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Cement-based materials for stress sensing by dielectric measurement

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Abstract

The self-sensing of stress by measurement of the relative dielectric constant (κ) has been shown in cement pastes containing steel fibers of 8 μm diameter and carbon filaments of 0.1 μm diameter. The κ value increases nonlinearly and quite reversibly with compressive stress up to 6.4 MPa, although the reversibility is not complete. Inferior sensing performance was observed in cement paste with carbon fibers of 15 μm diameter, although the performance was still better than cement paste without admixture.

Keywords: Electrical properties; Mechanical properties; Fiber reinforcement; Strain effect; Dielectric constant; Cement paste

1. Introduction

The sensing of stress or strain experienced by a concrete structure is relevant to structural vibration control, traffic monitoring, weighing in motion and hazard mitigation. The self-sensing of stress or strain by a cement-based material is advantageous to sensing by means of embedded or attached sensors (such as strain gages and optical fibers), as it is associated with low cost, high durability, large sensing volume and absence of mechanical property degradation. Self-sensing has been attained by cement-based materials by means of electrical resistivity measurement (i.e., the piezoresistive effect) [1–12] and voltage measurement (i.e., the direct piezoelectric effect) [13,14]. In contrast, this paper reports self-sensing in cement-based materials by means of measurement of the relative dielectric constant (κ).

The effect of stress on κ relates to the direct piezoelectric effect, as the piezoelectric coupling coefficient d is given by Eq. (1)

$$d = \varepsilon_o E \left| \frac{\partial \kappa}{\partial \sigma} \right| \qquad (1)$$

where σ is the stress, E is the electric field amplitude used in the κ measurement, and ε_o is the permittivity of free space. However, a high value of d does not imply effectiveness for stress sensing by κ measurement, as the effectiveness depends on the noise associated with the curve of κ versus σ, and on the reversibility of the change in κ due to stress. The piezoelectric voltage coefficient g is given by

$$g = \frac{d}{(\kappa - 1)\varepsilon_o} \qquad (2)$$

A high value of g requires a high value of d and a low value of κ. Although g is directly related to the voltage change (the output of the direct piezoelectric effect), it does not give any indication of the effectiveness for stress sensing. Therefore, this paper is not intended to address the direct piezoelectric effect of cement-based materials. Rather, it addresses the ability of cement-based materials for stress sensing by κ measurement.

Due to the presence of ionic bonding and moisture in cement, electric dipoles are present, and κ has been measured for the purpose of fundamental understanding of cement-based materials. Such fundamental studies have addressed the effects of moisture [15–20], chlorides [21], curing age [22–31], aggregate type [21], air entrainment [32] and admixtures such as silica fume [33,34], latex [34] and short fibers [34]. In particular, it has been reported that κ at 10 kHz–1 MHz is decreased by silica fume addition, increased by latex addition, decreased by stainless-steel fiber (60 μm diameter) addition and increased by carbon fiber (15 μm diameter) addition [34].

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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 water/cement ratio was 0.35.

The effects of three fibrous admixtures were investigated. In this paper, fibers refer to those of diameter of at least 1 μm, whereas filaments refer to those of diameter less than 1 μm. The admixtures were (i) short carbon fibers (1.0% by mass of cement, corresponding to 1.0 vol.%, 15 μm diameter, ~5 mm long, isotropic pitch based, unsized, Ashland Petroleum, Ashland, KY, ozone-treated [35] to improve the fiber–matrix bond), together with silica fume (15% by mass of cement, Elkem Materials, Pittsburgh, PA, EMS 965), methylcellulose (0.4% by mass of cement, Dow Chemical, Midland, MI, Methocel A15-LV) and a defoamer (0.13 vol.%, Colloids, Marietta, GA, 1010), (ii) carbon filaments (3.0% by mass of cement, corresponding to 3.0 vol.%, 0.1 μm diameter, >100 μm long, Applied Sciences, Cedarville, OH), together with silica fume, methylcellulose and defoamer as described in (i) above and (iii) steel fibers (No. 304 austenitic stainless steel, Bekaert Fiber Technologies, Marietta, GA, 8 μm diameter, 6 mm long, 0.9% by mass of cement, corresponding to 0.18 vol.%), together with polyvinyl alcohol (PVA, 0.10% by mass of cement, corresponding to 0.16 vol.%). The mixing may have caused some degree of breakage of the fibers or filaments, especially in the case of carbon fibers and carbon filaments.

A rotary mixer with a flat beater was used for mixing. For the case of steel fibers, cement, water and fibers were mixed for 5 min. In the case of carbon fibers or filaments, methylcellulose was dissolved in water and, then, the defoamer was added and stirred by hand for about 2 min. Then, the methylcellulose mixture, cement, water, silica fume and fibers (or filaments) were mixed in the mixer for 5 min. In all cases, 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 were cured in air at room temperature (relative humidity = 100%) for 28 days.

2.2. Testing

Specimens were in the form of cyclindrical discs of 12.3 mm diameter and 2.0 mm thickness. Due to the small thickness, the fibers in each specimen were bound to have a degree of preferred orientation in the plane of the disc. A specimen, after mechanical polishing on both sides by using alumina particles 0.25 μm in size such that the two sides are rendered exactly parallel, was sandwiched by two copper discs (similarly polished) of 12.3 mm diameter. The copper discs served as electrical contacts. Silver paint was applied between the specimen and each copper disk in order to avoid any air gap at the interface.

The impedance was measured along the thickness of the specimen using the two-probe method and an RLC meter (QuadTech 7600) at frequencies ranging from 10 kHz to 1 MHz. The magnitude of voltage applied across the thickness (2 mm) of a specimen was 1.000 V. Hence, the magnitude of the applied electric field was 500 V/m. The resistance and reactance were obtained from the impedance by assuming that they were in series connection. The capacitance was obtained from the reactance. The dielectric constant was obtained from the capacitance. Six specimens of each type were tested in order to ensure statistical significance to the data in spite of possible nonuniformity in the fiber/filament distribution.

To show that the dielectric constant measurement using the method described above was accurate, measurement was made on a Kapton (a commercial polymer) film. The known dielectric constant of Kapton is 3.9 at 1 kHz. Measurement in this work at 1 kHz gave a value of 3.9 also.

For testing the piezoelectric behavior, during the impedance measurement, compressive stress was applied to the sandwich so that the stress was parallel to the direction of impedance measurement. The stress (repeated loading at increasing stress amplitudes within the elastic regime) was provided by a hydraulic mechanical testing system (MTS Model 810). Repeated loading was used in order to investigate the reversibility of the effect. The minimum compressive stress was 1.68 kPa. Six specimens of each type were tested.

The DC volume electrical resistivity was measured by the four-probe method (outer two probes for passing current and inner two probes for voltage measurement) using silver paint for the electrical contacts, which were applied around the perimeter of the specimen (160 × 40 × 40 mm) in four parallel planes perpendicular to the current direction (along the longest dimension of the specimen).

3. Results and discussion

Figs. 1–4 show the relative dielectric constant (κ) and the applied stress (negative for compression) during repeated

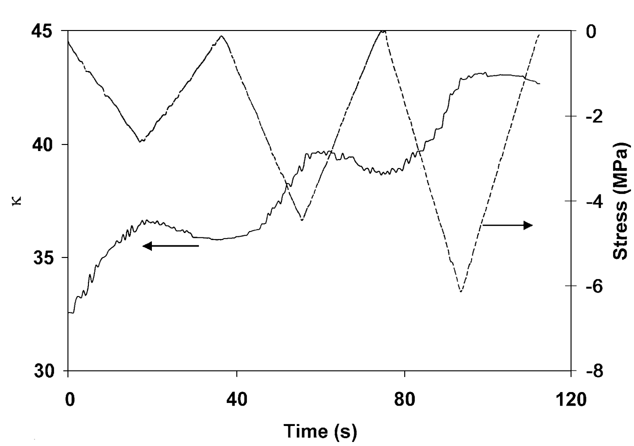

Fig. 1. Variation of κ during repeated application of compressive stress for plain cement paste.

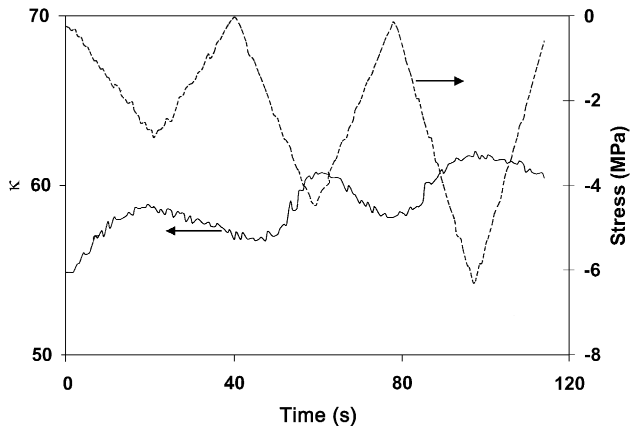

Fig. 2. Variation of κ during repeated application of compressive stress for carbon fiber (15 μm diameter) cement paste.

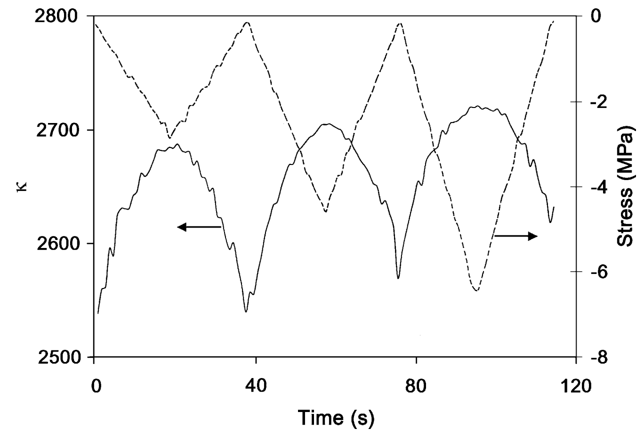

Fig. 4. Variation of κ during repeated application of compressive stress for steel fiber (8 μm diameter) cement paste.

compressive loading of plain cement paste (no admixture), carbon fiber cement paste, carbon filament cement paste and steel fiber cement paste, respectively. For all the pastes, κ increases (i.e., the reactance decreases) nonlinearly upon loading. The effect of the compressive strain (value of stress divided by the modulus) on the capacitance is negligible. The greater the stress amplitude, the more κ increases. The longitudinal piezoelectric coupling coefficient d, as averaged over the first half of the first stress cycle for each specimen, is shown in Table 1 for each of the cement pastes studied. Also shown in Table 1 are κ (before stress application), g (calculated by using Eq. (2)) and the DC electrical resistivity.

Among the three fibrous admixtures, carbon fibers 1.0 vol.%) resulted in cement paste with the lowest resistivity, whereas carbon filaments (3 vol.%) gave the highest resistivity. The high resistivity of the carbon filament cement paste is as previously reported [36]. It is attributed to the small filament diameter and the consequent large amount of interface between filament and matrix. The interface is associated with a contact resistance. The low resistivity of the carbon fiber cement paste is as previously reported [37]. It is attributed to a more optimum fiber diameter. Steel fibers (0.18 vol.%) gave a higher resistivity than carbon fibers (1.0 vol.%) due to the low volume fraction of steel fibers.

The κ value is increased from 33 to 55 by the addition of carbon fibers, but was increased to 90 by the addition of carbon filaments. These increases are attributed to the functional groups at the fiber–matrix interface, which is more abundant in the filament case.

For the steel fiber cement paste, κ reached 2500, in spite of the low volume fraction of steel fibers. In a separate experiment, it was found that κ was 148 ± 11 at 10 kHz for cement paste containing PVA in the amount of 0.1% by mass of cement, in the absence of steel fibers. Thus, the high κ for the steel fiber cement paste is not due to the PVA, but is probably due to the oxide at the fiber–matrix inteface [38].

The increase of κ with stress is quite irreversible for plain cement paste (Fig. 1), probably due to the largely irreversible nature of the ion movement that occurs during stress application. The behavior is more reversible, but not totally reversible, for cement pastes with carbon fibers (Fig. 2), carbon filaments (Fig. 3) and steel fibers (Fig. 4). The

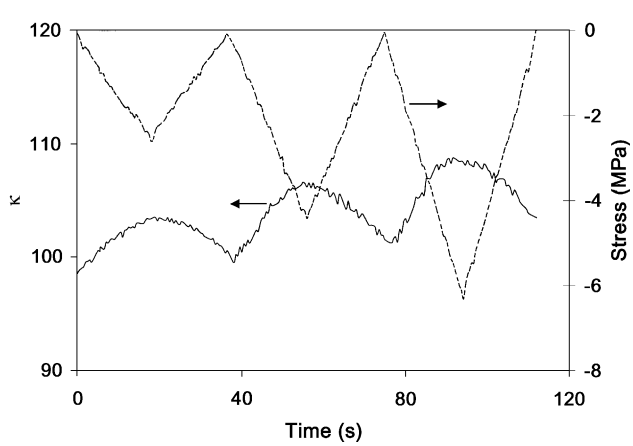

Fig. 3. Variation of κ during repeated application of compressive stress for carbon filament (0.1 μm diameter) cement paste.

Table 1
Electrical properties of cement pastes

Cement paste	DC electrical resistivity (Ω cm)	κ[a]	d[a] (m/V)	g[a] (10^{-3} m^2/C)
Plain cement paste	$(4.8 \pm 0.4) \times 10^5$	33 ± 4	3.1×10^{-13}	1.0
Carbon fiber cement paste	$(8.3 \pm 0.5) \times 10^2$	55 ± 5	4.4×10^{-13}	0.89
Carbon filament cement paste	$(1.5 \pm 0.1) \times 10^4$	98 ± 8	4.9×10^{-13}	0.55
Steel fiber cement paste	$(4.5 \pm 0.4) \times 10^3$	2500 ± 200	2.5×10^{-11}	1.1

[a] At 10 kHz.

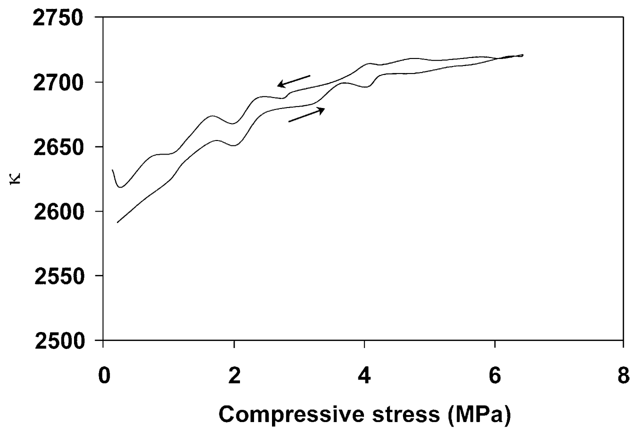

Fig. 5. Variation of κ with the compressive stress for the third stress cycle of steel fiber (8 μm diameter) cement paste.

greater reversibility in the presence of fibers or filaments is probably due to the reversible nature of the slight movement of functional groups on the fibers or filaments.

The variation of κ with stress is less noisy for the pastes with carbon filaments (Fig. 3) and steel fibers (Fig. 4) than that with carbon fibers (Fig. 2). This is probably due to the large interface area provided by the small diameter of the carbon filaments and steel fibers.

Comparison of Figs. 1–4 shows that the carbon filament cement paste and the steel fiber cement paste are quite effective for stress sensing by κ measurement, though the incomplete reversibility is not desirable. In spite of the good stress-sensing performance, *d* and *g* are both low for the carbon filament case.

Fig. 5 shows the relationship between κ and the compressive stress for the third stress cycle of the paste with steel fibers. The κ value is lower during loading than during subsequent unloading, as also shown in Fig. 4. The third cycle is shown in Fig. 5 because it reflects the long-term behavior better than the prior cycles. The relationship between κ and stress is less noisy for the paste with steel fibers than for the paste with carbon filaments. Thus, the effectiveness for stress sensing is better for the paste with steel fibers than that with carbon filaments.

4. Conclusion

Cement pastes containing carbon filaments (0.1 μm diameter) and steel fibers (8 μm diameter) are effective as compressive stress sensors that are based on the measurement of the relative dielectric constant (κ). The κ value increases nonlinearly and quite reversibly with stress up to 6.4 MPa, although the reversibility is not complete. The effectiveness is superior for the paste with steel fibers than for that with carbon filaments. Similar behavior observed in carbon fiber (15 μm diameter) cement paste is noisier in the variation of κ with stress. The behavior is quite irreversible in the case of plain cement paste.

Acknowledgments

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