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Effect of stress on the electric polarization in cement

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Abstract

Compressive stress was found to diminish the extent of electric polarization in the transverse direction in cement pastes with and without carbon fibers, as shown by electrical resistivity measurement conducted over time. In addition, the stress decreased the time for polarization to essentially reach completion. The extent of polarization was much smaller when carbon fibers were present. It was smaller for carbon fiber cement paste containing silica fume than that containing latex. The time for polarization to reach completion was less than 5 s for carbon fiber silica fume cement paste at a compressive stress of 6.74 MPa. Polarization reversal was hastened by stress. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Fiber reinforcement; Cement paste; Electrical properties; Silica fume; Polarization

1. Introduction

Electric polarization refers to the phenomenon in which the centers of positive and negative charges do not coincide. It commonly occurs in a dielectric material when it is exposed to an electric field. As an electric field is present during electrical resistivity measurement, polarization can occur in a material during electrical resistivity measurement. As a consequence of the polarization-induced electric field in the material being opposite in direction from the applied electric field, polarization causes the measured resistivity to increase with time during resistivity measurement.

Polarization can occur within cement as well as at the interface between cement and an electrical contact. The former dominates when the four-probe method is used, whereas the latter dominates when the two-probe method is used [1].

The effect of stress or strain on the electrical behavior of cement-based materials is relevant to the ability of the cement-based materials to sense stress or strain. This ability is desirable for smart structures, particularly in relation to structural vibration control, traffic monitoring, and weighing in motion. It has been reported that the electrical resistivity of cement-based materials in the stress direction decreases upon compression, such that the effect is large and reversible when the cement-based materials contain short carbon fibers [2–11]. However, the effect of stress or strain on the polarization has not been previously reported in any cement-based material. In this paper, we report that the polarization in the direction perpendicular to the stress direction decreases significantly with increasing compressive stress. The effect is comparable whether the cement contains carbon fibers or not. It is attributed to the effect of stress or strain on the microstructure, which affects the polarizability of the cement-based material. It is not attributed to the effect of stress or strain on the electrical resistivity, since the effect on the resistivity is much larger in the presence of carbon fibers and the observed effect is comparable whether fibers are present or not.

2. Experimental methods

2.1. Materials

No aggregate (fine or coarse) was used. The cement used was portland cement (Type I) from Lafarge (Southfield, MI). The fibers used were in the amount of 0.5 wt.% cement.

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Table 1
Resistivity and absolute thermoelectric power of carbon fiber cement pastes

Fiber content % by wt. of cement	vol.%	Admixture	Resistivity (Ω cm)[a]	Absolute thermoelectric power[b] (μV/°C)
0	0	/	$(4.7 \pm 0.4) \times 10^5$	1.96 ± 0.05
0.5	0.48	SF	$(1.5 \pm 0.1) \times 10^4$	0.89 ± 0.09
0.5	0.41	L	$(9.7 \pm 0.6) \times 10^4$	1.14 ± 0.05

SF: silica fume; L: latex.

[a] Measured within 1 s from the start of resistivity measurement in order to avoid polarization effect [1].

[b] The absolute thermoelectric power for silica fume cement paste without fiber is 1.98 ± 0.03 μV/°C, and for latex cement paste without fiber is 2.04 ± 0.02 μV/°C [12].

Either silica fume or latex was used as an admixture when carbon fibers were used. Silica fume (EMS 965, Elkem Materials, Pittsburgh, PA) was used in the amount of 15 wt.% cement. The methylcellulose, used along with silica fume in the amount of 0.4 wt.% cement, was Methocel A15-LV (Dow Chemical, Midland, MI). The defoamer (Colloids, Marietta, GA, 1010) used along with methylcellulose was in the amount of 0.13 vol.%.

The latex, used in the amount of 20 wt.% cement, was a styrene butadiene copolymer (460NA, Dow Chemical) with the polymer making up about 48% for the dispersion and with the styrene and butadiene having a mass ratio of 66:34. The latex was used along with an antifoaming agent (No. 2410, 0.5 wt.% latex, Dow Corning).

The carbon fibers were isotropic pitch based, unsized, and of length ~5 mm, diameter 15 μm, and density 1.6 g/cm^3, as obtained from Ashland Petroleum (Ashland, KY). The fiber resistivity is 3.0×10^{-3} Ω cm.

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), and fibers were mixed in the mixer for 5 min. After pouring into oiled molds, an external electrical vibrator was used to facilitate compaction and decrease the amount of air bubbles. The samples were demolded after 1 day and cured in air at room temperature (relative humidity = 100%) for 28 days.

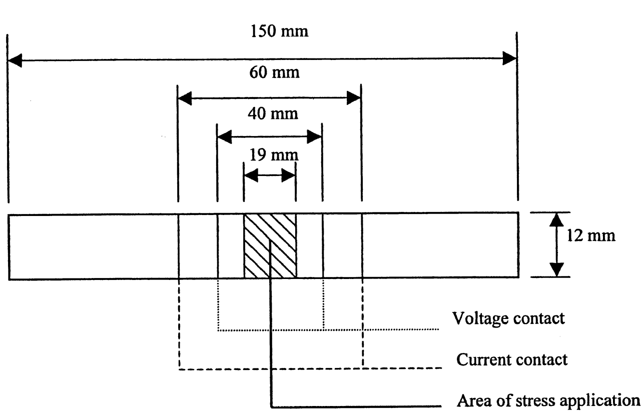

Fig. 1. Sample configuration for testing.

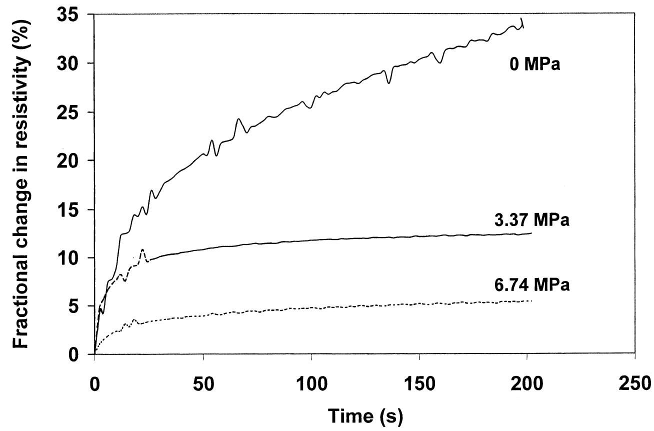

Fig. 2. Variation of the measured resistivity with time for plain cement paste.

Three types of cement pastes were prepared, as listed in Table 1. The water/cement ratio was 0.35 for all pastes, except that it was 0.23 for pastes with latex.

2.2. Testing

Electrical resistivity measurements were conducted using the four-probe method, with silver paint in conjunction with copper wires for electrical contacts. The two-probe method gave essentially the same resistivity result as the four-probe method, due to the high sample resistance. A Keithley 2001 multimeter (Cleveland, OH) was used.

Samples for transverse resistivity measurement were in the form of rectangular bars of size 150 × 12 × 11 mm. Each electrical contact was applied around the entire 12 × 11-mm perimeter of the bar. The voltage contacts were at two parallel cross-sectional planes that were 40 mm apart. Thus, the resistivity was measured along the length of the rectangular bar.

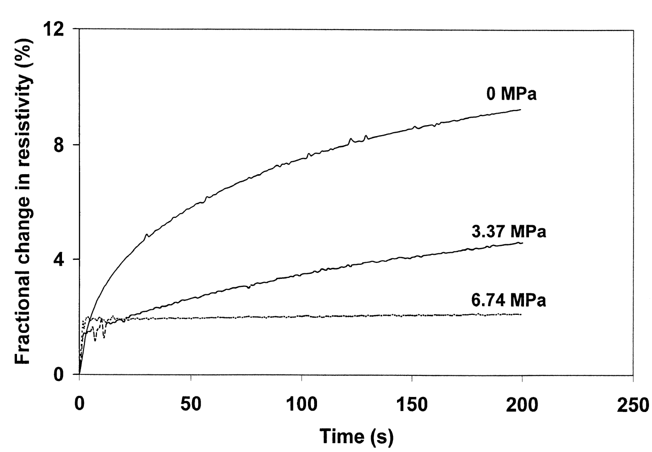

Fig. 3. Variation of the measured resistivity with time for cement paste with carbon fibers and silica fume.

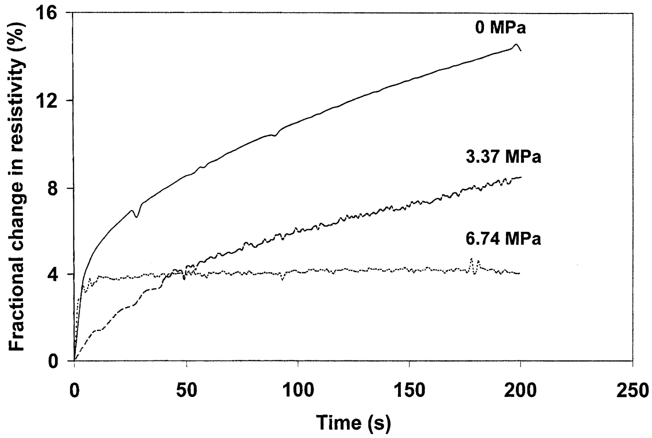

Fig. 4. Variation of the measured resistivity with time for cement paste with carbon fibers and latex.

The electrical resistivity was measured as a function of time from the start of the resistivity measurement in order to observe the effect of polarization. During the resistivity measurement, compressive stress was applied to the middle portion (19 × 12 mm) of the rectangular sample (Fig. 1), such that the electrical contacts were away from the stressed portion and the stress was in a direction perpendicular to the direction of resistivity measurement. The stress was provided by a hydraulic press.

For the purpose of confirming the occurrence of polarization, the polarity of the resistivity measurement was switched after 200 s of resistivity measurement. The resistivity measurement was conducted continuously before and after the switching, which was conducted by controlling the voltage.

3. Results and discussion

Figs. 2–4 show the fractional change in resistivity vs. time from the start of resistivity measurement (two-probe

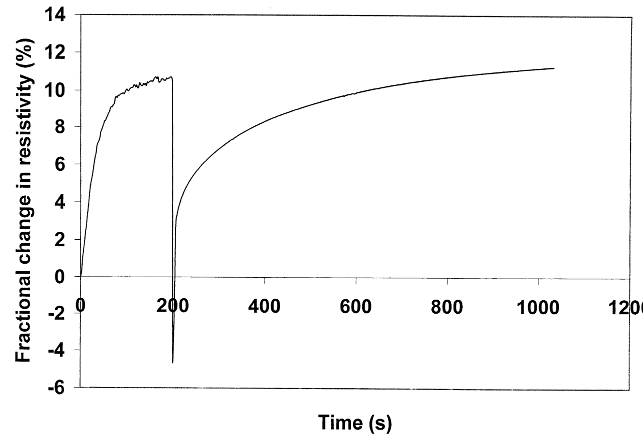

Fig. 6. Variation of the measured resistivity (two-probe method) with time before and after voltage polarity switching for plain cement paste at a compressive stress of 3.37 MPa.

method) for plain cement paste, carbon fiber silica fume cement paste, and carbon fiber latex cement paste, respectively. At the same time from the start of resistivity measurement, the resistivity decreased with increasing stress for all types of cement paste, except that the fractional change in resistivity at 6.74 MPa was higher than that at 3.37 MPa for the carbon fiber cement pastes when the time was less than 50 s. This exceptional behavior relates to the shorter time taken for polarization to reach its limit when the stress was 6.74 MPa rather than 3.37 MPa. It is attributed to the large decrease of the resistivity with increasing stress for carbon fiber cement pastes and the effect of the resistivity on the time for polarization to build up. This exceptional behavior did not occur in the plain cement paste (paste without fibers), because the decrease of the resistivity with increasing stress was much smaller in the absence of the fibers.

The extent of polarization, as indicated by the fractional change in resistivity reached at a particular time (say, 200 s), was much larger in the absence of fibers (Fig. 2) than in

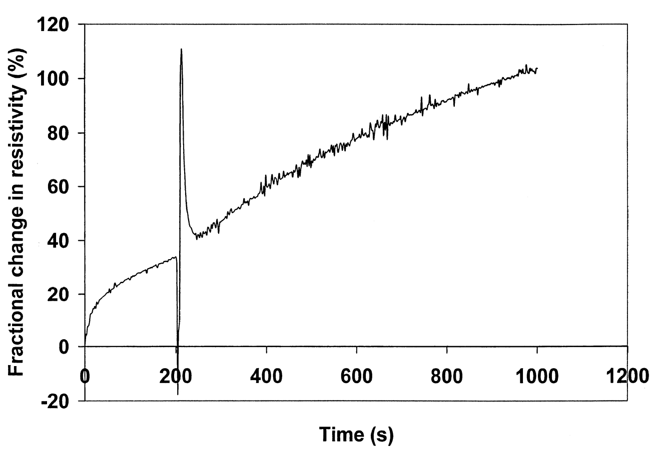

Fig. 5. Variation of the measured resistivity (two-probe method) with time before and after voltage polarity switching for plain cement paste without stress.

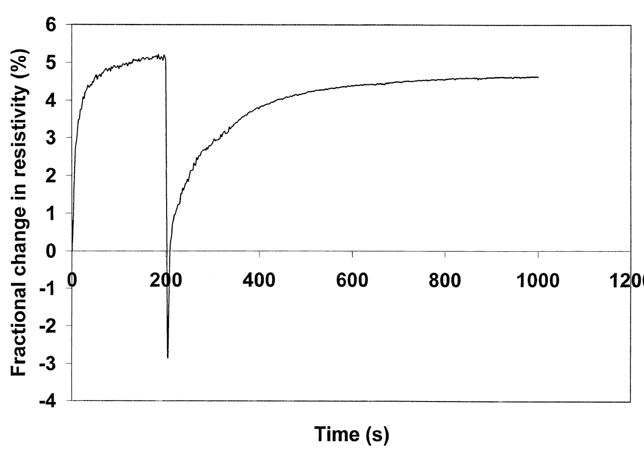

Fig. 7. Variation of the measured resistivity (two-probe method) with time before and after voltage polarity switching for plain cement paste at a compressive stress of 6.74 MPa.

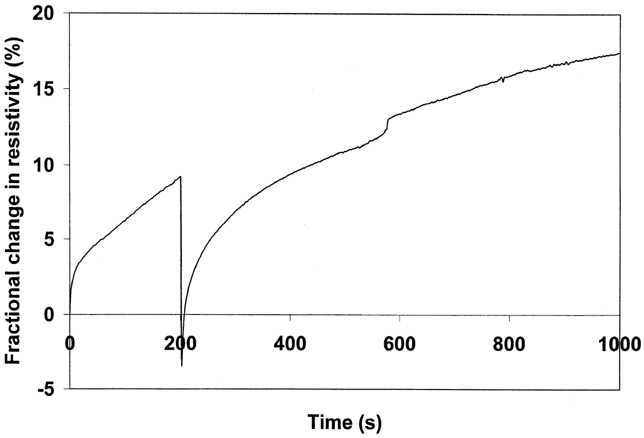

Fig. 8. Variation of the measured resistivity (four-probe method) with time before and after voltage polarity switching for plain cement paste without stress.

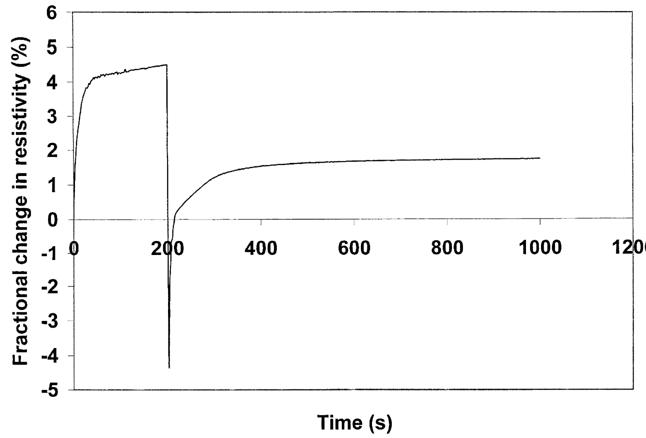

Fig. 10. Variation of the measured resistivity (four-probe method) with time before and after voltage polarity switching for plain cement paste at a compressive stress of 6.74 MPa.

the presence of fibers (Figs. 3 and 4). This is attributed to the low resistivity of the carbon fiber cement pastes (Table 1) and the tendency of low resistivity to be associated with less polarization. Between the two carbon fiber cement pastes, the one with latex (Fig. 4) gave more polarization than the one with silica fume (Fig. 3) due to the higher resistivity of the former (Table 1).

Figs. 5–7 and Figs. 8–10 show the effect of polarity switching on the measured resistivity for plain cement paste, as observed by using the two- and four-probe methods, respectively. The extent of polarization was much larger when the two-probe method was used, indicating the dominance of the polarization at the contact–sample interface when the two-probe method was used [1]. In all of Figs. 5–10, the measured resistivity dropped abruptly at the time of switching to a value below the initial (time = 0 s) value. The abrupt drop confirmed the occurrence of polarization. In the absence of stress (Figs. 5 and 8), after the switching, the measured resistivity increased much beyond the value immediately before the switching. In the presence of stress, after the switching, the measured resistivity increased only to values either below or slightly above the value immediately before the switching (Figs. 6, 7, 9, and 10), due to the tendency for the extent of polarization to diminish with stress. The extent of increase of the measured resistivity after the switching in the presence of stress was less for the four-probe method (Figs. 9 and 10) than for the two-probe method (Figs. 6 and 7), as previously reported for the case of no stress and for carbon fiber cement paste, and attributed to the more complete polarization reversal for the polarization at the contact–sample interface (two-probe method) than for the polarization of the sample itself (four-probe method) [1]. Without stress, the time taken for the measured resistivity to reach the value immediately before the switching was much longer for the four-probe method (Fig. 8) than the two-probe method (Fig. 5), as expected from the faster polarization reversal for polarization at the contact–sample interface than for polarization within the sample [1]. The origin of the sharp peak in Fig. 5 is not totally clear, though it may relate to the large extent of polarization together with the rapidity of the polarization reversal causing some kind of instability. This peak is absent in the presence of stress (Figs. 6 and 7) and in corresponding plots obtained for the carbon fiber cement pastes using the two-probe method [1], probably because of the relatively small extent of polarization when either stress or carbon fibers is (are) present. With stress, the time taken for the measured resistivity to increase (after the switching) to an essentially stable value was less, whether the two- or four-probe method was used, due to the stress hastening polarization reversal; the effect of stress was particularly large when the stress was increased from 0 to 3.37 MPa.

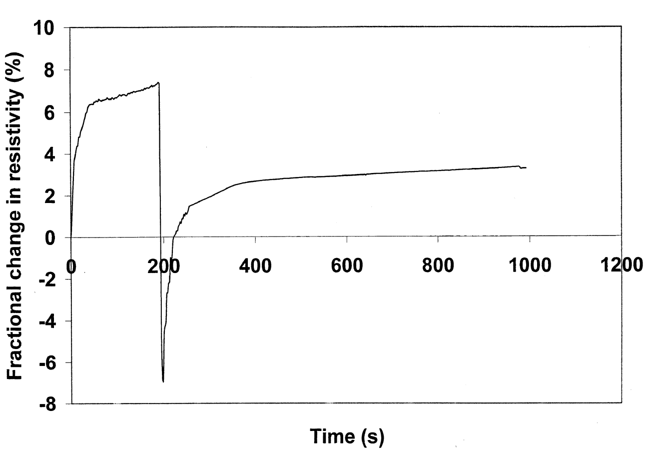

Fig. 9. Variation of the measured resistivity (four-probe method) with time before and after voltage polarity switching for plain cement paste at a compressive stress of 3.37 MPa.

In spite of the dominance of polarization at the contact–sample interface in the case of the two-probe method and that the stressed portion of the sample was away from the contact–sample interface, the stress strongly affected the polarization. This is attributed to the long-range effect of the stress on the polarization, as made possible by the stiffness of the sample material.

For all three types of cement paste, the stress diminished the extent of polarization and decreased the time for polarization to essentially reach completion. The time for polarization to reach completion was particularly short for carbon fiber pastes at 6.74 MPa. In addition, the extent of polarization was particularly small for carbon fiber pastes (especially that containing silica fume) at 6.74 MPa. Hence, carbon fibers and stress are useful in practice for diminishing polarization effects in applications that are complicated by polarization.

This paper addresses the effect of compressive stress on the transverse polarization. The effect of compressive stress on the longitudinal polarization (along the stress axis) and the effect of tensile stress on polarization in both directions remain to be investigated.

The effect of stress on the polarization is consistent with the previously reported effect of stress on the reactance [13], as the capacitance relates to the extent of polarization. Both effects relate to the direct piezoelectric effect. Although polarization complicates electrical resistance measurement, it is desirable for a large piezoelectric effect, which provides another mechanism for strain sensing.

4. Conclusion

Stress was found to affect the extent of electric polarization in cement paste. In particular, compressive stress diminished the extent of polarization in the transverse direction in cement pastes with and without carbon fibers. In addition, the stress hastened the completion of polarization and hastened polarization reversal upon voltage polarity switching. The extent of polarization was also diminished by the presence of carbon fibers, such that the polarization was less for carbon fiber silica fume cement paste than for carbon fiber latex cement paste.

Acknowledgment

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