effect. A test procedure is under scrutiny at ASTM. In this procedure, the surface cracks of a plain concrete panel are compared with those of a fiber-reinforced concrete panel under conditions of severe and controlled moisture loss. The results of an experimental project aiming to determine the validity and repeatability of the test procedure on plastic shrinkage under consideration by ASTM are reported. For this purpose, various fiber types (i.e., synthetics and steel), in different configurations (i.e., monofilament, fibrillated, deformed) and of various lengths, were used with the same concrete matrix. The results show that the proposed ASTM standard has merit. Its major drawback is that specimen performance characterization is based exclusively on crack width.

Volume changes of fresh concrete are due to water absorption and evaporation, sedimentation and segregation, cement hydration, and thermal changes. In addition to the mixture constituents and proportions, volume changes are influenced by the surrounding environment (i.e., temperature, humidity, and wind speed). Plastic shrinkage cracking occurs in the superficial layer of fresh concrete within a few hours after placement. The principal cause of this type of cracking is an excessively rapid evaporation of water from the concrete surface, such that it exceeds the rate at which bleeding water rises to the surface (*1,2*). The formation of plastic shrinkage cracking takes place when internal stress is higher than the tensile strength of concrete. Internal stress is closely related to the capillary pressure of the pore water within the fresh concrete (*1*). Plastic shrinkage cracking occurs most often in slabs and pavement construction exposed to hot and dry weather. Construction operations (screeding and finishing) have a very significant effect on plastic shrinkage cracking (*3*). Cracking can be avoided with the proper concrete mixture design and the proper construction and curing procedure.

In recent years, the use of fibers, particularly of the synthetic type, has become common to minimize plastic and early drying shrinkage cracking in slab-on-grade construction. From here, the need has emerged for a testing procedure that would quantify the beneficial effects of fiber addition and could help in selecting the most appropriate fiber parameters (i.e., fiber type, length, volume percentage) for a specific concrete matrix subjected to specific environmental conditions. Several test methods have been proposed (*4–6*). In 1985, Kraai mentioned in the introduction to his paper that a testing procedure was under consideration by ASTM (*4*). But 7 years later, no standard test has been approved. A task group within ASTM Subcommittee C09.03.04 has arrived at the fifth draft of a proposed method for evaluating plastic shrinkage cracking of restrained fiber-reinforced concrete (FRC). No data have been published in the literature on the performance of this proposed test method other than a summary diagram presented by Berke et al. (*6*). The diagram shows only the average crack area for nine mixtures using the same fiber type at three different lengths and three different volumes. The salient feature of the test procedure being considered is in the specimen configuration (see Figure 1). In this case, the restraining effect of a perimeter wire mesh as proposed by Kraai (*4*) is substituted with three stress risers. Shrinkage cracking is expected to initiate at the central riser, where the specimen thickness is reduced from 100 mm (4 in.) to 38 mm (1.5 in.). The experimental results obtained by Berke et al. (*6*) with this specimen are very similar to those obtained by Kraai and presented by Vondran and Webster (*7*). Significant shrinkage cracking reduction was obtained when using fibers in the concrete matrix.

The objective of this research project was to evaluate independently the validity and reliability of the proposed ASTM procedure by obtaining several experimental results on plain concrete and FRC mixtures.

TEST PROGRAM

Materials

The concrete matrix used for the entire project had the following proportions: portland cement Type I, 335 kg/m^3; water, 208 kg/m^3; coarse aggregate (20 mm maximum size), 1037 kg/m^3; fine aggregate, 814 kg/m^3. This mixture had a very high cement content and a very high water-cement ratio, and it did not contain any chemical or mineral admixtures. The slump was 180 mm (7 in.), the unit weight was 2286 kg/m^3 (3,853 lb/yd^3), and the air content was 0.9 percent. The 28-day compressive strength was 24.7 MPa (3,590 psi) with a standard deviation of 2.5 MPa (361 psi) for 15 specimens.

The fibers used in the testing program are described in Table 1; their sources are not identified. Two types of steel fibers were used from two different manufacturers. Three mixtures (B, C, and D) contained steel fibers (straight and deformed) at the low dosage of 0.62 percent by weight (corresponding to 25 lb/yd^3). The remaining nine FRC mixtures were made with synthetic fibers of two base materials and different configurations (monofilament and fibrillated). The

Department of Architectural Engineering, Pennsylvania State University, 104 Engineering Unit A, University Park, Pa. 16802.

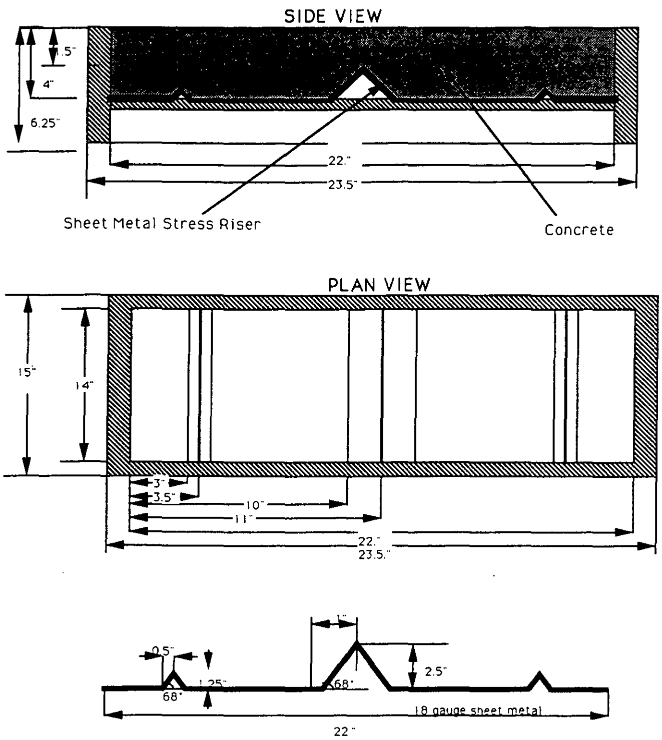

FIGURE 1 Specimen geometry and configuration (ASTM proposed standard) (not to scale).

TABLE 1 Specimen Key

MIXTURE	FIBER-MANUFACTURER	VOLUME (%)	CHARACTERISTICS
A	Plain Matrix	--	--
B	Steel-I	0.19	Straight
C	Steel-II	0.19	Deformed
D	Steel-I	0.19	Deformed
E	Synthetic-I	0.05	Monofilament
F	Synthetic-I	0.05	Monofilament
G	Synthetic-I	0.05	Monofilament
H	Synthetic-II	0.10	Fibrillated
I	Synthetic-II	0.10	Fibrillated
J	Synthetic-II	0.10	Fibrillated
K	Synthetic-II	0.10	Fibrillated
L	Synthetic-II	0.10	Fibrillated
M	Synthetic-II	0.07	Monofil

first type was used in different lengths and at the same dosage in three mixtures (E, F, and G). The second type was used in six mixtures (H, I, J, K, L, and M) with different lengths and at different dosages.

Fabrication and Testing Procedures

Each testing day 0.16 m^3 (5.5 ft^3) of concrete was batched. First, gravel and sand stored in sealed containers were placed into the mixer. While the aggregates were being weighed, the specimen molds were lightly oiled for bond breaking and preventing water absorption along the wooden sides of the molds. At the same time, predetermined amounts of fibers were prepared. After the aggregates were placed in the mixer, the mixer was turned on and half of the mixing water was added. Following a 3-min premixing, portland cement and, afterward, the rest of the mixing water were added. The concrete was then left to mix for another 5 min. A known amount of concrete was then discharged from the mixer. Part of this amount was used for the plain matrix specimen, compression cylinders, and fresh concrete tests (slump and air content). At this point, the selected fiber type was added to the concrete remaining in the mixer and mixed for an additional 3 min. This amount of FRC was sufficient for two identical specimens. After discharging the first FRC batch, the mixer was reloaded with an equal amount of plain matrix and the second fiber type was added for two more FRC specimens.

Five molds were filled with concrete and vibrated on a vibratory table for 12 sec and then screeded, floated, and weighed. The specimens were moved to an environmentally controlled room to be placed into individual air ducts. The room was equipped with a thermostat and a dehumidifier. At the start of each day, the room temperature was kept at approximately 38°C (100°F) and the relative humidity between 25 and 30 percent. Water pans were filled and weighed and then placed in each duct on a weighing scale positioned beside the specimen (so that the evaporation from the specimen would not interfere with the evaporation from the pan, and vice versa). The fans were turned on, pushing air across the specimens. Initial readings were taken (air and concrete temperature, humidity, and wind speed). Subsequent readings were taken every 30 min for 3 hr (for a total of seven readings). At the completion of the 3 hr period, the fans were turned off, a final water pan weight reading was taken, and the specimens were removed from the ducts. The specimens were then weighed and the length and width of cracks were measured. The width of each crack was measured with a crack scale at approximately every inch along its length. The crack length was determined by placing a string along the crack and then measuring the length of the string. The average width and the length were multiplied to compute the area of one crack. This procedure was repeated for each crack, and the total crack area was calculated by summing up individual values. After all measurements were taken, the specimens were disposed of.

With respect to the proposed ASTM test procedure, some comments that could lead to future improvements are offered:

- The procedure for filling the mold should be clearly spelled out. To the operator, it is natural to place scoops of concrete to the left and right of the central stress riser and then distribute the material over the entire mold. If this is done, the number of fibers crossing the riser may not be representative of the nominal fiber volume in the mixture.
- The water pan should be placed beside the specimen rather than behind it. The water pan placed on the scale in the wind stream can wobble and spill easily. If the pan is filled according to the proposed standard, the water will blow out of the pan.
- The specimens are large and unwieldy even for two people.

DISCUSSION OF RESULTS

Environmental Conditions

The proposed test procedure does not specify the environmental conditions in terms of temperature and relative humidity, but it specifies a minimum air flow velocity of 4.5 m/sec (10 mph). Any combination of these three parameters is suitable, provided that the evaporation rate in the water pan is at least 980 g/m^2/hr (0.2 lb/ft^2/hr). To satisfy this requirement, it was attempted to maintain environmental conditions inside the duct as close as possible to 35°C (95°F), 40 percent relative humidity, and a wind speed of 5.2 m/sec (11.5 mph). The crack area of plain matrix specimens can be plotted as a function of the average temperature, relative humidity, and wind speed recorded during the 3-hr test. In this case, it appears that matrix cracking is insensitive to environmental conditions within the ranges experienced during this project. Even the combination of the three independent variables in one single parameter (directly proportional to temperature and wind speed and inversely proportional to relative humidity) has no effect on cracking area. It is therefore concluded that, as long as the evaporation rate in the water pan remains close to the prescribed value of 98 g/m^2/hr, no significant effect on cracking is expected due to slight changes in environmental conditions.

The first shrinkage crack in all specimens was visible at the fifth (120 min) or sixth (150 min) interval reading. No significant difference in cracking time between plain matrix and FRC was observed. The average concrete temperature at the beginning of the test was 21.9°C (71.4°F) with a standard deviation of 1.1°C (1.9°F). After 3 hr, at the end of the test the average concrete temperature had climbed to 30.8°C (87.4°F) with a standard deviation of 2.9°C (5.2°F). The average room temperature and relative humidity over a 3-hr period were 36.8°C (98.2°F) and 38 percent.

Evaporation from Specimens

The addition of fibers to concrete has been reported to decrease the amount of water bleeding (*7*). The weight loss of all specimens was measured at the end of the 3-hr test. The crack area of all specimens can be plotted as a function of the weight loss (i.e., evaporated water). In this case, the trend of the data points would indicate that the higher the moisture loss, the higher the crack area. In addition, data points relative to the unreinforced matrix tend to cluster at the upper-right side of the diagram corresponding to higher values of evaporation and cracking. It can be concluded that, in general, water evaporation in FRC is less (and with less cracking) than for the respective plain matrix.

Plain Concrete and FRC Cracking

All specimens (plain matrix and FRC) cracked during the performance of the test. Given the specimen geometry and configuration, once a crack started over the central stress riser, it usually extended over the full width of the specimen and, obviously, could grow no further. The parameter that characterizes the performance of different samples becomes, therefore, the width of the crack. This is demonstrated by the two diagrams in Figure 2. In this diagram, the crack area is plotted as a function of the crack width for all specimens. The crack width given here represents the average value of all measurements for each sample. The first observation is that average crack width varied widely between 0.1 and 1 mm (one order of magnitude between maximum and minimum values), whereas the total length of cracks was about 380 mm (15 in.) (the width of the specimen was 356 mm, or 14 in.). The second observation is that the data points relative to the matrix concentrate at the higher values of the abscissa (wider cracks). It is concluded that for the specimen size and configuration of the proposed test method, the paramount characterization parameter is crack width.

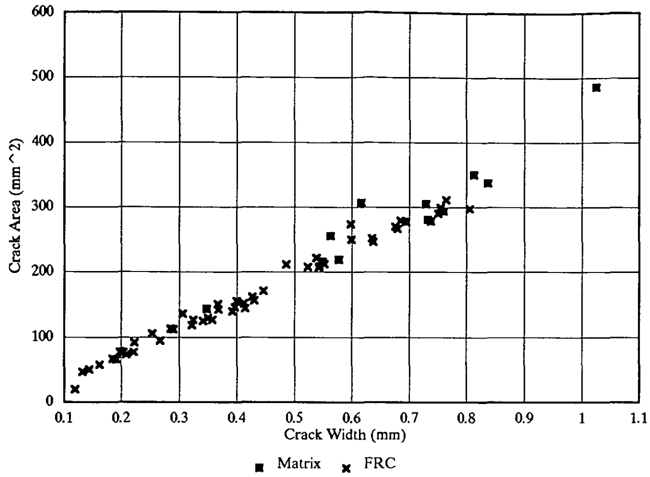

FIGURE 2 Crack area versus crack width (all specimens).

Evaluation of Proposed ASTM Standard

The average crack area of each FRC mixture (four samples), expressed as a percentage of the companion plain matrix specimen, is shown in Figure 3. In this diagram, the sample standard deviation is also plotted above and below the average value. From this figure, it is observed that with the exception of FRC Mixture F, the shrinkage cracking area of any FRC

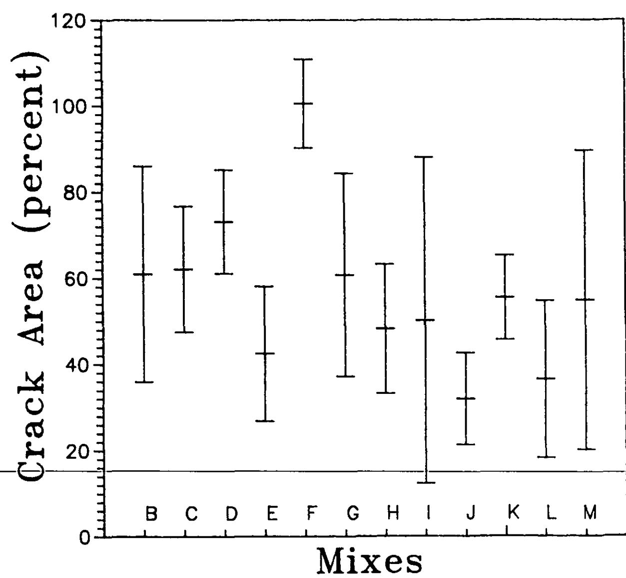

FIGURE 3 Average crack area (and standard deviation) for each FRC mixture relative to respective plain matrix.

is lower than that of the companion matrix. The variability is rather high but may be attributed to the nature of the parameter under study (shrinkage cracking) rather than the procedure itself.

Looking at the results from a practical end, assume that this project was intended to identify the most suitable fiber types to reinforce a given matrix. Would the proposed test method have helped? The answer is probably yes. The engineer could set an acceptability threshold (say, 50 percent shrinkage crack area reduction), consider all fiber types with better performance, and use this information with other parameters (e.g., cost, workability, etc.) to select the most desirable product. What is missing is the verification of the test results in terms of field performance. For this, only time and more work can provide the answer.

CONCLUSIONS

The objective of this work was to generate experimental data with a proposed ASTM standard test method meant to evaluate the ability of fibers to control plastic shrinkage cracking. The authors have concluded that the proposed method has merit and is not irremediably flawed. The major concern is in the fact that, because of the specimen configuration, crack width becomes the primary parameter to characterize the shrinkage cracking potential of different specimens. Rather than continuing an endless discussion, it is probably in the best interest of the public and the fiber industry to adopt a standard test method for the evaluation of plastic shrinkage cracking. The method can then be reevaluated after a fixed period.

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