Pergamon

Cement and Concrete Research 31 (2001) 1519–1521

CEMENT AND CONCRETE RESEARCH

Communication

Minor damage of cement mortar during cyclic compression monitored by electrical resistivity measurement

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Received 7 July 2000; accepted 18 June 2001

Abstract

Minor damage of cement mortar during cyclic compression in the elastic regime was monitored by measurement of the electrical resistivity in the stress direction. Defect generation (irreversible) resulted in an irreversible increase in the baseline resistivity as stress cycling progressed, whereas defect healing (reversible) resulted in a reversible decrease in the resistivity upon compression within a stress cycle. Defect generation was relatively significant in the early cycles and diminished upon cycling. As the cumulative damage increased, the extent of defect healing within a cycle also increased. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Fatigue; Electrical properties; Strain effect; Mortar; Electrical resistivity

1. Introduction

Concrete structures commonly encounter dynamic loading, whether due to live loads, wind, ocean waves, earthquakes or other stimuli. Fatigue damage of concrete due to dynamic loading is of concern. Fatigue in concrete is conventionally studied by destructive mechanical testing after different numbers of stress cycles. However, this method does not allow the monitoring of the progress of fatigue damage on the same specimen and is not very sensitive to minor damage. As different specimens can differ in the nature and number of flaws present, fatigue evolution is more effectively studied by monitoring one specimen throughout the fatigue process rather than interrupting the fatigue process at different times for different specimens. However, the monitoring of one specimen throughout the fatigue process requires a nondestructive method that is sensitive to minor damage. This paper shows that electrical resistivity measurement is effective for fatigue damage monitoring, particularly in the regime of minor damage, in addition to monitoring both defect generation and defect healing in real time.

Damage of cement paste has been shown to cause the electrical resistivity to increase, as shown by repeated compressive loading at increasing stress amplitudes [1]. This work extends to the case of fatigue loading, since fatigue tends to be associated with more subtle types of damage and fatigue is of practical concern. Furthermore, this work addresses mortar rather than cement paste, since mortar contains a fine aggregate and is thus closer to concrete than cement paste is.

Electrical resistivity measurement has been previously used to monitor fatigue damage in carbon fiber (short)-reinforced cement [2]. In this case, the resistivity decreases irreversibly upon damage in the early stage of fatigue due to the damage to the cement matrix at the junction of fibers, which almost touch one another, and the consequent increased chance for fibers to touch one another. In contrast, this work does not involve the use of fibers and is thus of more general interest.

2. Experimental methods

The cement used was Portland cement (Type I) from Lafarge (Southfield, MI). The sand used was natural sand (100% passing 2.36 mm sieve, 99.9% SiO_2). The sand/cement ratio was 1.0. The water/cement ratio was 0.35. A

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PII: S0008-8846(01)00590-7

water-reducing agent (WR) was used in the amount of 1.0% by weight of cement. The WR was TAMOL SN (Rohm and Haas, Philadelphia, PA), which contained 93–96% sodium salt of a condensed naphthalene sulfonic acid. No coarse aggregate was used. A Hobart mixer with a flat beater was used for mixing, which was conducted for 5 min. After that, the mix was poured into oiled molds. A vibrator was used to facilitate compaction and decrease the amount of air bubbles.

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 cyclic loading up to 100 cycles at a compressive stress amplitude of 34.5 MPa (compressive strain amplitude of 1.95×10^{-2}), such that each stress cycle (an isosceles triangle in the curve of stress vs. time and in the curve of strain vs. time within a cycle) took 20 s and the deformation was elastic (i.e., the strain was reversible).

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 made perimetrically around the specimen at four planes that were all perpendicular to the stress axis and that were symmetric with respect to the midpoint 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.

Due to the voltage present during electrical resistance measurement, electric polarization occurs as the resistance measurement is made continuously. The polarization results in an increase in the measured resistance [3]. The polarization -induced resistance increase, as separately measured as a function of the time of resistance measurement in the absence of stress (Fig. 1), was subtracted from the measured resistance change obtained during cyclic loading in order to correct for the effect of polarization.

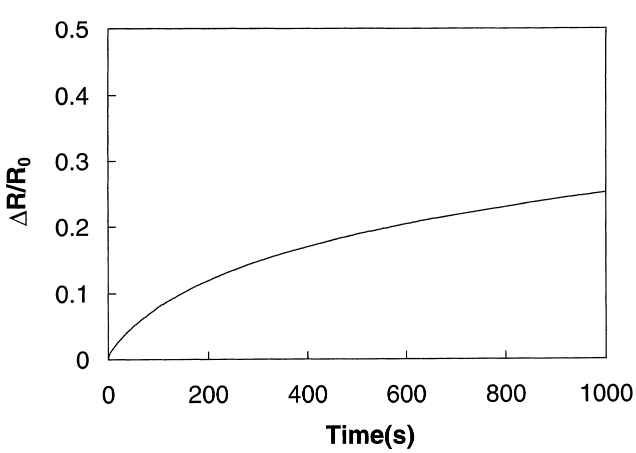

Fig. 1. Fractional change in resistance vs. time of resistance measurement under no stress.

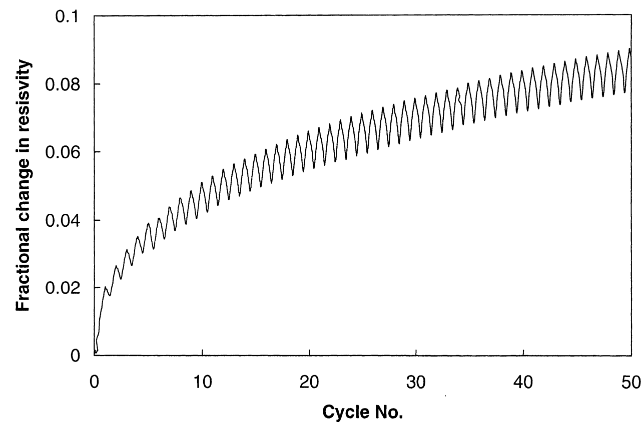

Fig. 2. Fractional change in resistance vs. compressive stress cycle number for Cycles 1–50.

The resistivity was obtained from the resistance and the dimensions, which changed with the measured longitudinal strain and with the calculated transverse strain due to the Poisson effect. Although the Poisson effect was included in the calculation, neglecting the transverse strain actually affected the resistivity value negligibly. The fractional change in resistance was essentially equal to the fractional change in resistivity.

In order to assess the extent of damage due to the cyclic loading, compressive testing involving static loading (at a loading rate of 0.287 MPa/s) up to failure was conducted before and after 100 stress cycles. Six specimens were tested before cycling and six specimens were tested after cycling.

3. Results and discussion

Figs. 2–4 show the fractional change in resistivity in the stress direction vs. cycle number during cyclic compression.

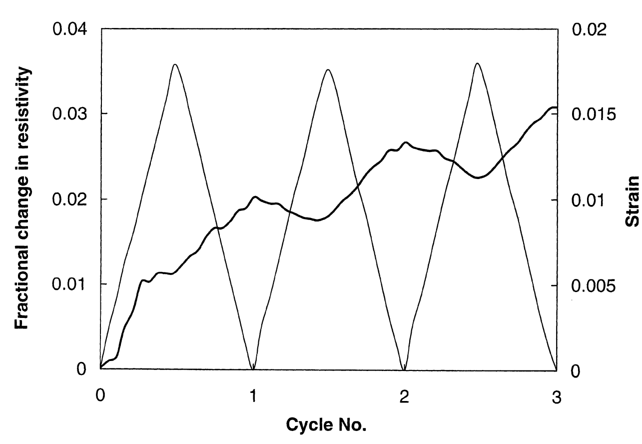

Fig. 3. Fractional change in resistance (solid curve) and strain (dashed curve), both vs. compressive stress cycle number for Cycles 1–3.

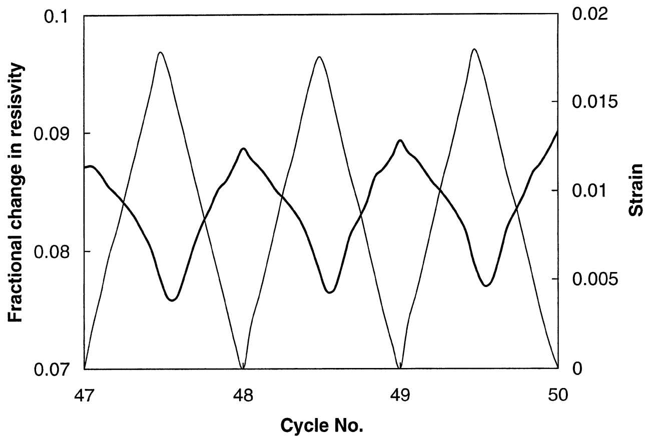

Fig. 4. Fractional change in resistance (solid curve) and strain (dashed curve), both vs. compressive stress cycle number for Cycles 48–50.

Except for the first cycle, the resistivity decreased with increasing strain in each cycle and then increased upon subsequent unloading in the same cycle. As cycling progressed, the baseline resistivity (i.e., the lower envelope of the resistivity variation) continuously increased, such that the increase was quite abrupt in the first three cycles (Fig. 2) and that subsequent baseline increase was more gradual. In addition, as cycling progressed, the amplitude of resistivity decrease within a cycle gradually and continuously increased (Fig. 2).

The increase in baseline resistivity dominated the first cycle and corresponded to a fractional change in resistivity per longitudinal unit strain of -1.1 (negative because the strain was negative). This negative value suggests that the baseline resistivity increase is due to damage (defect generation). The baseline resistivity increase was irreversible, indicating the irreversibility of the damage. The incremental increase in damage diminished as cycling progressed, as shown by the baseline resistivity increasing more gradually as cycling progressed.

The reversible decrease in resistivity within a stress cycle corresponds to a fractional change in resistivity per unit strain of $+0.72$ at cycle number 50. It is attributed to defect healing (reversible) under the compressive stress. As cycling progressed, the cumulative damage (as indicated by the baseline resistivity) increased and resulted in a greater degree of defect healing upon compression (hence, more decrease in resistivity within a cycle).

Both the baseline resistivity and the amplitude of resistivity decrease within a cycle serve as indicators of the extent of damage. Measurement of the baseline resistance does not need to be done in real time during loading, thus simplifying the measurement. However, its use in practice is complicated by possible shifts in the baseline by environmental, polarization and other factors. The measurement of the amplitude of resistivity decrease must be done in real time during loading, but it is not much affected by baseline shifts.

The compressive strength before stress cycling was 54.7 ± 1.7 MPa. That after 100 stress cycles was 53.1 ± 2.1 MPa. The modulus, as shown by the change of strain with stress in each cycle, was not affected by the cycling. Thus, the damage that occurred during the stress cycling was slight but was still detectable by resistivity measurement.

A comparison of the results of Ref. [4] on cement paste with those of this work on mortar shows that the magnitude of the fractional change in resistivity per unit strain (due to irreversible generation of defects) is higher for mortar (1.1) than for cement paste (0.10). Moreover, comparison shows that mortar more readily undergoes defect healing (reversible) than cement paste, as expected from the presence of the interface between fine aggregate and cement in mortar.

4. Concluding remarks

Minor damage of cement mortar during cyclic compression in the elastic regime was nondestructively monitored in real time by measurement of the electrical resistivity in the stress direction. The baseline resistivity irreversibly increased as cycling progressed due to defect generation, which was most significant in the first few cycles, and diminished as cycling progressed. Within a cycle, the resistivity decreased reversibly due to defect healing upon compression. The amplitude of resistivity decrease in a cycle increased upon cycling due to the increase in cumulative damage (indicated by the baseline resistivity) and the consequent increase in the extent of defect healing upon compression. Both the fractional increase in baseline resistivity and the amplitude of resistivity decrease in a cycle serve as indicators of damage.

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