Pergamon

Cement and Concrete Research 31 (2001) 665–667

CEMENT AND CONCRETE RESEARCH

Communication

Carbon fiber-reinforced cement as a strain-sensing coating

Sihai Wen, D.D.L. Chung*

Composite Material Research Laboratory, Department of Mechanical and Aerospace Engineering, State University of New York at Buffalo, Room 608, Furnas Hall, Buffalo, NY 14260-4400, USA

Received 20 September 2000; accepted 1 February 2001

Abstract

Cement paste containing short carbon fibers was found to be an effective strain-sensing coating. The coating (with fibers) was on either the tension side or the compression side of a cement specimen (without fiber) under flexure. The resistance was measured with surface electrical contacts on either side. The resistance increased reversibly on the tension side upon loading and decreased reversibly on the compression side upon loading. The behavior was similar whether the strain-sensing coating contained silica fume or latex. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Strain effect; Electrical properties; Fiber reinforcement; Silica fume; Sensing

1. Introduction

The sensing of strain is relevant to smart structures, structural vibration control, traffic monitoring, weighing, etc. Strain sensing is commonly attained by the use of strain gages attached to the structure. Strain gages are commonly of the resistive type. In other words, the resistance (not resistivity) changes with strain, thereby serving as an indicator of strain. Although the gage factor (fractional change in resistance per unit strain) is only 2 for a resistive strain gage, the signal-to-noise ratio is high and the strain gage is effective. However, strain gages are expensive compared to the structural material and they suffer from the tendency to be detached during use. Alternatively, optical fibers can be embedded in a structure to provide strain sensing, but the embedding means that the optical fibers are intrusive, and, as a consequence, the mechanical properties of the structure may be diminished.

Carbon fiber (short)-reinforced cement can function as a piezoresistive strain sensor [1–7]. In other words, the resistivity changes with strain. The gage factor is as high as 700. Upon tension (whether uniaxial tension or the case of the tension side of a flexural specimen), the resistivity increases reversibly; upon compression (whether uniaxial compression or the case of the compression side of a flexural specimen), the resistivity decreases reversibly. The piezoresistivity is due to the slight pull-out of a crack-bridging carbon fiber upon tension (crack opening) and the slight push-in of a carbon fiber upon compression (crack closing). The resistance can be measured by having electrical contacts (preferably four for the four-probe method) at equipotential planes perpendicular to the direction of resistance measurement, as achieved by applying each contact around the entire perimeter of a tensile or compressive specimen. In the case of a flexural specimen, the resistance on the tension side and on the compression side can be separately measured by using surface electrical contacts instead of perimetric contacts [7]. In other words, contacts applied on the tension surface are used for sensing the strain on the tension surface, whereas contacts applied on the compression surface are used for sensing the strain on the compression surface.

Whether the loading is tensile, compressive, or flexural, the sensing material (i.e., carbon fiber-reinforced cement) is in bulk form rather than coating form in all the previous work. Because most structures are not built with carbon fiber-reinforced concrete but with conventional concrete, the applicability of carbon fiber cement as a strain sensor can be widened by using the carbon fiber cement as a strain-sensing coating on conventional concrete. Therefore, this paper is aimed at extending the previous work by investigating the strain sensing ability of carbon fiber-reinforced

* Corresponding author. Tel.: +1-716-645-2593 ext. 2243; fax: +1-716-645-3875.

E-mail address: ddlchung@acsu.buffalo.edu (D.D.L. Chung).

0008-8846/01/$ – see front matter
PII: S0008-8846(01)00474-4

cement in coating form. In this work, the substrate is plain cement (no fiber) and the substrate coated on one side with carbon fiber-reinforced cement is subjected to flexure while the strain in the coating is sensed by using surface contacts on the coating.

Previous work involving self-sensing carbon fiber mortar in bulk form under flexure was performed at 7 days of curing [7]. The piezoresistive behavior of this mortar is very different at 7 and 28 days of curing [5]. A curing age of 28 days is more important technologically than that of 7 days. Therefore, this work is focused on the behavior of the coating form at 28 days of curing.

2. Experimental methods

The carbon fibers were isotropic pitch based, unsized, and of length ~5 mm, as obtained from Ashland Petroleum (Ashland, KY). They were used in the amount of 0.5% by mass of cement (0.5 vol.%). The fiber properties are shown in Table 1. Ozone treatment of the fibers [8] was performed to improve the fiber-matrix bond. No aggregate (fine or coarse) was used.

The cement used was portland cement (Type I) from Lafarge (Southfield, MI). Either silica fume (together with methylcellulose, a defoamer, and a water reducing agent [WR]) or latex (together with an antifoaming agent) was used along with the fibers, partly to help the fiber dispersion. The silica fume (Elkem Materials, Pittsburgh, PA, EMS 965) was used in the amount of 15% by mass of cement. The methylcellulose, used in the amount of 0.4% by mass of cement, was Dow Chemical, Midland, MI, Methocel A15-LV. The defoamer (Colloids, Marietta, GA, 1010) was in the amount of 0.13 vol.%. The WR, used in the amount of 1.0% by weight of cement when silica fume was also used, was TAMOL SN (Rohm and Haas, Philadelphia, PA), which contained 93–96% sodium salt of a condensed naphthalene sulfonic acid. The latex, used in the amount of 20% by mass of cement, was a styrene butadiene polymer (Dow Chemical, 460NA) with the polymer making up about 48% of the dispersion and with the styrene and butadiene having a mass ratio of 66:34. The latex was used along with an antifoaming agent (Dow Corning, #2410, 0.5% by mass of latex). The water/cement ratio was 0.35 for plain cement paste, 0.40 for the paste with silica fume, and 0.23 for the paste with latex. The plain cement paste (just cement + water) was used as the substrate, whereas the other two pastes contained fibers and were used as coatings on substrates.

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.%

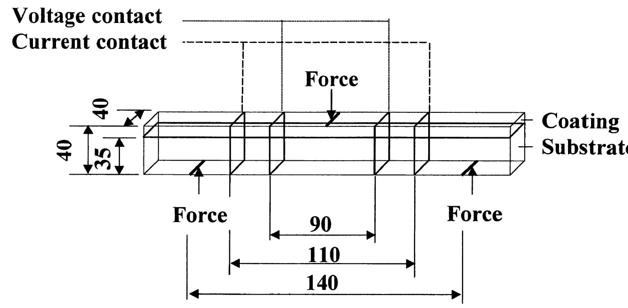

Fig. 1. Specimen configuration. All dimensions are in millimeters. The configuration shown is for the case of the coating at the compression side of the flexural specimen.

A rotary mixer with a flat beater was used for mixing. Methylcellulose (if applicable) was dissolved in water and then the defoamer was added and stirred by hand for about 2 min. Latex (if applicable) was mixed with the antifoam by hand for about 1 min. Then the methylcellulose mixture (if applicable), the latex mixture (if applicable), cement, water, silica fume (if applicable), WR (if applicable), and fibers (if applicable) were mixed in the mixer for 5 min. The substrate mix was poured into a mold about 10 min before the coating mix was poured on top of the substrate in the mold. After pouring into molds, an external vibrator was used to facilitate compaction and decrease the amount of air bubbles. The specimens were demolded after 24 h and then cured in air at room temperature and a relative humidity of 100% for 28 days.

The specimen configuration for flexural testing (three-point bending at a span of 140 mm) is illustrated in Fig. 1. The specimen was a rectangular bar of size 160 × 40 × 40 mm. It consisted of the substrate (35 mm thick) and the coating (5 mm thick) on one of the two 160 × 40-mm sides.

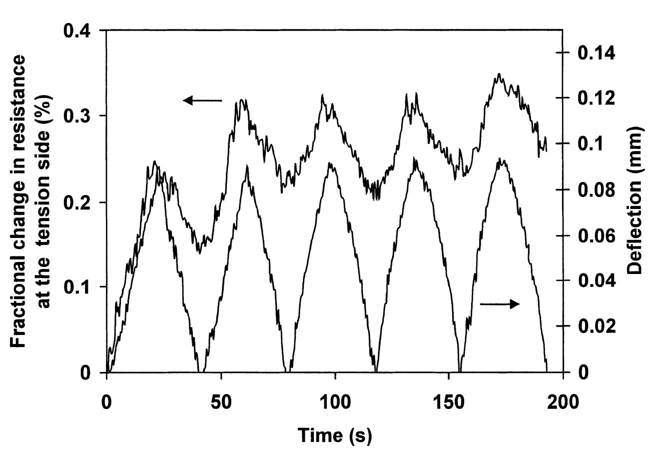

Fig. 2. Fractional change in resistance and deflection during cyclic flexure for the case of the strain-sensing coating being carbon-fiber latex cement paste at the tension side.

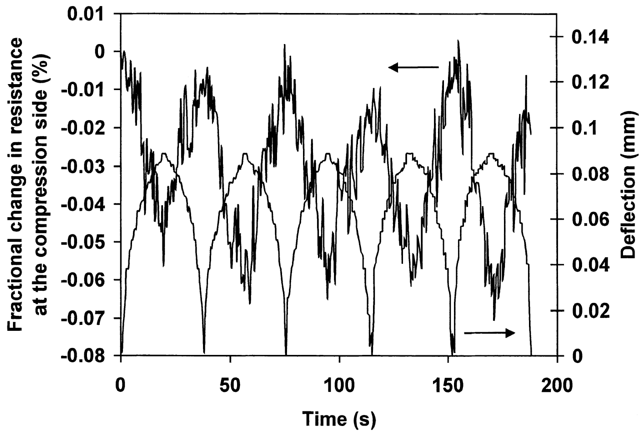

Fig. 3. Fractional change in resistance and deflection during cyclic flexure for the case of the strain-sensing coating being carbon-fiber latex cement paste at the compression side.

Electrical contacts in the form of silver paint in conjunction with copper wire were applied on the coating surface. The silver paint was only applied to the coating surface, while the copper wire wrapped perimetrically around the specimen was insulated from the specimen on all sides except the side with the coating. The outer two contacts (for passing current) were 110 mm apart. The inner two contacts (for voltage measurement) were 90 mm apart. A Keithley 2001 multimeter was used for DC resistance measurement using the four-probe method.

For each of the two types of cement coating, three-point bending was conducted on six specimens with the coating on the tension side, and on another six specimens with the coating on the compression side. Cyclic loading was provided by a hydraulic mechanical testing system (MTS 810), which also provided measurement of the displacement during flexure.

3. Results and discussion

Figs. 2 and 3 give the fractional change in resistance on the tension and compression sides, respectively, for the case of the coating containing carbon fibers and latex. The resistance on the tension side increased reversibly upon flexure in every cycle, except that the resistance was irreversibly increased after the first cycle, probably due to minor damage (Fig. 2). The resistance on the compression side decreased reversibly upon flexure in every cycle (Fig. 3). These reversible effects are consistent with the behavior of the bulk form of this material (28 days of curing) under tension and under compression [1–5]. Results similar to Figs. 2 and 3, but not shown here, were obtained for the coating containing carbon fibers and silica fume. The magnitude of the fractional change in resistance was higher at the tension side than that at the compression side for both types of coating.

4. Conclusion

Carbon fiber-reinforced cement was found to be effective as a strain-sensing coating, as shown for the coating on a cement substrate under flexure, whether the coating was on the tension side or the compression side of the flexural specimen. The resistance measured with surface electrical contacts on the strain-sensing coating increased reversibly at the tension side upon loading and decreased reversibly at the compression side upon loading.

Acknowledgments

This work was supported by National Science Foundation, USA.

References

[1] X. Fu, W. Lu, D.D.L. Chung, Ozone treatment of carbon fiber for reinforcing cement, Carbon 36 (9) (1998) 1337–1345.
[2] D.D.L. Chung, Self-monitoring structural materials, Mater. Sci. Eng. Rev. 22 (2) (1998) 57–78.
[3] X. Wang, X. Fu, D.D.L. Chung, Strain sensing using carbon fiber, J. Mater. Res. 14 (3) (1999) 790–802.
[4] X. Fu, W. Lu, D.D.L. Chung, Improving the strain sensing ability of carbon fiber reinforced cement by ozone treatment of the fibers, Cem. Concr. Res. 28 (2) (1998) 183–187.
[5] X. Fu, D.D.L. Chung, Effect of curing age on the self-monitoring behavior of carbon fiber reinforced mortar, Cem. Concr. Res. 27 (9) (1997) 1313–1318.
[6] X. Fu, E. Ma, D.D.L. Chung, W.A. Anderson, Self-monitoring in carbon fiber reinforced mortar by reactance measurement, Cem. Concr. Res. 27 (6) (1997) 845–852.
[7] P.-W. Chen, D.D.L. Chung, Concrete as a new strain/stress sensor, Composites, Part B 27B (1996) 11–23.
[8] X. Fu, W. Lu, D.D.L. Chung, Ozone treatment of carbon fiber for reinforcing cement, Carbon 36 (9) (1998) 1337–1345.