Pergamon

Cement and Concrete Research, Vol. 27, No. 6, pp. 845-852, 1997

0008-8846/97 $17.00 + .00

PII S0008-8846(97)00071-9

SELF-MONITORING IN CARBON FIBER REINFORCED MORTAR BY REACTANCE MEASUREMENT

Xuli Fu[*+], Erming Ma[+], D.D.L. Chung[*+] and W.A. Anderson[+]
[*]Composite Materials Research Laboratory
State University of New York at Buffalo
Buffalo, NY 14260-4400
[+]Center for Electronic and Electro-Optic Materials
State University of New York at Buffalo
Buffalo, NY 14260-1900

(Communicated by D.M. Roy)
(Received January 30, 1997; in final form April 7, 1997)

ABSTRACT

Self-monitoring in carbon fiber reinforced mortar was demonstrated by AC impedance measurement. The reactance X_s was found to be a more sensitive indicator of strain than the resistance R_s. The fractional increase in X_s was 38 at compressive failure, while the fractional increase in R_s was 23, for mortar with methylcellulose, silica fume and fibers (0.35 vol.%). © *1997 Elsevier Science Ltd*

Introduction

Concrete, reinforced with short carbon fibers, is attractive not only for its low drying shrinkage, high flexural strength, high tensile strength, high flexural toughness and high tensile ductility (1-19), but also for its ability to sense its own strain and damage (20-24). The self-monitoring ability is associated with the change in DC electrical resistivity upon strain or damage. Reversible strain in the elastic regime causes the resistivity to change reversibly, while damage causes the resistivity to increase irreversibly. The strain sensing ability stems from the slight (< 1 μm) pull-out of the crack-bridging conducting carbon fiber upon deformation and the consequent increase in the resistivity. The damage sensing ability stems from fiber breakage and crack propagation, both of which cause the resistivity to increase irreversibly. Without the fibers, crack opening is not restrained and the resistivity increases only at fracture.

Under AC rather than DC condition, the impedance Z consists of the resistance R_s (real part of Z) and the reactance X_s (imaginary part of Z), i.e., $Z = R_s + iX_s$, where the subscript s refers to a configuration in which the sample is in series connection with the measuring circuit. Although previous reports have been made concerning the effects of frequency, curing time and admixtures on the impedance of cement-based materials (4,25-34), the effect of deformation on the impedance has not been previously addressed. This paper extends the previous work on self-monitoring in carbon fiber reinforced concrete from DC to AC, because AC provides both resistance and reactance information and AC is relevant to data acquisition by wireless methods. We thus found that the reactance is a more sensitive indicator than the resistance, as the fractional change in reactance exceeds the fractional change in resistance upon deformation.

Experimental Methods

The carbon fibers used were short (nominally 5 mm in length), unsized and made from isotropic pitch. Their properties are shown in Table 1. They were provided under the trade name Carboflex by Ashland Petroleum Co., Ashland, Kentucky. The dispersion of the carbon fibers requires the use of additives, such as latex, methylcellulose and/or silica fume.

The cement used was Portland cement (Type I) from Lafarge Corp. (Southfield, MI). The sand used was natural sand (100% passing 2.36 mm sieve, 99.9% SiO_2. The particle size analysis of the sand is shown in Fig. 1 of Ref. 20. The sand/cement ratio was 1. Table 2 describes the four types of mortar studied. They were (i) plain mortar, (ii) mortar with methylcellulose and silica fume, (iii) mortar with fibers, methylcellulose and silica fume, and (iv) mortar with fibers and latex. Carbon fibers in the amount of 0.35 vol.% (corresponding to fibers in the amount of 0.5% by weight of cement) were used. Both the water/cement ratio and the water-reducing agent (WR)/cement ratio were chosen to maintain the slump at 160-170 mm. The required water/cement ratio and the WR/cement ratio varied with the admixture used. The water reducing agent powder used was TAMOL SN (Rohm and Haas), which contained 93-96% sodium salt of a condensed naphthalene sulfonic acid. The latex (Dow Chemical, 460 NA) was a styrene butadiene copolymer used in the amount of 20% of the weight of the cement. An antifoam agent (Dow Corning 2410) in the amount of 0.5% of the weight of the latex was used whenever latex was used. Methylcellulose (Dow Chemical, Methocel A15-LV) in the amount of 0.4% of the cement weight was used. A defoamer (Colloids 1010) in the amount of 0.13 vol.% was used whenever methylcellulose was used. The silica fume (Elkem Materials, EMS 960) was used in the amount of 15% by weight of cement.

A Hobart mixer with a flat beater was used for mixing. For the case of mortar containing latex, the latex, antifoam agent and carbon fibers first were mixed by hand for about 1 min. This mixture, sand, cement, water and the water reducing agent were mixed in the mixer for 5 min. In the case of mortar containing methylcellulose, the methylcellulose was dissolved in water and then the carbon fibers (if applicable) and the defoamer were added and stirred by hand for about 2 min. Then this mixture, sand, cement, water, the water reducing agent and silica fume were successively added and then mixed in the mixer for 5 min. After pouring the mix into oiled molds, a vibrator was used to facilitate compaction and decrease the amount of air

TABLE 1

Properties of Carbon Fibers

Filament diameter	10 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.%

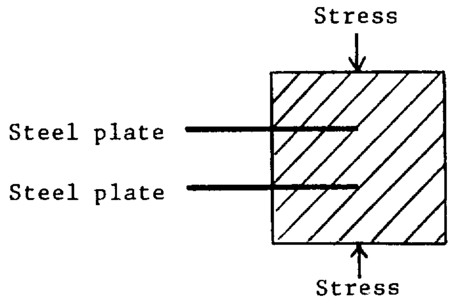

FIG. 1.
Specimen and electrical contact configuration for reactance measurement during compression.

bubbles. The specimens were demolded after 1 day and then allowed to cure at room temperature (25°C) and room humidity (30% relative humidity) in air for either 7 or 28 days.

Simultaneous to mechanical testing, AC impedance measurement was made using a QuadTech 7600 RLC meter (10 Hz-2 MHz). Unless stated otherwise, the frequency was 10 Hz. For compressive testing according to ASTM C109-80, specimens were prepared by using a 51 × 51 × 51 mm mold. The strain was measured by the crosshead displacement, while the fractional change in impedance along the stress axis was measured using the two-probe method. The two electrical contacts were made by embedding two stainless steel plates of thickness 0.4 mm and width 12 mm into the mortar by a depth of 25 mm, such that the plane of the plates is perpendicular to the stress axis, as illustrated in Fig. 1. The steel plates were of size 51 × 12 × 0.4 mm. They were parallel to one another and separated by a distance of 25 mm, such that the upper plate was 13 mm from the top surface of the mortar cube and the lower plate was 13 mm from the bottom surface of the cube. A hydraulic mechanical testing system (MTS Model 810) was used.

TABLE 2

Mix Proportions (by Weight Unless Indicated Otherwise) of Various Types of Mortar

Sample	Fiber vol.%	Water/cement ratio	Latex/ cement ratio	M/ cement (%)	SF/ cement ratio	WR/ cement (%)
Plain mortar	0	0.475	0	0	0	0.5
Mortar with M and SF	0	0.475	0	0.4	0.15	2
	0.35	0.475	0	0.4	0.15	2
Mortar with latex	0.35	0.23	0.2	0	0	1.5

Note: M = methylcellulose, SF = silica fume, WR = water reducing agent.

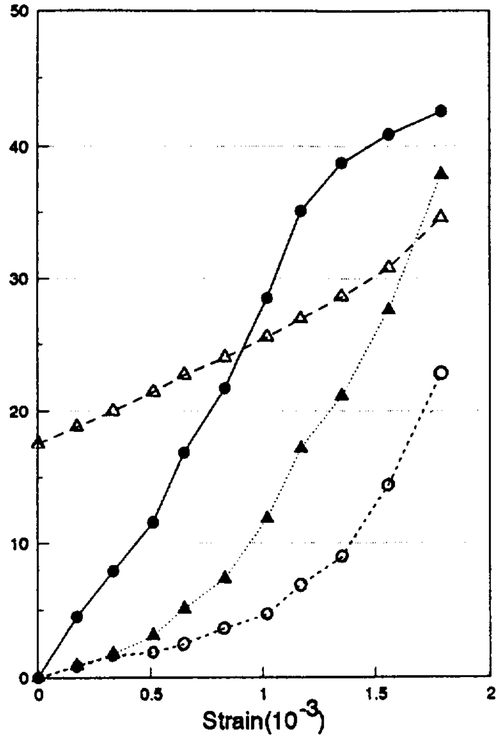

FIG. 2.
The compressive stress in MPa (solid circles), fractional increase in R_s (open circles), fractional increase in X_s (solid triangles) and phase angle θ in degrees (open triangles) during static compressive testing to failure of mortar with methylcellulose, silica fume and fibers at 7 days.

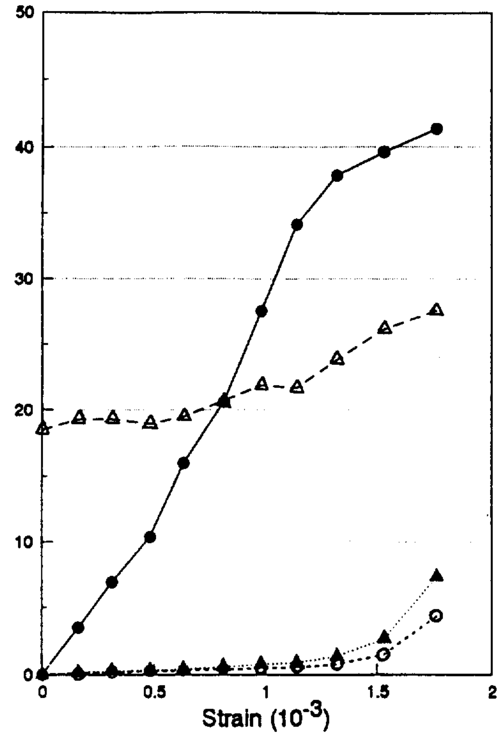

FIG. 3.
The compressive stress in MPa (solid circles), fractional increase in R_s (open circles), fractional increase in X_s (solid triangles) and phase angle θ in degrees (open triangles) during static compressive testing to failure of mortar with latex and fibers at 7 days.

Results and Discussion

Figures 2 and 3 show the stress, fractional increase in R_s, fractional increase in X_s, and phase angle θ of impedance Z during static compressive testing to failure of mortar with methylcellulose, silica fume and fibers and of mortar with latex and fibers, respectively. Both mortars were at 7 days of curing. For either mortar, as the stress/strain increased, θ, the fractional increase in R_s, as well as the fractional increase in X_s, increased, such that the fractional increase in X_s was larger than the fractional increase in R_s. Although both mortars are similar in their stress and strain at failure, the mortar with methylcellulose, silica fume and fibers (Fig. 2) exhibited much larger fractional increases in R_s and X_s than the mortar with latex and fibers (Fig. 3). This is consistent with the DC results, which showed that the fractional increase in DC resistance is much larger for the former mortar than the latter mortar (22,23). This difference is due to the higher degree of fiber dispersion in the former mortar (35).

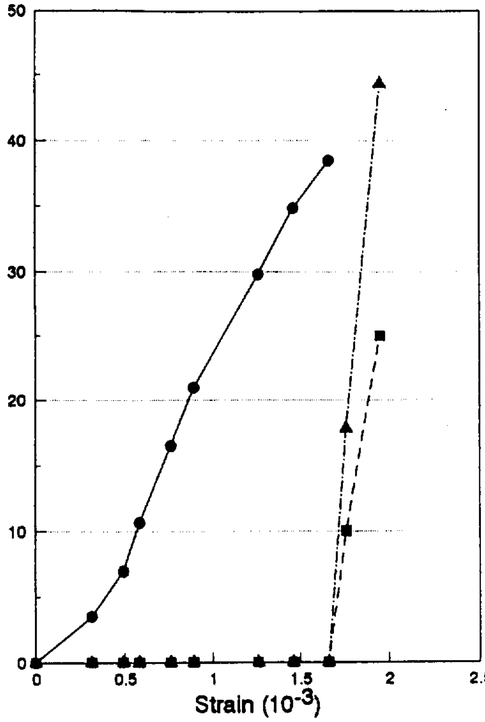

FIG. 4.
The compressive stress in MPa (circles), fractional increase in R_s (squares) and fractional increase in X_s (triangles) during static compressive testing to failure of plain mortar at 7 days.

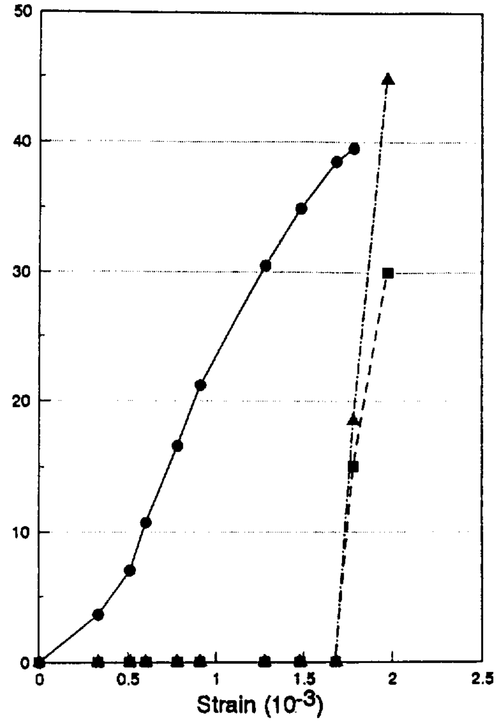

Fig. 5.
The compressive stress in MPa (circles), fractional increase in R_s (squares) and fractional increase in X_s (triangles) during static compressive testing to failure of mortar with methylcellulose and silica fume at 28 days.

Similar testing of plain mortar at 7 days (Fig. 4) and of mortar with methylcellulose and silica fume at 28 days (Fig. 5) showed that both R_s and X_s did not change until failure, at which both R_s and X_s increased abruptly. This negative result is consistent with a similar negative result obtained at DC for mortars without fibers (22,23). Hence, fibers are necessary in order for the mortar to serve as a strain sensor.

Figures 6 and 7 show R_s (upper curve) and X_s (lower curve) as functions of frequency (log scale) from 10 Hz to 2 MHz at a constant stress for mortar with methylcellulose, silica fume and fibers and for mortar with latex and fibers, respectively. The stress in Fig. 6 was the second highest stress level (each stress level shown by a solid circle) in Fig. 2; the stress in Fig. 7 was the second highest stress level in Fig. 3. For either mortar, R_s was larger than X_s at any frequency and both R_s and X_s decreased with increasing frequency. Similar results were obtained at other stress levels. The frequency dependence of R_s and X_s is consistent with that of Z in Ref. 4 for the case of cement paste with 1 vol.% carbon fibers at no load. This frequency dependence is due to various conduction mechanisms operating at various frequencies. The elucidation of the conduction mechanisms is beyond the scope of this paper.

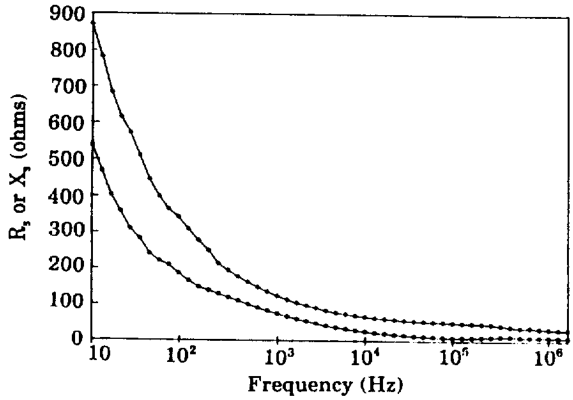

FIG. 6.

R_s (upper curve) and X_s (lower curve) as functions of frequency (log scale) from 10 Hz to 2 MHz at a constant stress, which is the second highest stress level in Fig. 2, for mortar with methylcellulose, silica fume and fibers.

Even though R_s is larger than X_s at the same frequency and stress (Figs. 5 and 6), the fractional increase in R_s is less than the fractional increase in X_s (relative to the values of R_s and X_s at no load) (Figs. 2 and 3). Thus, X_s is a more sensitive indicator of strain/stress than R_s. However, the difference in sensitivity is not huge. Since AC measurement requires more expensive electronics than DC measurement, DC measurement is recommended for practical use of carbon fiber mortar as a strain/stress sensor.

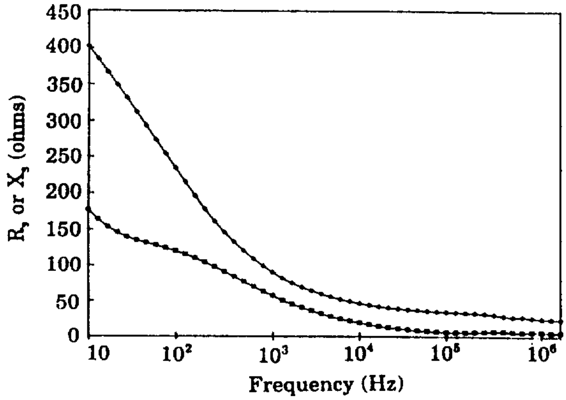

FIG. 7.

R_s (upper curve) and X_s (lower curve) as functions of frequency (log scale) from 10 Hz to 2 MHz at a constant stress, which is the second highest stress level in Fig. 3, for mortar with latex and fibers.

Conclusion

Self-monitoring in carbon fiber reinforced mortar was demonstrated by AC impedance measurement. The reactance X_s was found to be a more sensitive indicator of strain than the resistance R_s. The fractional increase in X_s was 38 at compressive failure, while the fractional increase in R_s was 23, for mortar with methylcellulose, silica fume and fibers (0.35 vol.%). At 7 days of curing, both fractional increase in reactance and fractional increase in resistance increased monotonically with strain up to failure, such that the former was larger than the latter at any strain. On the other hand, the resistance was larger than the reactance at any strain. Both resistance and reactance decreased with increasing frequency. Mortar with latex and fibers was a less sensitive strain sensor than mortar with methylcellulose, silica fume and fibers. Without fibers, mortars failed to function as strain sensors.

Acknowledgement

This work was supported in part by the National Science Foundation.

References

1. P. Chen and D.D.L. Chung, ACI Materials J. 93(2), 129 (1996).
2. P. Chen and D.D.L. Chung, Composites: Part B; 27B, 269 (1996).
3. X. Yang and D.D.L. Chung, Composites 23(6), 453 (1992).
4. N. Banthia, S. Djeridane and M. Pigeon, Cem. Concr. Res. 22, 804 (1992).
5. N. Banthia, A. Moncef, K. Chokri and J. Sheng, Can. J. Civ. Eng. 21, 999 (1994).
6. V.C. Li and K.H. Obla, Composites Engineering 4(9), 947 (1994).
7. A. Katz and A. Bentur, Cem. Concr. Res. 24(2), 214 (1993).
8. A. Katz and A. Bentur, Cem. Concr. Composites 17, 87 (1995).
9. A. Katz, V.C. Li and A. Kazmer, J. Mater. Civ. Eng., May 1995, p. 125-128.
10. H. Nakagawa, S. Akihama, T. Suenaga, Y. Taniguchi and K. Yoda, Adv. Composite Mater. 3(2), 123 (1993).
11. S.B. Park, B.I. Lee and Y.S. Lim, Cem. Concr. Res. 21(4), 589 (1991).
12. S.B. Park and B.I. Lee, Cem. Concr. Composites 15(3), 153 (1993).
13. H. Sakai, K. Takahashi, Y. Mitsui, T. Ando, M. Awata and T. Hoshijima, ACI SP-142, Fiber Reinforced Concrete, J.I. Daniel and S.P. Shah, eds., ACI, Detroit, Mich., 1994, p. 121-140.
14. P. Soroushian, F. Aouadi and M. Nagi, ACI Materials J. 88(1), 11 (1991).
15. P. Soroushian, M. Nagi and A. Okwuegbu, ACI Materials J. 89(5), 491 (1992).
16. P. Soroushian, M. Nagi and J. Hsu, ACI Materials J. 89(3), 267 (1992).
17. H.A. Toutanji, T. El-Korchi, R.N. Katz and G.L. Leatherman, Cem. Concr. Res. 23, 618 (1993).
18. H.A. Toutanji, T. El-Korchi and R.N. Katz, Cem. Concr. Composites 16, 15 (1994).
19. K. Zayat and Z. Bayasi, ACI Materials J. 93, 178 (1996).
20. P. Chen and D.D.L. Chung, Smart Mater. Struct. 2, 22 (1993).
21. P. Chen and D.D.L. Chung, J. Am. Ceram. Soc. 78, 816 (1995).
22. P. Chen and D.D.L. Chung, Composites: Part B, 27B, 11 (1996).
23. P. Chen and D.D.L. Chung, ACI Materials J. 93(4), 341 (1996).
24. X. Fu and D.D.L. Chung, Cem. Concr. Res. 26(1), 15 (1996).
25. I.L. Al-Qadi, O.A. Hazim, W. Su and S.M. Riad, J. Mater. Civ. Eng., August 1995, p. 192-198.
26. M. Perez-Pena, D.M. Roy and F.D. Tamás, J. Mater. Res. 4(1), 215 (1989).
27. S.A. Abo El-Enein, M.F. Kotkata, G.B. Hanna, M. Saad and M.M. Abd El Razek, Cem. Concr. Res. 25(8), 1615 (1995).

28. A.A. Kyi and Bill Batchelor, Cem. Concr. Res. 24(4), 752 (1994).
29. P.J. Tumidajski, A.S. Schumacher, S. Perron, P. Gu and J.J. Beaudoin, Cem. Concr. Res. 26(4), 539 (1996).
30. P.J. Tumidajski, Cem. Concr. Res. 26(4), 529 (1996).
31. P. Gu, Z. Xu, P. Xie and J.J. Beaudoin, Cem. Concr. Res. 23, 531 (1993).
32. P. Gu, P. Xie and J.J. Beaudoin, Cem. Concr. Res. 23, 581 (1993).
33. Z. Xu, P. Gu, P. Xie and J.J. Beaudoin, Cem. Concr. Res. 23, 853 (1993).
34. P. Xie, P. Gu and J.J. Beaudoin, J. Mater. Sci. 31, 144 (1996).
35. P. Chen, X. Fu and D.D.L. Chung, ACI Materials J., in press.