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Influence of polypropylene fiber geometry on plastic shrinkage cracking in concrete

Nemkumar Banthia *, Rishi Gupta [1]

University of British Columbia, Department of Civil Engineering, Vancouver, BC, Canada V6T 1Z4

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Abstract

Plastic shrinkage cracking remains a primary concern for placements with high surface/volume ratios that are subjected to early age drying. Polypropylene fiber reinforcement controls such cracking, but the exact influence of fiber diameter, length and geometry remains unknown. A test program was carried out to understand the influence of these variables. Four commercially available polypropylene fibers were investigated at dosage rates varying from 0.1% to 0.3%. A recently developed technique of plastic shrinkage testing using a fully bonded overlay was employed. In this technique, a fiber reinforced concrete overlay is cast on a fully matured subbase with protuberances and the whole assembly is allowed to dry in an environmental chamber. Cracking in the overlay is monitored with time and characterized. Results indicate that while polypropylene fibers in general are effective in controlling plastic shrinkage cracking in concrete, a finer fiber is more effective than a coarser one, and a longer fiber is more effective than a shorter one. Further, fiber fibrillations appear to be highly effective in controlling plastic shrinkage cracking.

Keywords: Concrete; Plastic shrinkage; Cracking; Fiber reinforcement

1. Introduction

When concrete is in the plastic state, moisture loss may occur both by evaporation to the atmosphere and absorption by subbase or formwork. Although some of the water lost this way is replenished by bleeding, if the surface moisture loss exceeds 0.5 kg/m^2/h [1], negative capillary pressures develop in the concrete causing internal compressive strains. If concrete is restrained, these compressive strains may result in tensile stresses far in excess of those needed to cause cracking in young concrete with poorly developed strength. In spite of every effort, plastic shrinkage cracking remains a serious concern, particularly in large surface area placements like slabs on grade, thin surface repairs, patching, tunnel linings, etc. In these applications, the exposed surface area per unit volume of the overlay material is high and the old concrete substrate or the rock surface offers a high degree of restraint.

The most effective technique of mitigating plastic shrinkage cracking is by preventing the loss of water from the concrete surface by extended curing. In some instances, however, curing alone is not adequate, and additional measures need to be adopted. These include temperature control, shielding from high winds, reduced use of admixtures that prevent bleeding and the use of shrinkage reducing admixtures [2,3].

One highly effective technique of controlling plastic shrinkage cracking is by reinforcing concrete with fibers. Randomly distributed fibers of steel, polypropylene, etc. provide bridging forces across cracks and thus prevent them from growing [4,5]. Of all fibers used today for this purpose, polypropylene is considered to be the most effective. Polypropylene is inexpensive, inert in high pH cementitious environment and easy to disperse. However, the exact influence of polypropylene fiber geometry, diameter, length, fibrillations, etc. is not well understood.

There exist several techniques of studying shrinkage induced cracking in cement-based materials. Most commonly used methods include a ring type specimen [4], a linear specimen with anchored ends [6], a linear specimen held between a

* Corresponding author. Tel.: +1 604 822 9541; fax: +1 604 822 6901.
E-mail address: banthia@civil.ubc.ca (N. Banthia).
[1] Doctoral candidate.

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movable and a fixed grip such that a complete restraint and one-dimensional fixity are achieved by returning the movable grip to the original position after shrinkage [7], and a plate type specimen where the restrain is provided in two orthogonal directions [8]. Qi et al. [5] have used a stress riser to amplify plastic shrinkage cracking in restrained slab specimen. These methods might be effective for studying a material in the laboratory but do not simulate stress fields that are produced in reality. A technique producing realistic shrinkage conditions was recently developed [9–11]. In this method, a layer of fresh mortar is placed as an overlay directly on a fully hardened substrate base. This 'substrate base' has protuberances, which enhances its roughness and, in turn, imposes a uniform restraint on the overlay. The whole assembly is then subjected to a drying environment to induce cracking in the overlay, which is then characterized using a high magnification microscope.

1.1. Research significance

Plastic shrinkage cracking remains a major concern with many concrete placements. Cracking at early ages can accelerate deterioration, promote steel corrosion and cause significant durability related concerns in the long run. Polypropylene fiber reinforcement can inhibit such cracking but the exact influence of fiber parameters such as diameter, length and deformed geometry is not understood. A test program was conducted in order to understand the influence of such parameters. It is anticipated that such efforts will allow us to design better fibers for controlling plastic shrinkage cracking in concrete.

2. Experimental program

Substrate bases (Fig. 1) with dimensions of 40 × 95 × 325 mm were cast using the mixture proportions given in Table 1. Two 10 mm diameter rebar were used as reinforcement in the substrate bases to provide additional stiffness. After casting, the bases were covered using a plastic sheet for a period of 24 h after which they were transferred in a tank with lime-saturated water and stored for at least 60 days until used in tests. The substrate concrete developed a compressive strength of 89 MPa when tested in accordance to ASTM C 39. The substrate bases had 18.5 mm semicircular protuberances on the surface and were designed to provide uniform restraint to the overlay to be placed on top.

Table 1
Mix proportions

	Cement	Silica Fume	Water	Sand	Aggregate	Superplasticizer
	kg/m^3					
Substrate base	535.5	59.5	166.6	809.2	809.2	1.61
Overlay mortar	1200	–	576	601	–	–

On the day of the test, three identical specimens of the overlay to be investigated were prepared using the following procedures. A fully cured, air-dried substrate base was first placed in the PVC mould measuring 100 × 100 × 375 mm. A 60 mm deep overlay with mixture proportions given in Table 1 was then poured over the substrate base and finished with a trowel. The overlay was either plain or fiber reinforced depending on the material being investigated. The substrate and the overlay 'assembly' was then transferred to an environmental chamber and demolded after 2 h to increase the surface area exposed to drying. A typical specimen after demolding is shown in Fig. 2(a). The specimen remained in the environmental chamber for an additional 20 h after which the crack pattern developed in the overlay was characterized. Fig. 2 (b) shows a typical specimen with cracked overlay. For crack characterization, a high magnification microscope with an accuracy of 0.01 mm was used. In addition to recording the maximum crack width observed in a given specimen, for each crack, the width was measured at several locations and averaged. These width and length measurements were then used to calculate the total crack area in a specimen.

The environmental chamber used for the tests is shown in Fig. 3. The 1705 mm × 1705 mm × 380 mm environmental chamber was equipped with temperature and humidity probes capable of regulating and monitoring the conditions inside.

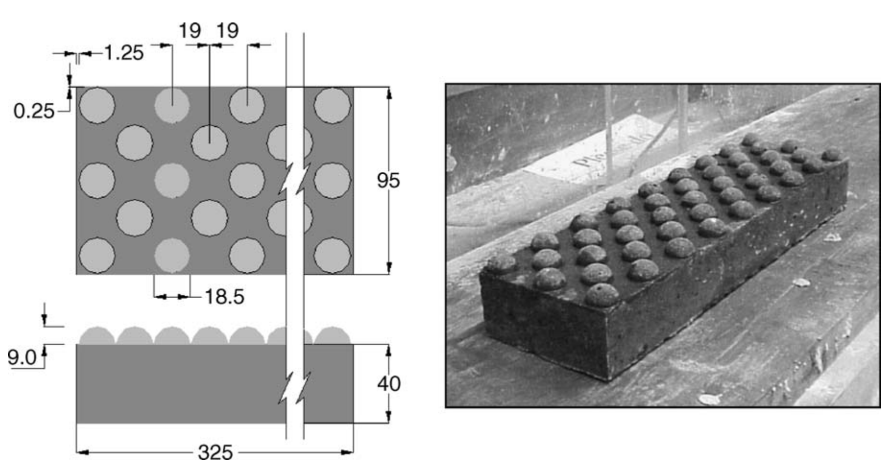


Fig. 1. A substrate base with protuberances.

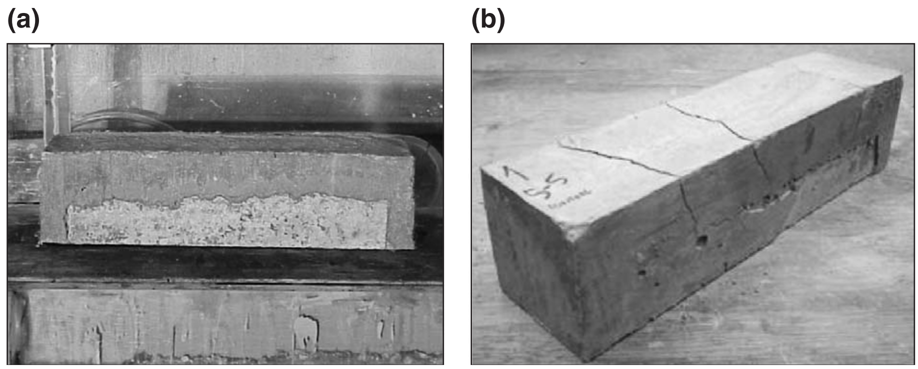


Fig. 2. Specimen (a) after demolding and (b) after cracking.

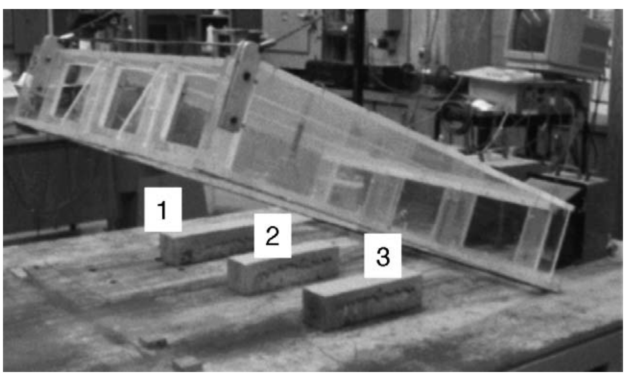


Fig. 3. Environmental chamber.

Three heater/blower units (240 V, 4800 W with a 1/30 HP, 1550 RPM internal electrical fan) supplied heated air to the chamber. These units were, in turn, controlled by the temperature sensor to maintain a constant temperature in the chamber. The heated air was allowed to escape the chamber through three 240 mm × 175 mm openings. A constant temperature of 50 °C ± 1 °C was maintained along with an RH of about 5%. Under these conditions, an approximate rate of surface evaporation of 0.80 kg/m^2/h was measured at the location of the specimen. Three specimens of a given overlay mixture were simultaneously tested as shown in Fig. 3.

As mentioned before, the overlay mixture was reinforced with fibers to be investigated. Four types of polypropylene fibers–three monofilament type and the fourth a fibrillated type–were investigated as shown in Table 2. Three volume fractions of 0.1%, 0.2% and 0.3% were investigated for each of the four fibers unless cracking was completely arrested at a lower volume fraction.

3. Results and discussion

Detailed results are given in Table 3 in terms of crack area and maximum crack width. The results reported in Table 3 are averages of three specimens for fiber reinforced mixes and six specimens for the control mix without fibers. In Fig. 4, representative crack patterns observed for plain and fiber reinforced composites with Fiber F1 at 0.1% and 0.2% are shown. Notice a clear effect of increasing the fiber dosage, and the absence of cracking at 0.2%.

The influence of fiber reinforcement on crack pattern is shown in Figs. 5 and 6. In Fig. 5, the crack areas noted in various individual tests are plotted against the maximum crack widths observed in these tests. In Fig. 6, the number of cracks

Table 2
Polypropylene fiber properties and dosages investigated

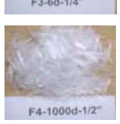
Fiber		Fiber type	Diameter (denier)	Length (mm)	Density (kg/m^3)	Dosages investigated
F1		Monofilament	3	12.5	900	0.1, 0.2%
F2		Monofilament	6	12.5	900	0.1, 0.2 and 0.3%
F3		Monofilament	6	6.35	900	0.1, 0.2 and 0.3%
F4		Fibrillated	1000	12.5	900	0.1, 0.2 and 0.3%

Table 3
Results

Fiber type	Crack area (mm^2)				Maximum crack width (mm)			
	0%	0.10%	0.20%	0.30%	0%	0.10%	0.20%	0.30%
Control	329.9				3.00			
F1, monofilament 3d–1/2″		120.9	3.8			1.32	0.18	
F2, monofilament 6d–1/2″		216.0	119.5	101.9		1.32	1.04	0.89
F3, monofilament 6d–1/4″		257.8	242.8	154.4		2.00	1.42	1.40
F4, fibrillated 1000d–1/2″		172.9	42.9	31.0		1.02	0.54	0.38

observed in individual tests is plotted against the maximum crack width. Centroids of the families of data points for plain overlays and fiber reinforced overlays are located in both Figs. 5 and 6. Notice that the effect of fiber reinforcement is apparent in terms of reductions in crack area, maximum crack width and the number of cracks.

Fiber F2 was seen as more effective than Fiber F3 indicating that a longer fiber of the same denier is more effective (Fig. 7). This implies that polypropylene fibers develop a poor bond with the cementitious matrix and a longer fiber length is necessary for an efficient transfer of stress across a crack. Comparison of Fiber F1 with Fiber F2 indicates that a finer denier fiber is more effective than a coarser denier fiber. This is expected as a finer fiber would have a larger surface area over which it would bond with the cementitious matrix and thus result in a greater transfer of tensile stress to the fiber. Also, at a given fiber volume fraction, a finer fiber will have more fibers crossing a given section. This will allow for an effective truncation in the lengths of unsupported matrix cracks between fibers, reduce the stress concentration and improve the resistance to crack growth.

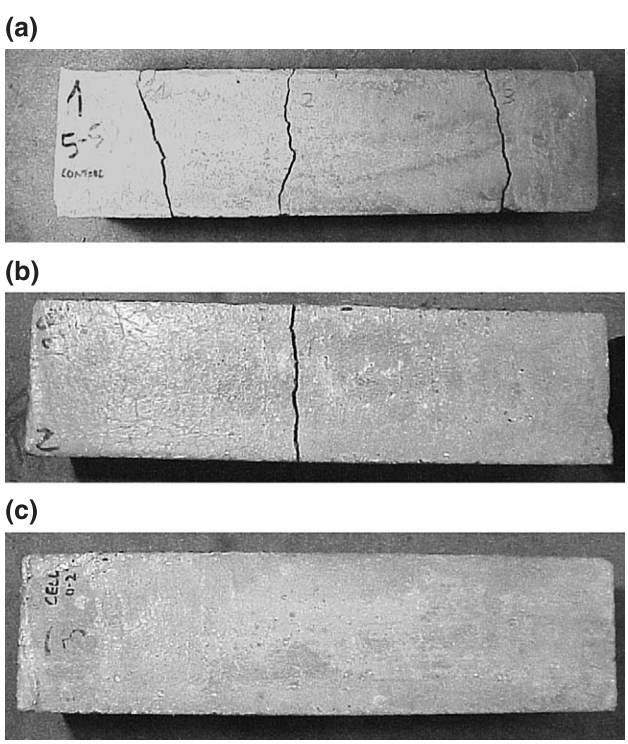


Fig. 4. Crack patterns noted for Fiber F1: (a) no fiber (control); (b) 0.1% fiber; (c) 0.2% fiber.

Finally, comparison of Fibers F2 and F4 indicates that fiber fibrillations in Fiber F4 are highly effective in controlling plastic shrinkage cracking. Clearly, fiber fibrillations provide an effective mechanical anchorage sufficient to overcome the otherwise poor adhesion between fiber and the matrix. It is also likely that the fibrillated fibers disperse better than their monofilaments counterparts.

4. Concluding remarks

Polypropylene fibers are highly effective in controlling plastic shrinkage cracking in concrete. In general, fibers reduce the total crack area, maximum crack width and the number of cracks. As fiber volume fraction increases, effectiveness of fiber reinforcement increases. Among the various fibers investigated,

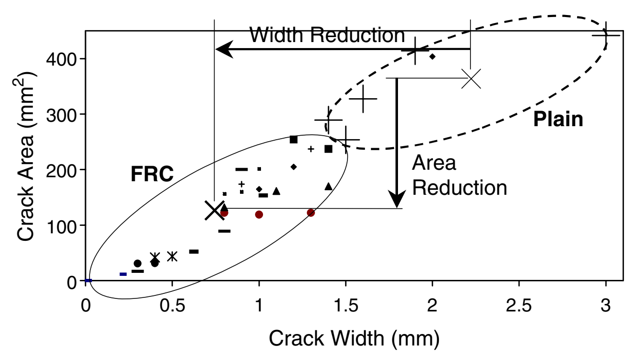


Fig. 5. Comparison between plain and fiber reinforced concrete based on crack area and crack widths. Notice a reduction in both crack area and crack width due to fiber reinforcement.

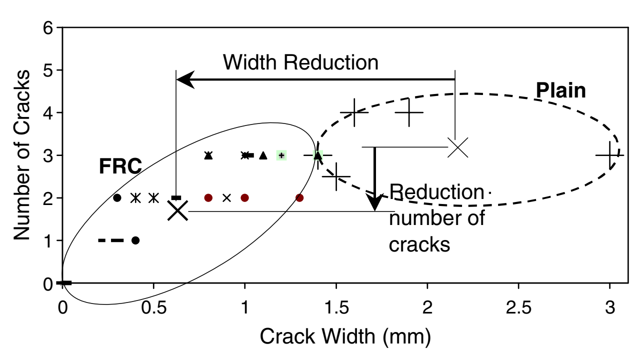


Fig. 6. Comparison between plain and fiber reinforced concrete based on crack width and number of cracks. Notice a reduction in both the crack width and number of cracks due to fiber reinforcement.

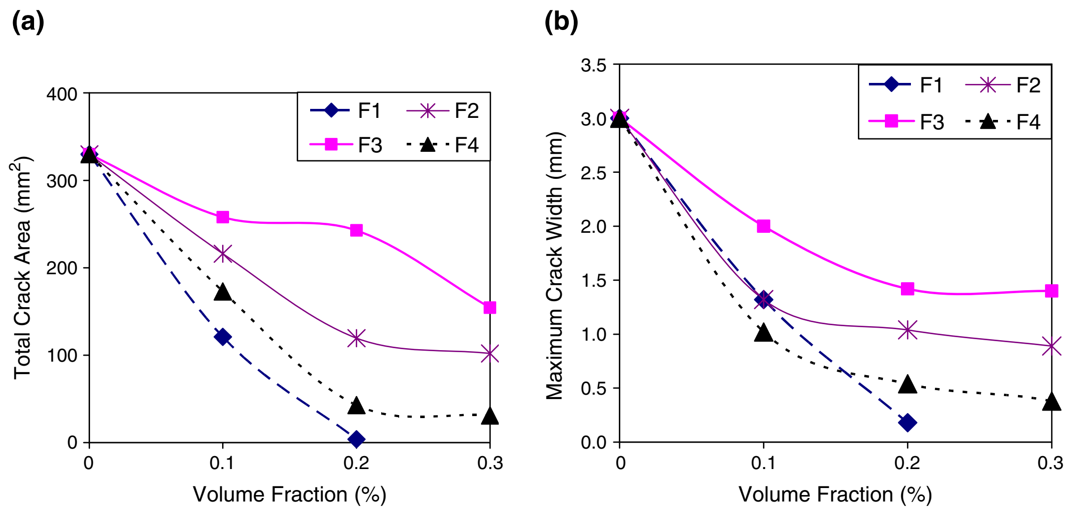


Fig. 7. (a) Total crack area and (b) maximum crack width for various fiber types (F1–F4).

Fiber F1 (3d–1/2″) was seen as the most effective. Longer fibers and low denier fibers were more effective in reducing crack areas and crack widths. Finally, fibrillated fibers were more effective in controlling shrinkage cracking than their comparable monofilament counterparts.

Acknowledgements

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References

[1] S. Mindess, J. Francis Young, D. Darwin, Concrete, 2nd edition, Prentice Hall, NJ, 2003.
[2] W.J Weiss, S.P. Shah, Recent trends to reduce shrinkage cracking in concrete pavements, Proceedings of the Airfield Pavement Conference, Aircraft/Pavement Technology: In the Midst of Change, 1997, pp. 217–228.
[3] S.P. Shah, M.E. Karaguler, M. Sarigaphuti, Effects of shrinkage-reducing admixtures on restrained shrinkage cracking of concrete, ACI Materials Journal 89 (3) (1992 (May–Jun)) 291–295.
[4] M. Grzybowski, S.P. Shah, Shrinkage cracking of fiber reinforced concrete, ACI Materials Journal (1990 (March–April)) 138–148.
[5] C. Qi, J. Weiss, J. Olek, Characterization of plastic shrinkage cracking in fiber reinforced concrete using image analysis and a modified Weibull function, Materials and Structures 36 (260) (2003 (July)) 386–395.
[6] N. Banthia, M. Azzabi, M. Pigeon, Restrained shrinkage cracking in fiber reinforced cementitious composites, Materials and Structures RILEM (Paris) 26 (161) (1993) 405–413.
[7] R. Bloom, A. Bentur, Free and restrained shrinkage of normal and high strength concrete, ACI Materials Journal 92 (2) (1995).
[8] A. Khajuria, P. Balaguru, Plastic shrinkage characteristics of fiber reinforced cement composites, in: R.N. Swamy (Ed.), Fiber Reinforced Cement and Concrete, E&FN Spon, London, 1992, pp. 82–90.
[9] N. Banthia, C. Yan, S. Mindess, Restrained shrinkage cracking in fiber reinforced concrete: a novel test technique, Cement and Concrete Research 26 (1) (1996) 9–14.
[10] N. Banthia, K. Campbell, Restrained shrinkage cracking in bonded fiber reinforced shotcrete, in: Katz, Bentur, Alexander, Arligui (Eds.), The Interfacial Transition Zone in Cementitious Composites, RILEM Proc., vol. 35, E and F N. Spon, 1998, pp. 216–223.
[11] N. Banthia, C. Yan, Shrinkage cracking in polyolefin fiber reinforced concrete, American Concrete Institute, Materials Journal 97 (4) (2000) 432–437.