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Damage monitoring of cement paste by electrical resistance measurement

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Abstract

Electrical resistance measurement is effective for monitoring damage (due to damage infliction and subsequent microcrack opening) and healing (due to microcrack closing) of cement pastes (plain, with silica-fume, and with latex) in real time during repeated compressive loading. Damage causes the resistance to increase; healing causes the resistance to decrease.

Keywords: Electrical properties; Cement paste; Strain effect; Microcracking; Damage monitoring

1. Introduction

Damage monitoring (i.e., structural health monitoring) is valuable for structures for the purpose of hazard mitigation. It can be conducted during the damage by acoustic emission detection. It can also be conducted after the damage by ultrasonic inspection, liquid penetrant inspection, dynamic mechanical testing, or other techniques. Real-time monitoring gives information on the time, load condition, or other conditions at which damage occurs, thereby facilitating the evaluation of the cause of the damage. Moreover, real-time monitoring provides information as soon as damage occurs, thus enabling timely repair or other hazard precaution measures.

In our previous paper [1], we reported the use of electrical resistance measurement to sense damage in cement pastes in the elastic deformation regime. However, damage in the plastic deformation regime is much more significant than that in the elastic regime. In order to show the effectiveness of the electrical resistance measurement to monitor damage, it is necessary to extend our previous work to the plastic deformation regime. This extension is the purpose of this paper.

Damage monitoring must be distinguished from strain sensing, as strain can be reversible and is not necessarily accompanied by damage. There has been considerable work on the use of electrical resistance measurement to sense strain in cement reinforced with short carbon fibers [2–7]. Compressive strain causes the resistance to decrease reversibly, as observed at 28 days of curing [2–5]. However, this paper is not concerned with carbon fiber-reinforced cement.

2. Experimental methods

The cement used was portland cement (Type I) from Lafarge (Southfield, MI). The silica fume (Elkem Materials, Pittsburgh, PA, microsilica EMS 965) was used in the amount of 15% by weight of cement. The latex, used in the amount of 15% by the weight of cement, was styrene butadiene copolymer (Dow Chemical, Midland, MI, 460NA) with the polymer making up about 48% of the dispersion and with styrene and butadiene in the weight ratio 66:34, such that the latex was used along with an antifoam (Dow Corning, #2210, 0.5% by weight of latex). Three types of cement paste were studied, namely (i) plain cement paste (consisting of just cement and water), (ii) silica-fume cement paste (consisting of cement, water, and silica fume), and (iii) latex cement paste (consisting of cement, water, latex, and antifoam). The water/cement ratio was 0.35 for pastes (i) and (ii), and was 0.23 for paste (iii). Six specimens of each of the five types of paste were tested.

A rotary mixer with a flat beater was used for mixing. Latex (if applicable) was mixed with the antifoam by hand for about 1 min. Then the latex mixture (if applicable),

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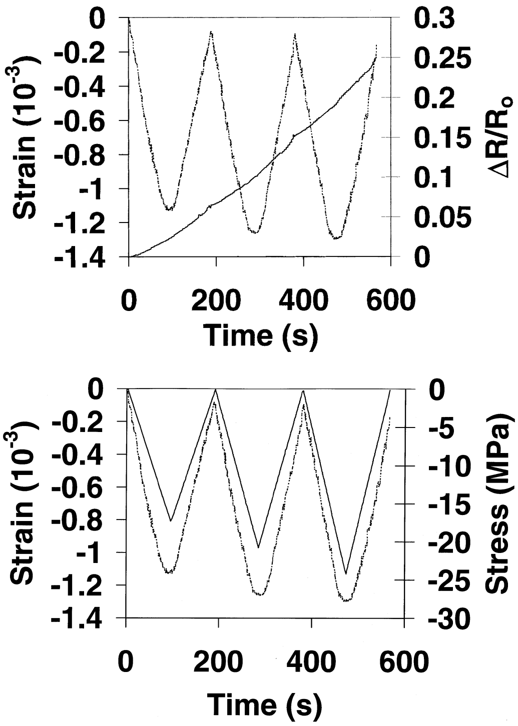

Fig. 1. Variation of the fractional change in electrical resistivity with time (a), of the stress with time (b), and of the strain (negative for compressive strain) with time (a,b) during dynamic compressive loading at increasing stress amplitudes for plain cement paste.

cement, water, and silica fume (if applicable) were mixed in the mixer for 5 min. After pouring the mix into oiled molds, an external electric vibrator was used to facilitate compaction and decrease the amount of air bubbles. The specimens were demolded after 1 day and then allowed to cure at room temperature in air (relative humidity = 100%) for 28 days.

For compressive testing according to ASTM C109-80, specimens were prepared using a 2×2×2 in. (51×51×51 mm) mold. The strain was measured by using a strain gage attached to the middle of one of four side surfaces of a specimen. The strain gage was centered on the side surface and was parallel to the stress axis. Compressive testing under load control was performed using a hydraulic mechanical testing system (MTS Model 810). Testing was conducted under repeated loading at various stress amplitudes.

During compressive testing, DC electrical resistance measurement was made in the stress axis, using the four-probe method, in which silver paint in conjunction with copper wires served as electrical contacts. Four contacts were perimetrically around the specimen at four planes that were all perpendicular to the stress axis and that were symmetric with respect to the mid-point along the height of the specimen. The outer two contacts (typically 40 mm apart) were for passing current. The inner two contacts (typically 30 mm apart) were for measuring the voltage. A Keithley 2001 multimeter was used.

3. Results and discussion

The fractional change in resistance $\Delta R/R_0$ given below is essentially equal to the fractional change in resistivity.

Fig. 1(a) shows the fractional change in resistance along the stress axis as well as the strain during repeated compressive loading at an increasing stress amplitude for plain cement paste. Fig. 1(b) shows the corresponding variation of stress and strain during the repeated loading. The strain varies linearly with the stress up to the highest stress amplitude (Fig. 1(b)). The strain does not return to zero at the end of each cycle of loading, indicating plastic deformation.

The resistance increases during loading and unloading in every loading cycle (Fig. 1(a)). The slope of the curve of resistance vs. time increases with time, due to the increasing stress amplitude cycle by cycle (Fig. 1(b)) and the non-linear increase in damage severity as the stress amplitude increases. The resistance increase during loading is attributed to damage infliction. The resistance increase during unloading is attributed to the opening of microcracks generated during loading.

Fig. 2 gives the corresponding plots for silica-fume cement paste at the same stress amplitudes as Fig. 1. The strain does not return to zero at the end of each loading cycle, as in Fig. 1. The resistance variation is similar to Fig. 1, except that the resistance decreases

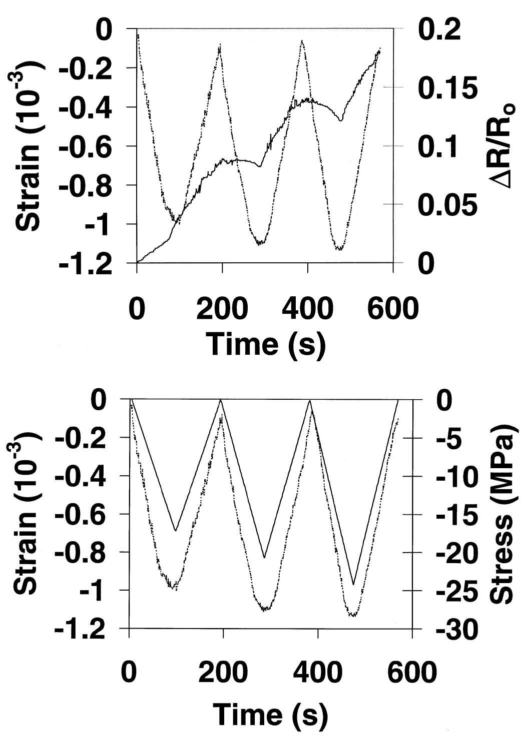

Fig. 2. Variation of the fractional change in electrical resistivity with time (a), of the stress with time (b), and of the strain (negative for compressive strain) with time (a,b) during dynamic compressive loading at increasing stress amplitudes for silica-fume cement paste.

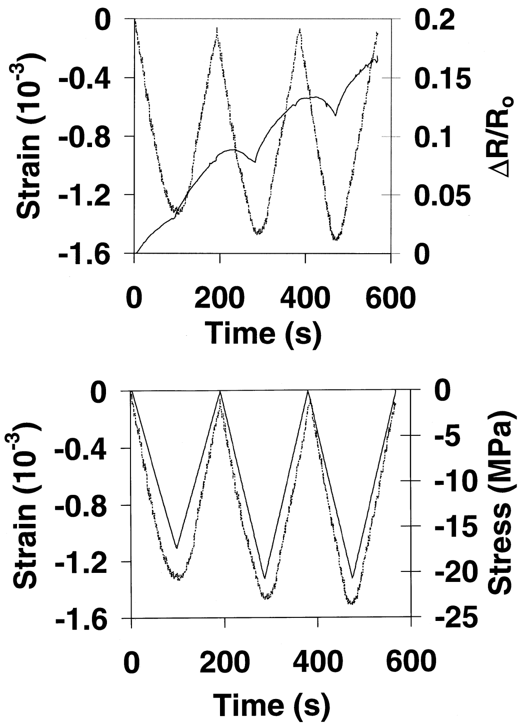

Fig. 3. Variation of the fractional change in electrical resistivity with time (a), of the stress with time (b), and of the strain (negative for compressive strain) with time (a,b) during dynamic compressive loading at increasing stress amplitudes for latex cement paste.

during loading after the first cycle. The absence of a resistance increase during loading after the first cycle is attributed to the lower tendency for damage infliction in the presence of silica fume, which is known to strengthen cement [8–11]. The resistance decrease during loading after the first cycle is attributed to the partial closing of microcracks, as expected since the loading is compressive. In the absence of silica fume (i.e., plain cement paste, Fig. 1), the effect of damage infliction overshadows that of microcrack closing.

Fig. 3 gives the corresponding plots for latex cement paste. The resistance effects are similar to those of Fig. 2(a), except that the resistance curve is less noisy and the rate of resistance increase during first unloading is higher than that during first loading. This means that the microcrack opening during unloading has a larger effect on the resistance than the damage infliction during loading.

Comparison of the results of this work for deformation in the plastic regime with those of Ref. [1] for deformation in the elastic regime shows that both the fractional change in resistance and the strain are higher in this work than Ref. [1] by orders of magnitude. Another difference is that the resistance decreases are much less significant in this work than Ref. [1] for all three types of cement paste. In particular, in the case of plain cement paste, there is no resistance decrease at all in this work (Fig. 1(a)), but there are resistance decreases in Fig. 1(a) of Ref. [1]. These differences between the results of this work and of Ref. [1] are consistent with the much greater damage in plastic deformation than in elastic deformation and the tendency of damage to increase the resistance.

That the resistance decreases are not significant in the plastic deformation regime simplifies the use of the electrical resistance to indicate damage. Nevertheless, even when the resistance decreases are significant, the resistance remains a good indicator of damage, which includes that due to damage infliction (during loading) and that due to microcrack opening. Microcrack closing, which causes the resistance decreases, is a type of partial healing, which diminishes the damage. Hence, the resistance indicates both damage and healing effects in real time.

4. Conclusion

Damage monitoring of cement paste has been shown by electrical resistance measurement in the stress direction. For plain cement paste the resistance increases during compressive loading and unloading in every loading cycle due to damage infliction and microcrack opening, respectively. For cement paste containing silica fume or latex, the resistance decreases slightly during loading after the first cycle due to microcrack closing, although the resistance increases during unloading in every cycle and during first loading. In general, the resistance indicates both damage (due to damage infliction and subsequent microcrack opening) and healing (due to microcrack closing) effects in real time.

Acknowledgment

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