Pergamon

Cement and Concrete Research, Vol. 26, No. 1, pp. 9-14, 1996
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0008-8846/96 $15.00 + .00

0008-8846(95)00186-7

RESTRAINED SHRINKAGE CRACKING IN FIBER REINFORCED CONCRETE: A NOVEL TEST TECHNIQUE

N. Banthia, C. Yan and S. Mindess
Department of Civil Engineering, University of British Columbia,
Vancouver, B.C., Canada

(Communicated by D.M. Roy)
(Received November 6, 1995)

ABSTRACT

A novel experimental technique was developed to assess the cracking potential of cement-based materials when used as a bonded overlay. Specimens were cast directly on to a substrate and the assembly was subjected to a drying environment to induce cracking. Lengths and widths of the resulting cracks in the overlay were monitored as a function of time. The use of fibers was found to be very effective not only in reducing the widths of the shrinkage cracks but also in allowing multiple cracking to occur. Interestingly, these two phenomena occurred only up to a fiber volume fraction of 0.5%; at 1% by volume of fibers, only minimal cracking was seen to occur even under a particularly severe environment.

Introduction

In both its fresh and hardened states, cement paste has a tendency to shrink, due to the evaporation of mixing water, due to the natural process of hydration itself, or due to the removal of the physically adsorbed water from within the layers of C-S-H. If this change in volume is restrained in any way, the material develops shrinkage strains which may lead to cracking. This is of particular concern in thin applications such as slabs-on-grade, repairs and patching, overlays, shotcrete tunnel linings, etc., where the exposed surface area per unit volume of the overlay material is high and the old concrete substrate or the rock surface, which is generally stable with respect to the environment, offers a high degree of restraint. Among the different solutions proposed for controlling shrinkage cracking in such applications, the most promising is the use of randomly distributed fibers of steel or polypropylene which provide bridging forces across cracks and thus prevent them from growing. In spite of the well-known role of fibers in this regard, there is no generally accepted method of assessing the effectiveness of fibers in controlling shrinkage induced cracking.

In the past, several techniques have been proposed for studying shrinkage induced cracking in cement-based materials. These include a ring-type specimen (1), a linear specimen with anchored ends (2), a linear specimen held between a 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 (3), and a plate-type specimen where the restraint is provided in the two orthogonal directions (4). These tests, clearly, are idealized in nature, and do not represent the actual conditions of restraint in practice. In reality, the bonded overlay is subjected to restraining forces which occur only along the interface with the substrate, giving rise to a complex stress field in the shrinking overlay above. Also, these restraining forces, which are presumably uniform initially but relax with time and change both in magnitude and distribution, give rise to an even more complex stress field in the overlay. Clearly, a realistic assessment of shrinkage cracking in an overlay material is possible only when the applied restraint is close to the one in reality. Such an attempt was made in the study reported here.

Experimental

The main objective of the research was to develop a test procedure in which realistic conditions of restraint were imposed on an overlay undergoing early-age shrinkage. To accomplish this, shrinkage specimens were prepared in two steps: first, a 40 mm deep substrate (mix proportions given in Table 1) was prepared in a Plexiglas mold which was 1010 mm long and 100 mm wide. The surface of the substrate was given an enhanced roughness by manually placing 20 mm aggregates on the surface such that approximately half the aggregate depth remained exposed. This substrate was then cured in hot water at about 50°C for three days. After this period, the mold containing the substrate was cleaned and allowed to dry for two hours. A 100 mm deep layer of the overlay material to be investigated was then placed on the substrate and the whole assembly was transferred to an environmental chamber measuring 1740 mm × 350 mm × 380 mm. In the environmental chamber, a heater with an output of about 16000 BTU supplied the hot air which was circulated by a fan at the rate of 340 cfm. The chamber is equipped with humidity and temperature sensors (±1 °C; ± 2% r.h.) the signals from which are sent to a personal computer which not only keeps a record of these parameters during a test but also controls the power supply to the fan and the heater as necessary. For the tests reported here, a constant temperature of 38°C and a constant relative humidity of 5% were chosen. Under these conditions, an approximate rate of surface evaporation of 0.7 kg/m^2/h was estimated.

Two and a half hours after the assembly was transferred to the chamber, the specimens were demolded and the crack observations were begun. In this state, the only restraint applied to the specimen was that coming from the rough surface of the substrate on which it was cast (Figure 1). During the crack observations, the exact times at which the cracks appeared on the top

TABLE 1
Mix Proportions

Ingredients	Substrate Concrete	Concrete for Testing
f'_c (Mpa)	80	25
Cement	0.9	1.0
Silica Fume	0.1	—
Water	0.28	0.55
Sand	1.36	1.00
Aggregate (4.74 ~10.0 mm)	1.36	1.00
Superplasticizer (ml per kg cement)	2.5	—
Dramix ZC 30/50 Steel Fibers (%)	—	0.0, 0.1, 0.5, 1.0

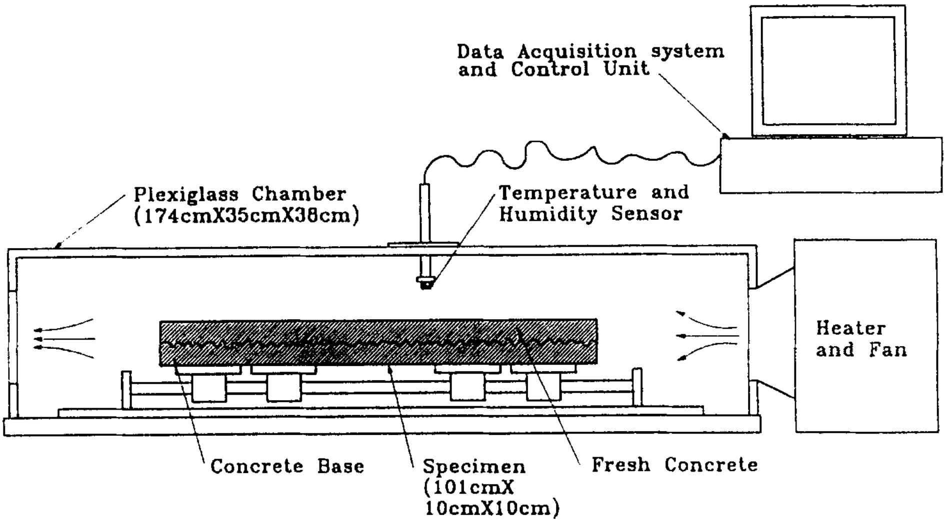

FIG. 1.
Schematic illustration of the shrinkage test set up.

surface of the specimen (observation area 1010 mm × 100 mm) were noted and the lengths and widths of the various cracks were monitored as a function of time. A small hand held microscope equipped with a vernier was employed for this purpose. Measurements were made every 30 minutes in the initial two hours and then every 4 hours afterwards. All measurements were terminated 48 hours after casting.

Test Results

The results reported here are only preliminary. In order to assess the validity of the data generated using the proposed technique, steel fiber reinforced concrete (SFRC) was investigated. The mix proportions for the SFRC and the fiber volume fractions are shown in Table 1.

As described previously, after demolding, cracks appeared in the specimen the widths and lengths of which were measured as a function of time. By taking the product of the two, a parameter termed the *total crack area* was calculated. Some cracked specimens are shown in Figure 2 and the final results at the termination of the test are given in Table 2. In Figure 3, the evolution of the total crack area is plotted as function of time for the various fiber composites and an increase in the total crack area with time can be noted. In Figure 4, the final values of the total crack area at the termination of the test are plotted as a function of fiber volume fraction.

Discussion

The crack patterns shown in Figure 2 indicate that in a plain concrete only two major cracks appeared after 48 hours and a maximum crack width of 2.83 mm was recorded. While this

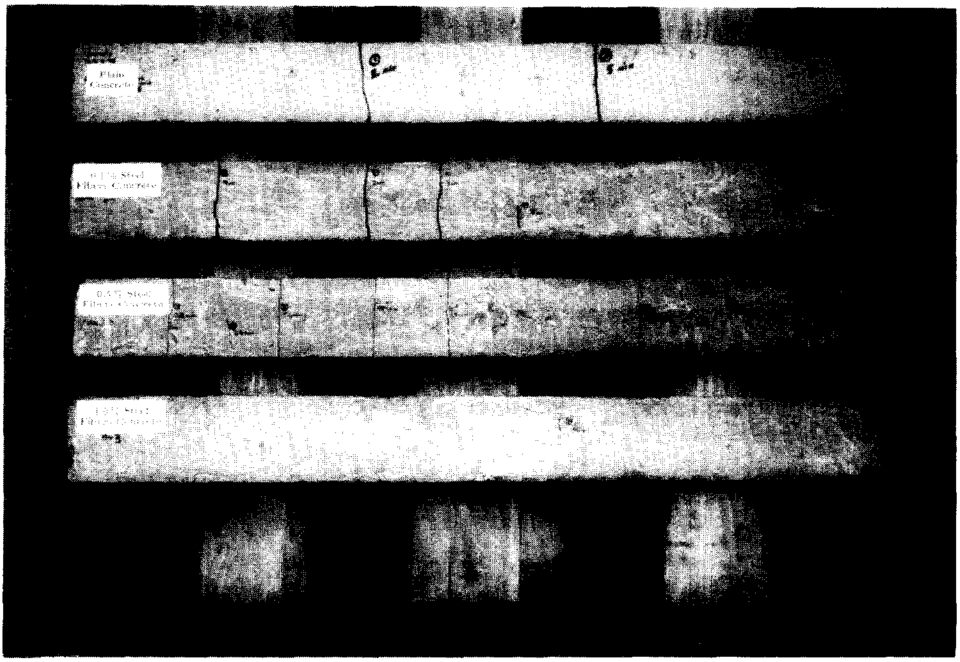

FIG. 2.
Representative crack patterns in plain and fiber reinforced concrete.

crack width itself is similar in magnitude to the ones seen to occur in specimens restrained only at the ends (2), the appearance of a second crack has not previously been observed in specimens restrained only at the ends, and is specific to the test setup used here. Steel fibers appear to be very effective not only in reducing the maximum crack widths, but also in distributing the cracks more uniformly. In spite of the multiple cracking, the total crack area in the case of SFRC, appears to decrease with an increase in the fiber volume fraction due to a marked

TABLE 2
Results from Shrinkage Test Results (48 h after casting)

	Vf (%)	$t_{first}^{(1)}$ (min)	$t_{80\%}^{(2)}$ (min)	$w_{max}^{(3)}$ (mm)	$w_c^{(4)}$ (mm)	$L_c^{(5)}$ (mm)	L_c/w_c	$A_{crack}^{(6)}$ (mm^2)	$n^{(7)}$
Plain	—	2	40	2.83	4.51	231	51.2	526	2
SFRC	0.1	2	65	1.84	4.17	342	82.0	473	3
	0.5	17	200	0.69	4.82	821	170.3	368	14
	1.0	50	240	0.38	0.38	72	189.5	27	1

(1) time after demolding at which the first crack appears
(2) time after demolding at which 80% of A_{crack} is achieved
(3) max observed crack width
(4) cumulative crack width
(5) cumulative crack length
(6) total crack area
(7) number of cracks

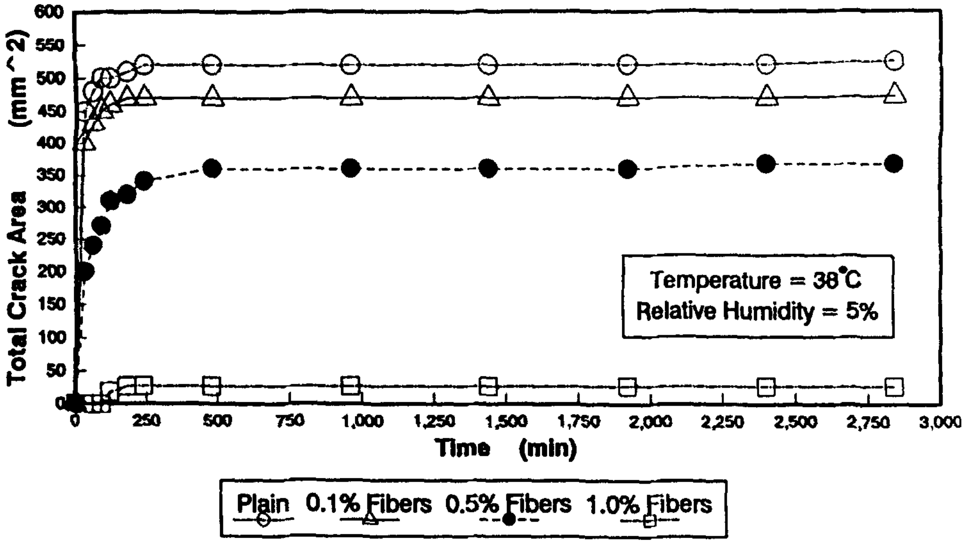

FIG. 3.
Evolution in the total crack area in various composites.

reduction in the crack widths. Note also that an increase in the fiber volume fractions led to a greater number of cracks only up to 0.5 % by volume of fibers; only minimal cracking occurred in specimens with 1% fibers.

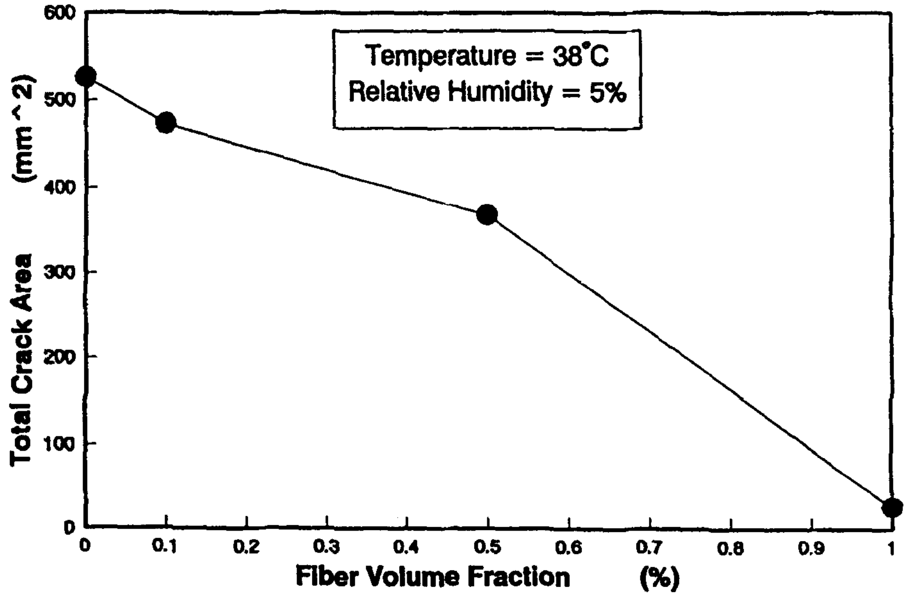

FIG. 4.
Total crack area plotted as a function of fiber volume fraction 48 h after casting.

Concluding Remarks

In this paper, a novel test technique of studying early-age cracking in cement-based materials when used as bonded overlays is described. Based on limited tests, steel fibers not only reduced the maximum crack widths but also caused multiple cracking in the composite up to a fiber volume fraction of 0.5%. At 1% fibers by volume, only minimal cracking was seen to occur even under a particularly severe environment.

Acknowledgments

The authors would like to acknowledge the continuing financial support of the Natural Sciences and Engineering Research Council of Canada.

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