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IMPROVING THE STRAIN-SENSING ABILITY OF CARBON FIBER-REINFORCED CEMENT BY OZONE TREATMENT OF THE FIBERS

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ABSTRACT

The strain-sensing ability of carbon fiber-reinforced cement was improved by ozone treatment of the fibers. The improvement pertains to better repeatability upon repeated loading (electrical resistance not decreasing from cycle to cycle) and increased gage factor (fractional change in electrical resistance per unit strain). © *1998 Elsevier Science Ltd*

Introduction

Short carbon fibers are used in concrete for increasing the tensile and flexural strengths, increasing the tensile ductility and flexural toughness, decreasing the drying shrinkage, and rendering the concrete the ability to sense its own strain (1–25). This work is focused on the strain-sensing ability, which is the most unique attribute of carbon fiber-reinforced concrete.

We have previously reported that increase of the curing age beyond 14 days causes the strain-sensing ability to be less repeatable, in that the electrical resistance decreases gradually from cycle to cycle during the first 120–350 loading cycles (24,26). This decrease is attributed to the low compliance beyond 14 days and the consequent damage of the cement matrix at the junction of adjacent fibers as cycling occurs. This damage increases the chance for adjacent fibers to touch one another, thus decreasing the resistivity of the composite. If this explanation is correct, an improvement of the mechanical properties (particularly the ductility) of the composite would diminish this undesirable effect. We have recently reported that the tensile strength, modulus, and ductility of carbon fiber-reinforced cement paste are all increased by ozone treatment of the fiber (27), because the ozone treatment increases the fiber-matrix bond strength (28). This result then motivated us to investigate the effect of ozone treatment of the fiber on the strain-sensing ability of carbon fiber-reinforced cement. In this paper, we report that ozone treatment of the fiber completely removes the undesirable effect involving the resistance decreasing from cycle to cycle, thus improving the repeatability of the sensing ability.

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TABLE 1
Properties of carbon fibers.

Filament diameter	15 ± 3 μm
Tensile strength	690 MPa
Tensile modulus	48 GPa
Elongation at break	1.4%
Electrical resistivity	3.0×10^{-3} Ω·cm
Specific gravity	1.6 g cm^{-3}
Carbon content	98 wt.%

Experimental Methods

The carbon fibers were isotropic pitch-based and unsized, as obtained from Ashland Petroleum Co. (Ashland, Kentucky). The fiber properties are shown in Table 1. As-received and ozone treated fibers were used. The ozone treatment involved exposure of the fibers to O_3 gas (0.6 vol.%, in O_2) at 160°C for 5 min. Prior to O_3 exposure, the fibers had been dried at 110°C in air for 1 h.

Cement paste made from Portland cement (Type 1) from Lafarge Corp. (Southfield, MI) was used for the cementitious material. The paste used contained fibers, methylcellulose in the amount of 0.4% by weight of cement, and silica fume (#965, Elkem Materials Inc., Pittsburgh, PA) in the amount of 15% by weight of cement (together with water reducing agent in the amount of 3% by weight of cement, and with water-cement ratio = 0.35). Fibers were in the amount of 0.5% by weight of cement (or 0.51 vol.%). The water reducing agent used was TAMOL SN (Rohm and Haas Co., Philadelphia, PA), which contained 93–96% sodium salt of a condensed naphthalenesulfonic acid. The methylcellulose used was Dow Chemical, Midland, MI, Methocel A15-LV. The defoamer (Colloids Inc., Marietta, GA, 1010) used whenever methylcellulose was used was in the amount of 0.13 vol.%.

A Hobart mixer with a flat beater was used for mixing. Methylcellulose was dissolved in water and then the defoamer was added and stirred by hand for about 2 min. Then this mixture, cement, water, water reducing agent, and silica fume were mixed in the mixer for 5 min. After pouring the mix into oiled molds, a vibrator was used to decrease the amount of air bubbles. The specimens were demolded after 1 day and then allowed to cure at room temperature in air (40% relative humidity) for 28 days.

Dog-bone shaped specimens of the dimensions shown in Figure 1 of Ref. 27 were used for testing their tensile strain-sensing ability under cyclic loading within the elastic regime. The specimens were prepared by using molds of the same shape and size. Tensile testing was performed using a screw-type mechanical testing system (Sintech 2/D). The displacement rate was 1.27 mm/min. The tensile strain was measured by a strain gage. Six specimens of each composition were tested. The electrical contacts were made by silver paint. Although the spacing between the contacts changed upon deformation, the change was so small that the measured resistance remained essentially proportional to the resistivity.

Results and Discussion

Figure 1 gives the fractional DC resistance increase ($\Delta R/R_o$) during first tensile loading of cement paste with 0.51 vol.% as-received carbon fibers at a stress amplitude of 0.9 MPa, or

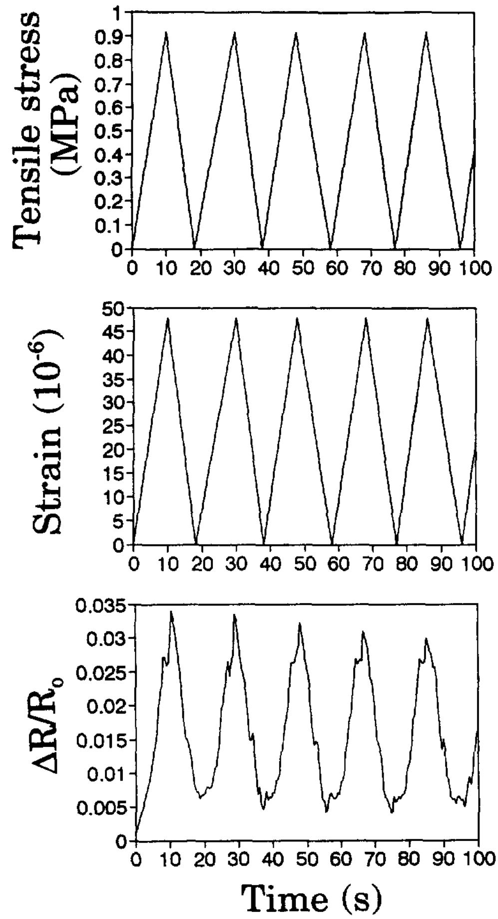

FIG. 1.
$\Delta R/R_o$, strain and stress during cyclic tensile loading of cement paste with as-received fibers at 28 days of curing.

a strain amplitude of 4.8×10^{-5}, which was within the elastic regime, at 28 days of curing. (The tensile strength was 1.97 MPa (27).) The resistance was in the stress direction. Both stress and strain returned to zero at the end of each cycle. The $\Delta R/R_o$ increased during tensile loading in each cycle and decreased during unloading in each cycle, with a gage factor (fractional change in resistance per unit strain) of 625. This is due to fiber pull-out during loading and fiber push-in during unloading, as explained in Ref. 20–23. At the end of the first cycle, $\Delta R/R_o$ was positive rather than zero. This resistance increase is attributed to damage of the fiber-cement interface due to the fiber pull-out and push-in. As cycling progressed, both the maximum $\Delta R/R_o$ and minimum $\Delta R/R_o$ 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 one another, thereby decreasing the resistivity.

Figure 2 shows results similar to Figure 1, but for ozone-treated fibers instead of as-

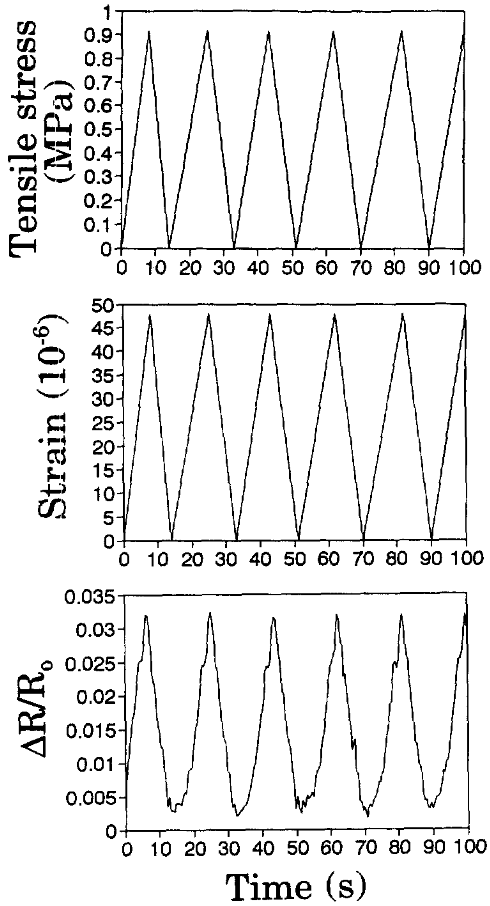

FIG. 2.

$\Delta R/R_o$, strain and stress during cyclic tensile loading of cement paste with ozone-treated fibers at 28 days of curing.

received fibers. The main difference between Figure 2 and Figure 1 is that the downward trend in $\Delta R/R_o$ in Figure 1 is absent in Figure 2. Although Figure 2 only shows a small number of cycles, repeated loading for many more cycles confirmed the absence of a downward trend in $\Delta R/R_o$ when ozone treated fibers were used. This is due to the superior mechanical properties of the cement paste with ozone-treated fibers compared to those of the cement paste with as-received fibers (27). The gage factor is 700 from Figure 2—higher than the value of 625 from Figure 1. Thus, ozone treatment of the fibers resulted in improvement of the strain-sensing ability in two ways, i.e., increase in gage factor and better repeatability upon repeated loading. Similar improvement of the strain-sensing ability in both these ways was observed under cylic compression.

The improved repeatability obtained by ozone treatment is similar to that obtained by decreasing the curing age to 7 days (26), as both ozone treatment (28) and curing age decrease (29) increased the fiber-matrix bond strength.

The gage factor of a conventional resistive strain gage is around 2. The gage factors reported here are exceptionally high.

Conclusion

Ozone treatment of carbon fibers was found to improve the strain-sensing ability of carbon fiber-reinforced cement. The main improvement relates to the better repeatability, in that the electrical resistance did not decrease from cycle to cycle during cyclic loading. The other improvement pertains to the increased gage factor. The improved repeatability is attributed to the improved mechanical properties of the composite due to the ozone treatment of the fibers.

Acknowledgment

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