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Defect dynamics and damage of concrete under repeated compression, studied by electrical resistance measurement

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Abstract

The electrical resistance of concrete in the stress direction increased during compressive loading in the first cycle, due to defect generation. It decreased during loading in all subsequent cycles, due to defect diminution. It increased during unloading in the first and all subsequent cycles, due to defect extension. The baseline resistance and the amplitude of resistance variation increased with cycling, due to minor damage. The interface between mortar and coarse aggregate contributed to the defect dynamics, particularly defect diminution. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Defects and damage affect the structural performance of concrete. It is therefore important to monitor damage and understand how defects respond to mechanical stress or strain. This article investigates both defect dynamics and damage of concrete by electrical resistance measurement.

Defects in a solid respond to applied stress. When the applied stress is dynamic, the response of the defects is also dynamic. The response encompasses the generation, diminution and extension of defects [1,2]. Defect generation refers to the formation of defects, such as microcracks; it usually occurs during loading. Defect diminution refers to the diminution of defects, such as the closing of microcracks; it can occur during compressive loading of a brittle material, such as a cement-based material. Defect extension refers to the propagation or enlargement of defects such as microcracks; it can occur during removal of a compressive stress from a brittle material.

Prior work on the defect dynamics of cement-based materials was limited to cement paste and mortar [1,2]. It was found that the interface between sand and cement contributes to the defect dynamics, particularly the defect diminution [2]. Therefore, it is expected that the interface between the coarse aggregate and mortar also contributes, perhaps even more so. This paper is aimed at extending the work from mortar to concrete.

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.

Prior work on the use of electrical resistance measurement to sense damage in cement-based materials was limited to mortar without fibers [3] and concrete with carbon fibers [4]. In the former case, it was found that defect generation results in an irreversible increase in the baseline resistivity as stress cycling progresses, whereas

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defect diminution results in a reversible decrease in the resistivity upon compression within a stress cycle. Defect generation is relatively significant in the early cycles and diminishes upon cycling. As the cumulative damage increases, the extent of defect diminution within a cycle also increases [3]. In the latter case, it was found that damage results in an increase in resistance, probably due to interface (e.g., interface between fiber and matrix) degradation [4]. As concrete without fibers is far more commonly used than that with fibers, and concrete is more commonly used than mortar, it is desirable to investigate the use of electrical resistance measurement to sense damage in concrete without fibers. This constitutes the second objective of this paper.

2. Experimental methods

The cement used was Portland cement (Type I) from Lafarge (Southfield, MI). Both fine and coarse aggregates were used. The fine aggregate was natural sand (99.9% SiO_2), 100% of which passed #8 US sieve. The coarse aggregate was #57 (ASTM C33-84), 100% of which passed 25 mm (1 in.) standard sieve. The ratio of cement/fine aggregate/coarse aggregate was 1:1.5:2.5.

The water/cement ratio was 0.45. A water-reducing agent (TAMOL SN, Rohm and Hass, Philadelphia, PA; sodium salt of a condensed naphthalenesulphonic acid) was used in the amount 2% of the cement mass.

All ingredients except water were mixed in a concrete mixer at a low speed for 1 min. After that, water was added and then mixing was conducted at a high speed for 5 min. The concrete mix was then poured into oiled cylindrical molds (125 mm diameter, 250 mm high). A vibrator was used to facilitate compaction and decrease the amount of air bubbles.

Four electrical contacts in the form of silver paint in conjunction with copper wire strands were applied circumferentially around a cylindrical specimen for the purpose of electrical resistance measurement by the four-probe method. The outer two contacts (240 mm apart, symmetrically positioned relative to the center plane perpendicular to the cylindrical axis) were for passing current. The inner two contacts (230 mm apart, symmetrically positioned relative to the center plane perpendicular to the cylindrical axis) were for voltage measurement. A Keithley 2002 (Cleveland, OH) multimeter was used for DC resistance measurement. Due to the large diameter of the cylinder, the current did not penetrate uniformly to the whole cross-section of a cylindrical specimen. As a result, the resistivity was not determined; only resistance on a relative scale was determined. No temperature rise occurred during the resistance measurement.

Compressive stress at a stress amplitude of 5.44 MPa (32.5% of the compressive strength, within the elastic regime) was applied to the top flat surface of a cylindrical specimen, while the resistance was measured. As a separate experiment, testing was conducted under repeated compressive loading at increasing stress amplitudes up to 5.44 MPa. A hydraulic mechanical testing system (MTS 810) was used to provide the stress under load control. Testing was conducted under cyclic loading up to 40 cycles, such that each stress cycle (an isosceles triangle in the curve of stress vs. time within a cycle) took 20 s.

Due to the voltage present during electrical resistance measurement, electric polarization occurred as the resistance measurement was made continuously. The polarization resulted in an increase in the measured resistance, although the effect was only significant when the time of measurement was long [5], as in the case of cyclic loading for dozens of cycles. The polarization-induced resistance increase, as separately measured as a function of the time of resistance measurement in the absence of stress, was subtracted from the measured resistance change obtained during cyclic loading in order to correct for the effect of polarization.

In order to assess the extent of damage due to the cyclic loading, compressive testing involving static loading (at a loading rate of 0.0604 MPa/s) up to failure was conducted before and after 40 stress cycles. Six specimens were tested before cycling and six specimens were tested after cycling.

All testing was conducted at ordinary room temperature and humidity.

3. Results

Figs. 1–3 show the fractional change in resistance in the stress direction vs. cycle number during cyclic compression. Except for the first cycle, the resistance decreased with increasing stress in each cycle and then increased upon subsequent unloading in the same cycle. As cycling progressed, the baseline resistivity gradually

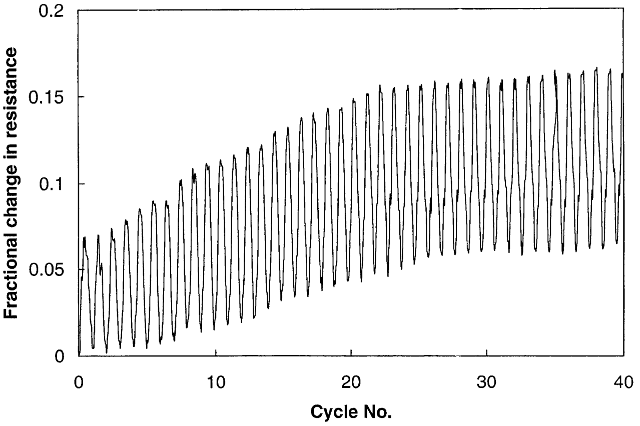

Fig. 1. Fractional change in resistance vs. compressive stress cycle number for Cycles 1–40.

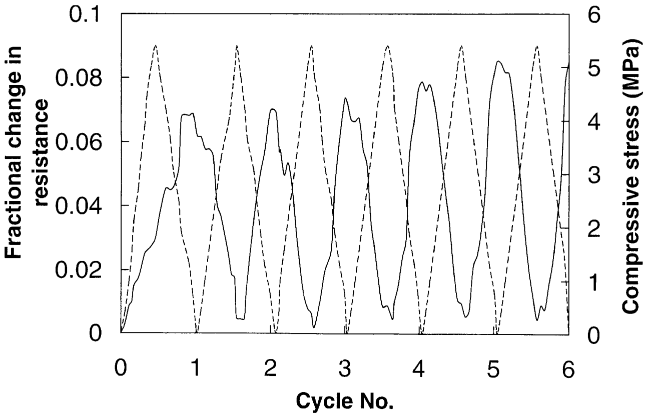

Fig. 2. Fractional change in resistance (solid curve) and stress (dashed curve) both vs. compressive stress cycle number for Cycles 1–6.

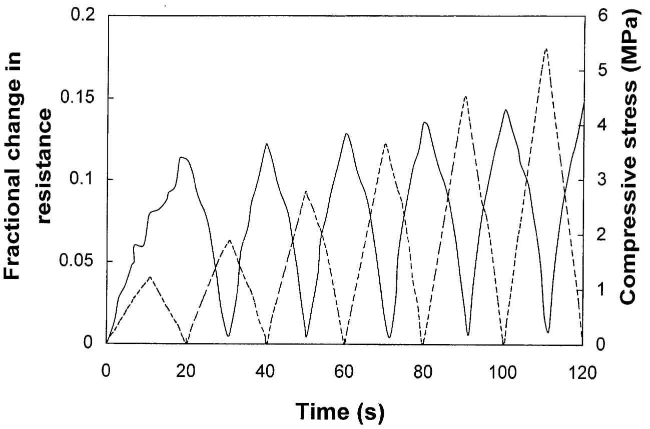

Fig. 4. Fractional change in resistance (solid curve) and stress (dashed curve) both vs. time during repeated compressive loading at increasing stress amplitudes.

and irreversibly increased (Fig. 1). In addition, as cycling progressed, the amplitude of resistance decrease within a cycle gradually and continuously increased especially in Cycles 1–9 (Fig. 1).

In the first cycle, the resistance increased upon loading and unloading, in contrast to all subsequent cycles, where the resistance decreased upon loading and increased upon unloading (Fig. 2).

The compressive strength before stress cycling was 16.73 ± 0.86 MPa. After 40 stress cycles it was 14.24 ± 0.97 MPa. Thus, the damage that occurred during the stress cycling was slight, but was still detectable by resistance measurement.

Fig. 4 shows the fractional change in resistance in the stress direction during repeated compressive loading at increasing stress amplitudes. The resistance increased during loading and unloading in Cycle 1, decreased during loading in all subsequent cycles and increased during unloading in all subsequent cycles, as in Fig. 2. The higher the stress amplitude, the greater was the amplitude of resistance variation within a cycle.

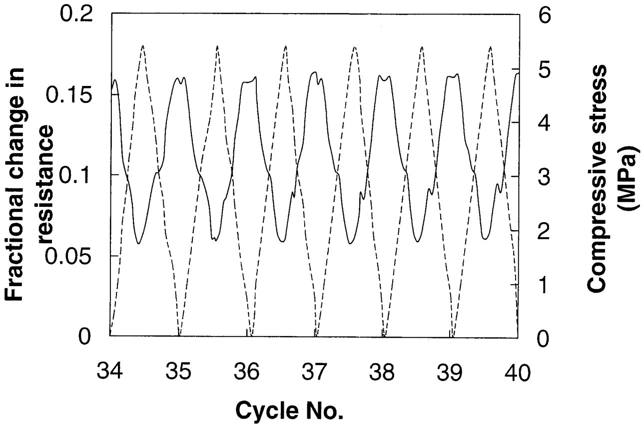

Fig. 3. Fractional change in resistance (solid curve) and stress (dashed curve) both vs. compressive stress cycle number for Cycles 35–40.

4. Discussion

The increase in resistance during loading in Cycle 1 is attributed to defect generation; that during subsequent unloading in Cycle 1 is attributed to defect extension (Figs. 2 and 4). In all subsequent cycles, the decrease in resistance during loading is attributed to defect diminution and the increase in resistance during unloading is attributed to defect extension.

The gradual increase in baseline resistance as stress cycling progressed (Fig. 1) is attributed to irreversible and slight damage. The increase in the amplitude of resistance variation as cycling progressed (Fig. 1) is attributed to the effect of damage on the extent of defect dynamics. In other words, the greater the damage, the greater was the extent of defect diminution during loading and the greater was the extent of defect extension during unloading. Consistent with this observation is that the amplitude of resistance variation increased with the stress amplitude (Fig. 4).

The results of this work on concrete are consistent with those of previous work on mortar and cement paste [1–3]. The compressive strength was higher for mortar than concrete [3]. The fractional loss in compressive strength after the cycling was greater for concrete than mortar [3]. Nevertheless, the baseline resistance increase was more significant for mortar than concrete, probably due to the relatively large area of the interface between cement and fine aggregate and the consequent greater sensitivity of the baseline resistivity to the quality of the interface between cement and fine aggregate than to the quality of the interface between mortar and coarse aggregate. The defect dynamics, as indicated by the fractional change in resistance within a cycle, were more significant for concrete (this work) than mortar [2,3]. The first defect diminution, as indicated by the resistance decrease during loading in Cycle 2 (Figs. 2 and 4), was much more complete for concrete than mortar [2,3]. These observations mean that the interface between mortar and coarse aggregate contributed to the defect dynamics (particularly defect diminution), due to the interfacial voids and defects. However, the interface between cement and fine aggregate dominated the irreversible electrical effects.

The electrical method described in this paper provides a nondestructive method for monitoring damage and dynamic stress in concrete. The simultaneous monitoring of these two quantities is attractive for identifying the cause of the damage. Both the baseline resistance and the resistance variation amplitude contribute to indicating damage.

5. Conclusions

Defect dynamics and minor damage of concrete under repeated compression were studied by measurement of the electrical resistance in the stress axis. The resistance increased during loading in the first cycle, due to defect generation. It decreased during loading in all subsequent cycles, due to defect diminution. It increased during unloading in the first and all subsequent cycles, due to defect extension. The baseline resistance increased gradually as cycling progressed, due to minor damage. The amplitude of resistance variation increased as cycling progressed, due to the increasing amount of damage. The interface between mortar and coarse aggregate contributed to the defect dynamics, particularly defect diminution.

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