Plastic Shrinkage Cracking of Polypropylene Fiber–Reinforced Concrete Slabs

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The effects of polypropylene fibers and construction operations on the plastic shrinkage cracking of concrete slabs were investigated. Statistical methods of experimental design and analysis were used to derive statistically reliable conclusions. Polypropylene fibers, at relatively low fiber volume fractions, were observed to reduce substantially the total area and maximum crack width of slab surfaces subjected to restrained plastic shrinkage movements. The rate of screeding of the fresh concrete surface was also a critical factor (particularly in plain concrete). Slower screeding rates led to reduced plastic shrinkage cracking.

When concrete surfaces dry at early ages, plastic shrinkage cracks form before the concrete hardens. The surface dries when the rate of water loss from the surface exceeds the rate at which the bleed water is made available to the surface. Polypropylene fibers have become popular in recent years for the reinforcement of concrete materials, mainly because of their effectiveness in reducing cracking at early ages under the effects of restrained plastic shrinkage.

Reducing the rate of evaporation is the conventional approach to the control of plastic shrinkage cracks during the construction of concrete slabs in dry conditions. It is likely, however, that under given evaporation conditions, the extent and severity of plastic shrinkage cracking may be increased by certain construction practices, particularly those relating to the finishing operations (screeding rate and direction, bullfloating, floating, and troweling).

The thrust of this investigation was to produce a comprehensive set of experimental data, on the basis of the practice of concrete slab construction, in order to derive statistically reliable conclusions about the effects of low-volume fractions of collated fibrillated polypropylene fibers on the plastic shrinkage cracking of concrete slabs finished by different construction methods. The work was motivated by the limited test data reported on the plastic shrinkage cracking of concrete materials. The available test data generally deal with fine-aggregate mortars that, because of size effects, may behave differently from coarse-aggregate concrete materials.

BACKGROUND

Unrestrained (free) shrinkage is rarely found in typical concrete structures. Restraints are always present, either internal or external, because of support conditions and reinforcement or nonuniform drying. These restraints induce tensile stresses that approach the tensile strength of concrete and cause cracking.

Plastic shrinkage cracks occur during the first few hours after casting the concrete while the material is still in a semifluid or plastic state. The study of plastic shrinkage cracking is complicated because the material properties that determine whether such cracks will form are time-dependent and change rapidly during the first few hours. To develop reliable means of preventing this type of damage to the concrete, it is desirable to know the physical or chemical origins of plastic shrinkage. Because plastic shrinkage takes place within the first few hours after placing the concrete, it can be shown that chemical shrinkage does not contribute to plastic shrinkage to a significant extent. One common observation, which is recorded in nearly all of the relevant papers, is that plastic shrinkage–induced cracks are created as soon as the surface of the fresh concrete dries. In other words, plastic shrinkage is likely to occur when the rate of evaporation exceeds the rate at which the bleeding water rises to the surface (*1*). It is also believed that plastic shrinkage cracking occurs at the exposed surfaces of freshly placed concrete because of the consolidation of the concrete mass. This leads to open water channels that produce tensile stress in surface tears and cracks that destroy surface integrity and impair durability.

The use of polypropylene fibers at low fiber volume fractions improves several aspects of the production and application of fiber-reinforced concrete, including shrinkage and crack control, impact resistance, and toughness characteristics. Many parameters govern the performance of polypropylene fiber–reinforced concrete subjected to restrained shrinkage. These include the potential extent of shrinkage, the degree of restraint, time-dependent tensile properties of concrete, and fiber-to-matrix interfacial bond characteristics (*2–4*).

When plastic shrinkage forces are applied to concrete in the presence of polypropylene fibers, the fibers resist early shrinkage cracking and increase the stability of concrete at the initial and early set stages, causing the material to be less susceptible to settlement cracking and to adverse vibration effects at the same time.

There is currently no standardized procedure for quantifying the effects of polypropylene fibers or any other synthetic fibers on plastic or drying shrinkage cracking.

It has been found that the quantity of surface bleed water is significantly reduced by the addition of polypropylene fi-

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bers. It is suggested that fibers cause a reduction in consolidation and thus reduce the formation of damaging capillary bleed channels and cause an increase in intergranular pressure in the plastic concrete (*5*).

Although unrestrained shrinkage tests do provide some information about the shrinkage characteristics of fiber-reinforced cement composites, results of these tests may not provide any useful information on how composites respond to shrinkage-induced stresses in restrained conditions when shrinkage strains translate into tensile stresses in concrete. After cracking, polypropylene fibers are believed to transfer the tensile stresses across cracks and to arrest or interrupt crack tip extensions so that many fine (hairline) cracks occur instead of few larger cracks (*4–6*).

The leveling operation after placing the concrete into forms, known as striking off or screeding, has been found to be a critical factor in plastic shrinkage cracking (*6*). Thus the effects of the rate and direction of screeding and the effects of the finishing operations on plastic shrinkage cracking were investigated.

EXPERIMENTAL PROGRAM

Plastic shrinkage cracking of polypropylene fiber–reinforced concrete was investigated experimentally. Three variables were considered, each at two levels, to assess their effects on plastic shrinkage cracking of concrete. The three variables and their corresponding levels are given:

Variable	*Level 1*	*Level 2*
Fiber volume fraction	0.0%	0.1%
Screeding speed	3 m/min (2.74 ft/min)	12 m/min (10.97 ft/min)
Screeding direction	Long side	Short side

A 2-×-2-×-2 factorial combination of the variables was considered; the screeding direction was eventually used as a blocking variable to form a randomized block design of experiments. Because screeding direction has only a secondary effect of changing the direction of cracking (as observed in this investigation), it was selected as a blocking variable in order to enhance the sensitivity of the statistical analysis. The statistical analysis method (factorial analysis of variance of randomized block design with screeding direction as the blocking factor) allows for determining the level of confidence in each of the conclusions derived on the basis of the test results.

Materials

The basic concrete mix constituents were cement, coarse aggregate, fine aggregate, and water. A brief description of all the materials used in this research is given in the following:

- *Portland cement*: Type I portland cement (ASTM C150-89) was used; the specific gravity was 3.15 and fineness (percentage retained on #325 sieve) was 10.7.
- *Coarse aggregate*: Crushed limestone with maximum aggregate size of 13 mm (0.5 in.) was used; its gradation met the ASTM C33 requirements. The specific gravity of coarse aggregate was 2.55, and its absorption capacity was 1.0 percent.
- *Fine aggregate*: Natural sand with fineness modulus of 3.0 was used in this research; its gradation met the ASTM C33 requirements. The specific gravity of fine aggregate was 2.50, and its absorption capacity was 3.5 percent.
- *Polypropylene fibers*: Collated fibrillated polypropylene fibers were used in this research. Some of the physical properties of these fibers are:

  –Tensile strength = 628 to 760 MPa (80 to 110 ksi)
  –Young's modulus = 3.5 GPa (500 ksi)
  –Specific gravity = 0.9
  –Melting point = 160 to 170°C (320 to 340°F)
  –Ignition point = 590°C (1,100°F)

The fibers also exhibit low thermal conductivity, low electrical conductivity, and high acid and salt resistance.

The mix proportions for all panels for cement:coarse aggregate:fine aggregate:water were 1:2.5:2.0:0.47. The cement content was 386 kg/m^3 (650 lb/yd^3). This mixture produced a slump of 100 to 125 mm (4 to 5 in.). The designated water-cement ratio was selected to produce plastic shrinkage cracking in the specific (relatively moderate) conditions of this investigation [temperature of 24 to 27°C (75 to 80°F), humidity of 50 ± 5 percent, and wind speed of 12.8 km/hr (8 mph)].

Construction

All mixtures were mixed in a conventional rotary drum concrete mixer with a capacity of 0.04 m^3 (1.41 ft^3). The mixing procedure for the concrete mixture followed ASTM C192-90. The mixer was first loaded with the coarse aggregate and a portion of the mixing water. After the mixer was started, the fine aggregate, cement, and rest of the water were added and mixed for 3 min. This was followed by 3 min of rest and 2 min of final mixing. For fibrous mixtures, the fibers were added after all other mix ingredients were. Fresh concrete mixtures were tested for bleeding (ASTM 232) and set time (ASTM 403). All the panels were cast immediately after mixing, and the tests were conducted after the adopted restrained plastic shrinkage test procedure prescribed in the following section.

Plastic Shrinkage Cracking Test Procedure

The test procedure proposed by Kraii (*7*) and refined by Shaeles and Hover (*6*) was used for evaluating the effects of polypropylene fibers on plastic shrinkage cracking of concrete.

Two 533- × 838-mm (21- × 33-in.) slabs 38 mm (1.5 in.) thick (one plain and the other fibrous concrete) were cast side by side and exposed to identical finishing processes and environmental conditions (temperature, humidity, and wind velocity). A vertical partition was used between the two panels to prevent nonuniformities arising from interference effects between the two fans and slabs. To monitor the weight of water lost from concrete during the test, two cylinders 152 mm (6 in.) across and 64 mm (2.5 in.) high filled with concrete were placed adjacent to the panels and weighed during the test. Open pans of water were similarly placed and weighed to monitor the rate of evaporation from a free water surface (see Figure 1). The fans were started 25 min after the addition of water to the mixer for all test slabs in order to have identical

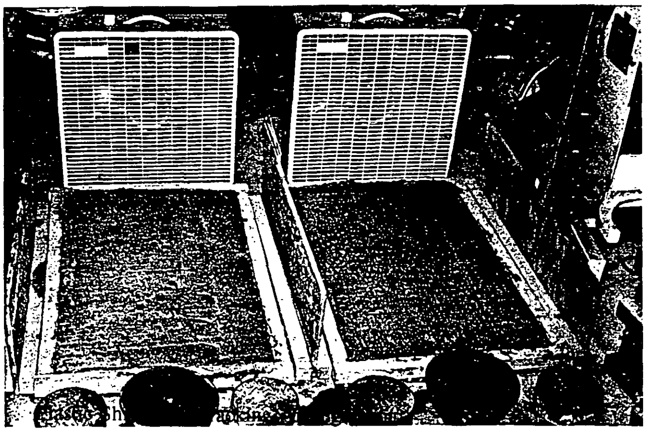

FIGURE 1 Plastic shrinkage cracking test arrangement.

conditions. The temperature, relative humidity, and wind velocity were measured during tests on each pair of panels.

Procedures for placing and finishing the concrete slabs were performed according to those described by Kosmatka and Panarese (*8*). The finishing procedures used in this project are summarized in the following:

1. Screeding (strike off): Screeding of the slab surface was done immediately after the concrete was poured into the forms using a wood straight edge that was moved across the concrete surface with a sawing motion and advanced forward a short distance with each movement.
2. Bullfloat or Darby: Immediately after screeding, an aluminum bullfloat was applied to eliminate high and low spots and embed large aggregate particles. Bullfloat application was completed before bleed water accumulated on the surface of the slab.

TEST RESULTS AND DISCUSSION OF RESULTS

The formation of plastic shrinkage cracks was visually determined. Generally, the cracks began to form within 40 to 120 min after the fans were started. The fan was stopped after 5 hr. Subsequently, the crack widths and lengths were measured using optical lenses. Total crack area was calculated by multiplying the width of each crack by its length. Characterizing the cracks by their total area instead of their total length helps to account for the fact that some cracks are simply hairlines and others are much wider.

The rate of evaporation from concrete surfaces was found to range from 0.25 to 3.18 kg/m^2/hr (0.05 to 0.65 lb/ft^2/hr), whereas the rate of free water evaporation was almost twice that amount. The times of setting for plain and polypropylene fiber–reinforced concretes are shown in Figure 2. The initial and final setting times were decreased by 9 and 27 percent, respectively, with the addition of polypropylene fibers. This reduction is expected to reduce the period of exposure of fresh concrete (before setting) to the dry environment; the drying period is responsible for plastic shrinkage cracking. The amount of bleed water for plain and fiber concretes is shown in Figure 3. The addition of polypropylene fibers caused an 18 percent decrease in the amount of bleed water of concrete; the fibers could be reducing the settlement of heavier mix constituents (e.g., aggregates), thereby reducing the upward movement (and bleeding) of concrete.

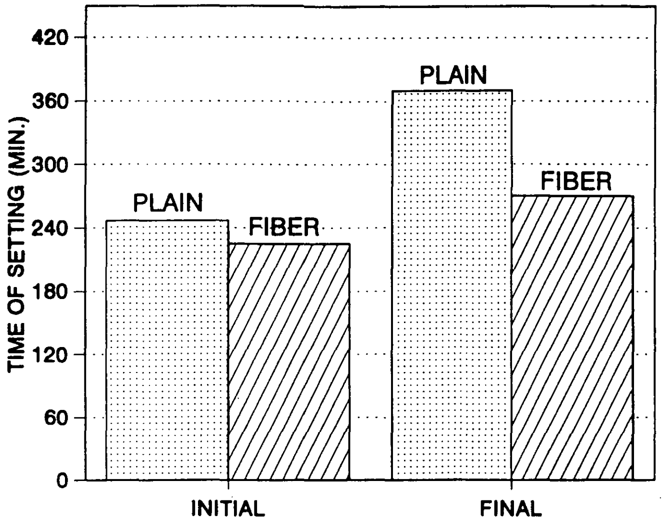

FIGURE 2 Time of setting for plain and fiber concretes.

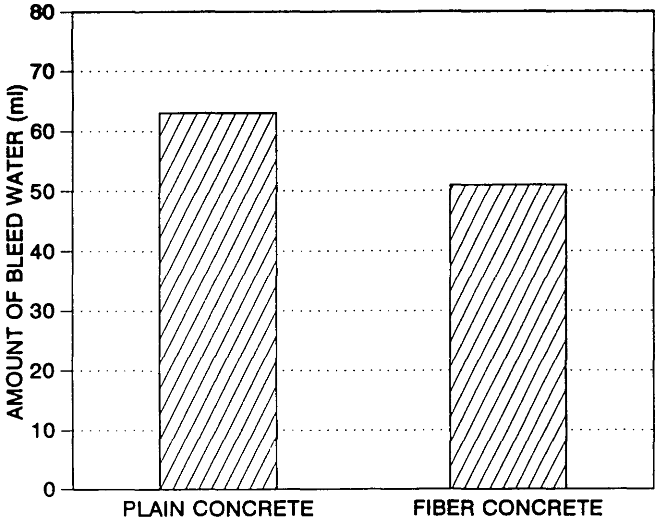

FIGURE 3 Bleeding test results.

EFFECTS OF CONSTRUCTION OPERATIONS

The average values of the total crack areas and maximum crack widths are shown in Figures 4 and 5, respectively. The average values are obtained from two test results (with two screeding directions). Because of the relatively large range of the total crack area measurements, resulting from negligible crack widths of polypropylene fiber–reinforced panels, transformation of test results was necessary to perform a reliable statistical analysis of the total plastic shrinkage crack areas. Square root transformation was found to be suitable for the total crack area measurements. Randomized block analysis of variance of the transformed data revealed that fiber volume

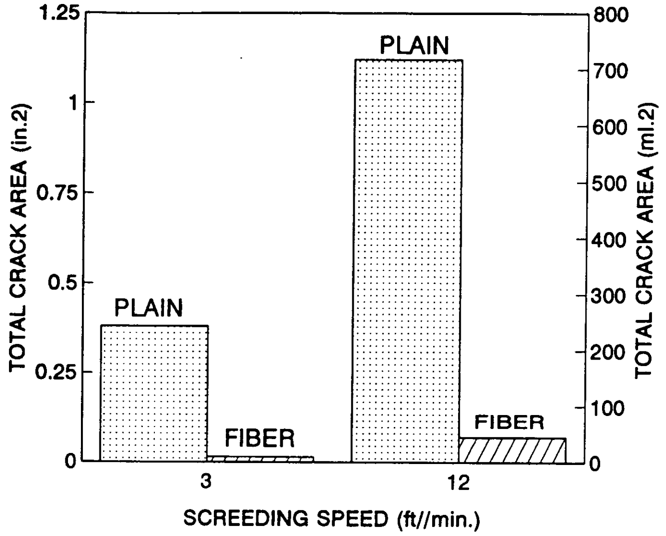

FIGURE 4 Effects of construction operations and fiber volume fraction on total plastic shrinkage crack area.

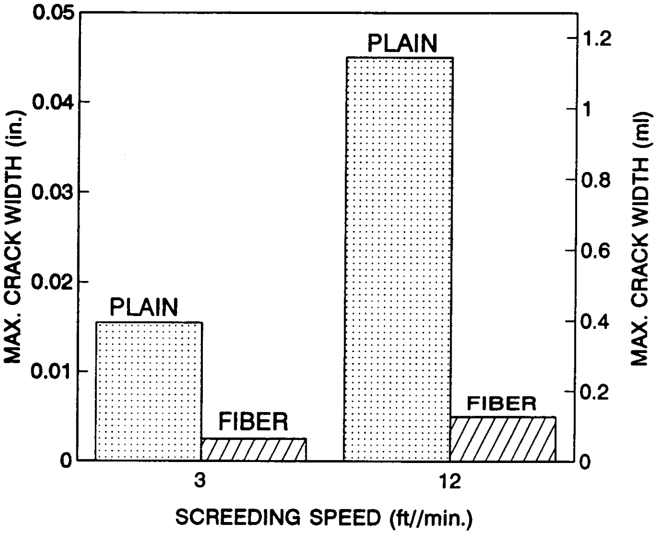

FIGURE 5 Effects of construction operations and fiber volume fraction on maximum plastic shrinkage crack width.

fraction and screeding speed had significant effects on the plastic shrinkage cracking area and maximum crack width at 99 and 95 percent levels of confidence, respectively. There appeared to be significant interaction between construction operations (screeding speed) and polypropylene fibers in influencing the total area of plastic shrinkage cracks. However, screeding speed had not statistically significant interaction with fibers in causing the maximum crack width.

Multiple comparisons of the test data indicated that in all cases the total plastic shrinkage cracking area in fiber concrete was significantly less than that in plain concrete. In fiber concrete, slow rate of screeding significantly reduced the total plastic shrinkage crack area of concrete panels.

The plastic shrinkage cracks were hairline cracks in polypropylene fiber–reinforced panels, so the multiple comparisons of the maximum crack width test results revealed that maximum crack widths were statistically comparable in all cases in the presence of fibers (irrespective of the screeding speed). Multiple comparison of the maximum crack width measurements in plain concrete panels confirmed that slower screeding led to narrower maximum crack widths when no fibers were present.

Polypropylene fibers reduced the total plastic shrinkage crack area by 95 percent at high screeding speed. Fibers eliminated any detectable plastic shrinkage cracks at low screeding speed.

SUMMARY AND CONCLUSIONS

The effects of collated fibrillated polypropylene fibers, at 0.1 percent fiber volume fraction, and construction operations on plastic shrinkage cracking of concrete were investigated experimentally. Statistical analysis of the data was performed to confirm the validity of the following conclusions at a 95 percent (or higher) level of confidence:

1. Polypropylene fibers significantly reduce the total plastic shrinkage crack area and maximum crack width at 0.1 percent fiber volume fraction.
2. The construction operations (screeding rate) affect the total plastic shrinkage crack area in both plain and fibrous concretes.
3. Because polypropylene fiber–reinforced concrete is characterized by fine plastic shrinkage cracks, the maximum crack width was not influenced by any of the construction operations (screeding rate) in fibrous concrete. On the other hand, the maximum plastic shrinkage crack widths of polypropylene fiber–reinforced concrete decreased significantly when compared with plain concrete. In plain concrete, higher screeding rates led to a statistically significant increase in the maximum crack width.

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