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EFFECT OF CURING AGE ON THE SELF-MONITORING BEHAVIOR OF CARBON FIBER REINFORCED MORTAR

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ABSTRACT

The self-monitoring behavior of carbon fiber reinforced mortar was found to be affected in two ways by curing age from 7 to 28 days. Firstly, the electrical resistance increased monotonically with increasing compressive strain during first loading at 7 days, but at 14 and 28 days it decreased monotonically. Secondly, the resistance decreased slightly and irreversibly at the end of each cycle as cycling progressed at 14 and 28 days, but not at 7 days. These effects of the curing age are associated respectively with the effects of the curing age on fiber-cement bond strength and on cement compliance. © *1997 Elsevier Science Ltd*

Introduction

The monitoring of dynamic strain and damage of structural components is needed for structural control and structural health monitoring. Self-monitoring refers to the ability of a structural component to monitor its dynamic strain and damage without the need for embedded or attached sensors. The structural material is itself a sensor, so the sensing volume is throughout the component and the problems of high cost, poor repairability and mechanical property degradation associated with embedded sensors (e.g., optical fibers) are eliminated. Concrete containing short electrically conducting microfibers, preferably carbon fibers, in an amount as low as 0.2 vol.% has been shown to be self-monitoring. The DC volume electrical resistivity of the concrete changes reversibly upon reversible strain, such that the fractional change in electrical resistance per unit strain (i.e., the gage factor) reaches 500 (extraordinarily high compared to conventional strain gages). The effect has been observed in cement paste, mortar as well as concrete, under tension, compression and flexure, though the effect is more pronounced in cement paste and mortar than in concrete. The reversible electromechanical effect stems from the reversible increase in the contact electrical resistivity between fiber and matrix upon slight opening (<1 μm) of the crack which the fiber bridges, and the consequent reversible increase in the volume electrical resistivity of the cement-matrix composite. Damage causes the volume electrical resistivity to change irreversibly (1–5).

Although the curing age has significant effect on the mechanical properties of concrete, it has relatively little effect on the DC volume electrical resistivity. For example, mortar containing latex and 0.53 vol.% short carbon fibers exhibit resistivity 1.20×10^3, 1.23×10^3,

1.33×10^3 and 1.41×10^3 Ω.cm at 1, 7, 14 and 28 days respectively (6). On the other hand, the bond strength between steel fiber and cement paste decreases with increasing curing age from 7 to 28 days, while the contact electrical resistivity increases (7). Both bond strength decrease and contact resistivity increase are due to the increase in the fiber-matrix interfacial void content resulting from the drying shrinkage of the cement paste (7). As the self-monitoring ability of carbon fiber reinforced concrete stems from fiber pull-out and the accompanying change in the contact resistivity between fiber and matrix, the effect of the curing age on the bond strength and contact resistivity suggests that the curing age probably affects the self-monitoring character. Indeed, this paper reports that the curing age affects the self-monitoring character in ways that are consistent with the effect of curing age on the bond strength and with the effect of curing age on the mechanical behavior.

Experimental Methods

The carbon fibers were isotropic pitch based and unsized, as obtained from Ashland Petroleum Co. (Ashland, Kentucky). The fiber diameter was 10 μm. The nominal fiber length was 5 mm. Fibers in the amount of 0.5% by weight of cement (corresponding to 0.24 vol.% of mortar) were used. Cement paste made from Portland cement (Type I) from Lafarge Corp. (Southfield, MI) was used for the cementitious material. The water/cement ratio was 0.35. The aggregate used was natural sand, the particle size analysis of which is shown in Fig. 1 of Ref. 1. The sand/cement ratio was 1.0. No large aggregate was used. The water reducing agent used in the amount of 3% by weight of cement was TAMOL SN (Rohm and Haas Co., Philadelphia, PA), which contained 93–96% sodium salt of a condensed naphthalenesulfonic acid. Methylcellulose and silica fume were added to help disperse the fibers. Silica fume (microsilica EMS-965, Elkem Materials Inc., Pittsburgh, PA) was used in the amount of 15% by weight of cement. Methylcellulose (Methocel A15-LV, Dow Chemical Corporation, Midland, MI) in the amount of 0.4% by weight of cement was used together with a defoamer (Colloids 1010, Colloids, Inc., Marietta, GA) in the amount of 0.13 vol.%.

Methylcellulose was dissolved in water and then fibers and defoamer were added and stirred by hand for about 2 min. Then this mixture, cement, sand, water, water reducing agent and silica fume were mixed in a Hobart mixer for 5 min. The mixer had a flat beater. The slump was 130 mm. After pouring the mix into oiled molds, a vibrator was used to decrease the amount of air bubbles. The specimens were demolded after 1 d and then allowed to cure at room temperature in air for 7, 14 or 28 d.

Simultaneous to mechanical testing, DC electrical resistance measurements were made. For compressive testing according to ASTM C109-80, specimens were prepared by using a $2 \times 2 \times 2$ in. ($5.1 \times 5.1 \times 5.1$ cm) mold. The strain was measured by the crosshead displacement, while the fractional change in electrical resistance along the stress axis was measured using the four-probe method. The electrical contacts were made by silver paint. Although the spacing between the contact decreased upon compressive deformation, the increase was so small that the measured resistance remained essentially proportional to the resistivity. In addition to static loading to failure, testing was performed under cyclic loading (compressive) within the elastic regime. A hydraulic mechanical testing system (MTS Model 810) was used.

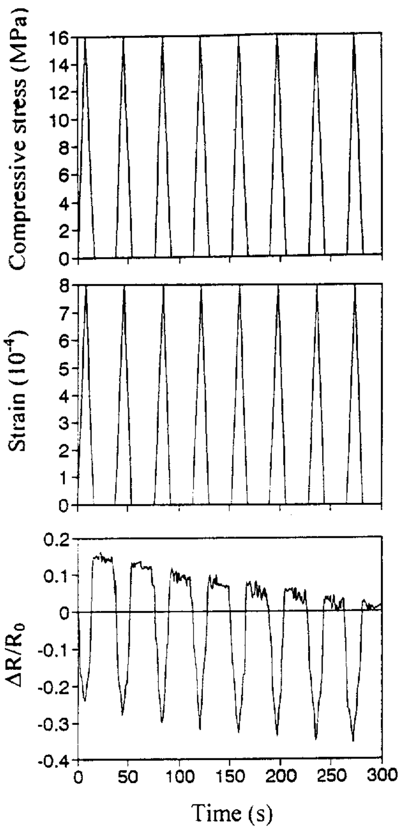

FIG. 1.
$\Delta R/R_0$, strain and stress during first cyclic compressive loading of mortar at 28 days of curing.

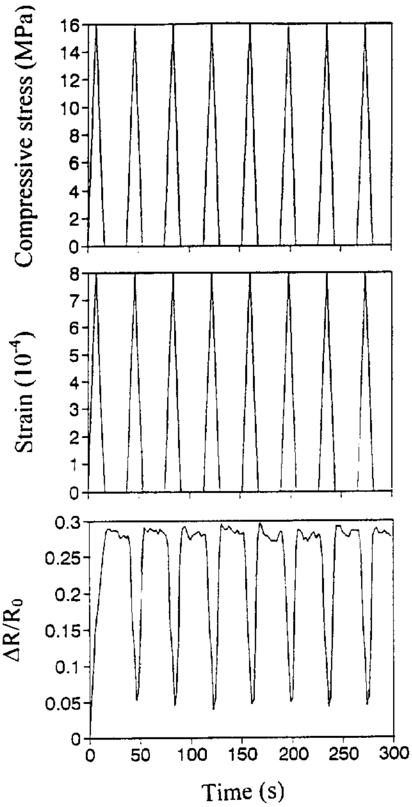

FIG. 2.
$\Delta R/R_0$, strain and stress during first cyclic compressive loading of mortar at 7 days of curing.

Results and Discussion

Figure 1 gives the fractional DC resistance increase ($\Delta R/R_0$) during first cyclic compressive loading of mortar with 0.24 vol.% carbon fibers at a stress amplitude of 16 MPa, or a strain amplitude of 8×10^{-4}, which was within the elastic regime at 28 days of curing. (The compressive strength was 45 MPa). The resistance was in the stress direction. Both stress and strain returned to zero at the end of each cycle. The $\Delta R/R_0$ decreased during compressive loading in each cycle and increased during unloading in each cycle. This is due to fiber push-in during loading and fiber pull-out during unloading, as explained in Ref. 1–4. At the end of the first cycle, $\Delta R/R_0$ was positive rather than zero. This resistance increase is attributed to damage of the fiber-cement interface due to the fiber push-in and pull-out. As cycling progressed, both the maximum $\Delta R/R_0$ and minimum $\Delta R/R_0$ in a cycle decreased. This is attributed to damage of the cement matrix separating adjacent fibers at their junction; this damage increased the chance for adjacent fibers to touch each other, thereby decreasing

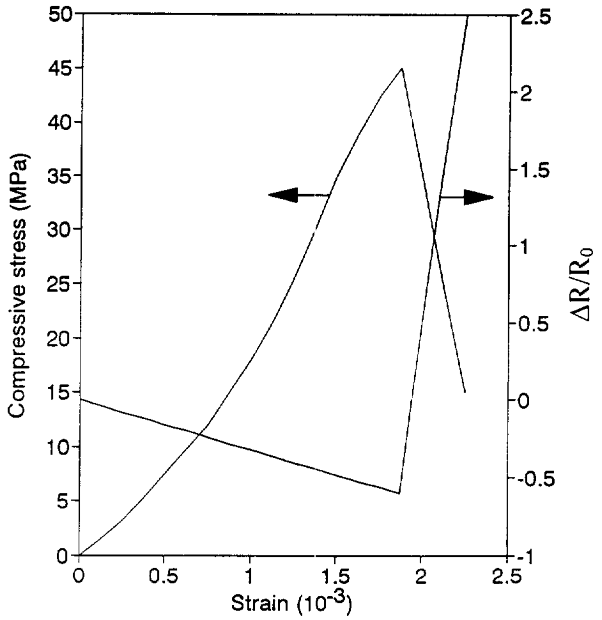

FIG. 3.
$\Delta R/R_0$ versus strain and stress versus strain during first static compression up to failure of mortar at 28 days of curing.

the resistivity. This decrease from cycle to cycle persisted for the first ~150 cycles, after which the maximum and minimum $\Delta R/R_0$ did not change with cycling.

At 28 days of curing (Fig. 1), since the amplitude of resistance variation in a cycle is 0.4 and the strain amplitude is 8×10^{-4}, the gage factor is 0.4 divided by 8×10^{-4}, or 500. At 7 days of curing (Fig. 2), the gage factor is 375. These exceptionally large values of the gage factor means that the mortar is an extremely sensitive strain gage. The gage factor of a conventional resistive strain gage is around 2.

Figure 3 shows $\Delta R/R_0$ versus strain and stress versus strain during first static compression up to failure of mortar with 0.24 vol.% carbon fibers at 28 days of curing. The resistance decreased monotonically upon loading up to failure.

Results similar to Figs. 1 and 3 were obtained at 14 days of curing, except that the decrease in maximum $\Delta R/R_0$ and minimum $\Delta R/R_0$ from cycle to cycle was less pronounced. However, at 7 days of curing, the resistance increased monotonically upon first static compression up to failure (Fig. 4). Consistent with the static compression result of Fig. 4 is the cyclic compression result of Fig. 2. During the first cycle, the resistance increased upon loading, increased further upon subsequent unloading (due to fiber pull-out), decreased upon loading in the second cycle (due to fiber push-in), and increased upon unloading in the second cycle (due to fiber pull-out); the behavior was similar in second and subsequent cycles, but was different in the first cycle. The behavior at 7 days of curing is attributed to the relatively strong fiber-matrix bonding at 7 days and the consequent need to weaken the bond prior to fiber pull-out. Bond weakening is accompanied by irreversible increase in the contact electrical resistivity (8), which results in the irreversible resistance increase observed in the first cycle (3). This irreversible resistance increase was larger in magnitude when the stress

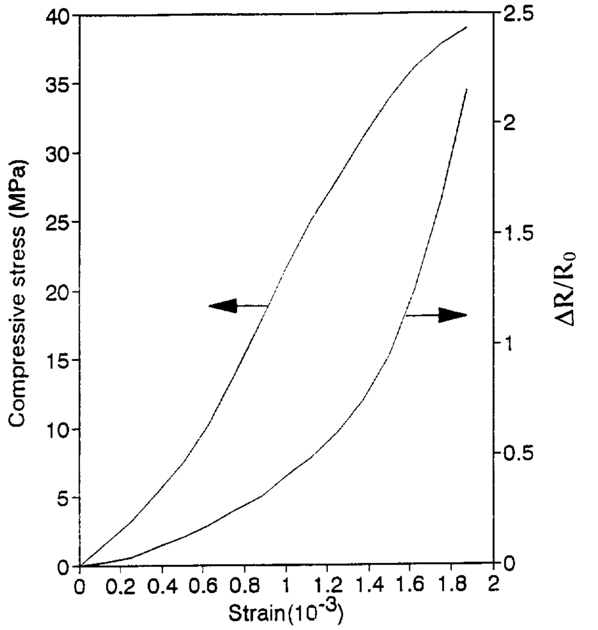

FIG. 4.
$\Delta R/R_0$ versus strain and stress versus strain during first static compression up to failure of mortar at 7 days of curing.

amplitude increased (3). The fiber-cement bond strength decreased with increasing curing time from 7 to 14 days, while the contact resistivity increased, as shown for stainless steel fiber (5). At 14 or 28 days of curing, the bond strength was weak to start with, so bond weakening was not necessary prior to fiber pull-out. The monotonic resistance increase up to failure at 7 days of curing is due to the bond weakening at least in the low stress regime; in the high stress regime, it is probably due to damage. Note from Fig. 2 that the maximum $\Delta R/R_0$ and minimum $\Delta R/R_0$ did not change from cycle to cycle, in contrast to the decrease in these quantities at 14 and 28 days of curing. This effect of the curing age is attributed to the decrease in compliance with increasing curing age and the resulting increased tendency for repeated fiber pull-out and push-in during cyclic loading to cause damage to the cement matrix separating adjacent fibers. The effect of the curing age is not due to the effect of the moisture content, as the humidity during curing had essentially no effect on the electromechanical behavior (3) and the volume electrical resistivity of the mortar increased negligibly with curing age (6).

During the few cycles before fatigue failure at 28 days of curing, the resistance did not increase irreversibly and significantly, indicating that the mortar is poor in its ability to monitor damage. This poor damage sensitivity is also reflected by the absence of a resistance increase prior to static failure at 28 days (Fig. 3).

Conclusion

The self-monitoring behavior of carbon fiber reinforced mortar was found to be affected by curing age from 7 to 28 days. The electrical resistance increased monotonically with increasing compressive strain during first loading at 7 days, but at 14 and 28 days it decreased monotonically; this effect of the curing age is due to the weakening of the fiber-cement interface as curing progresses. The resistance decreased slightly and irreversibly at the end of each cycle as cycling progressed at 14 and 28 days, but not at 7 days; this effect of the curing age is due to the decreasing compliance of the cement matrix as curing progresses.

Acknowledgement

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