



## Communication

# Effect of strain rate on cement mortar under compression, studied by electrical resistivity measurement

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**Abstract**

The electrical resistivity of cement mortar increased monotonically during compression. An increase in strain rate caused the resistivity at any strain level to decrease, in addition to causing the resistivity at failure to decrease. This means that the microstructural change that occurred continuously during loading decreased with increasing strain rate. © 2002 Elsevier Science Ltd. All rights reserved.

**Keywords:** Electrical properties; Mechanical properties; Cement mortar; Microstructure; Strain rate

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**1. Introduction**

The mechanical properties of cement-based material are strain rate sensitive. As for most materials (whether cement-based or not), the measured strength (whether tensile or compressive) increases with increasing strain rate [1]. This effect is practically important due to the high strain rate encountered in earthquakes and in impact loading. The effect is less for high-strength concrete than normal concrete [2] and is less at a curing age of 28 days than at an early age [3]. The cause of the effect is not completely understood, although it is related to the effect of strain rate on the crack propagation [1,4–6].

Although fracture mechanics [2,7,8], failure analysis [4] and mechanical testing over a wide range of strain rate [4,9,10] have been used to study the phenomenon and cause of the strain rate sensitivity of cement-based materials, the current level of understanding is limited. This is partly because of the experimental difficulty of monitoring the microstructural change during loading. Observation during loading is in contrast to that after loading. The former gives information on the damage evolution, whether the latter does not. Previous work on observation during loading is

limited to determination of the stress–strain relationship during loading. Although this relationship is important and basic, it does not give microstructural information. The use of a nondestructive real-time monitoring technique during loading is desirable. Microscopy is commonly used for microstructural observation, but it is usually not sensitive to subtle microstructural changes in a cement-based material and is not suitable for real-time monitoring.

In this work, electrical resistivity measurement is used for nondestructive monitoring, since the measurement is fast and is known to provide damage monitoring of cement paste; upon damage, the resistivity increases [11]. Previous work involving electrical resistivity measurement did not address the effect of strain rate.

**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<sub>2</sub>). The sand/cement ratio was 1.0. The water/cement ratio was 0.35. A 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,

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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  $2 \times 2 \times 2$ -in ( $51 \times 51 \times 51$ -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 static loading up to failure. The loading rates used were 0.144, 0.216 and 0.575 MPa/s. Six specimens were tested for each loading rate.

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 perimetricaly 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 [12]. 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. However, the correction was almost negligible, due to the short time taken for loading up to failure.

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

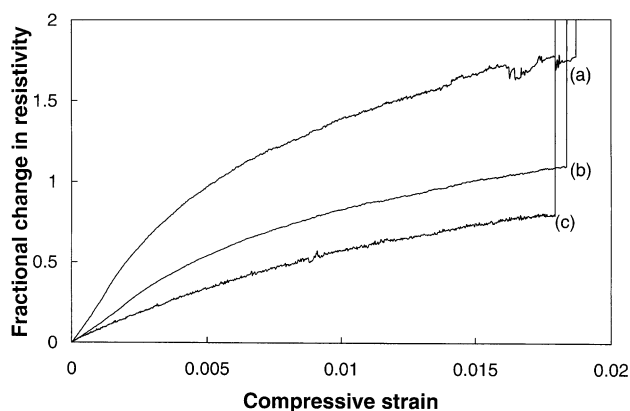


Fig. 1. Fractional change in resistivity versus strain during compressive testing up to failure at loading rates of (a) 0.144, (b) 0.216 and (c) 0.575 MPa/s.

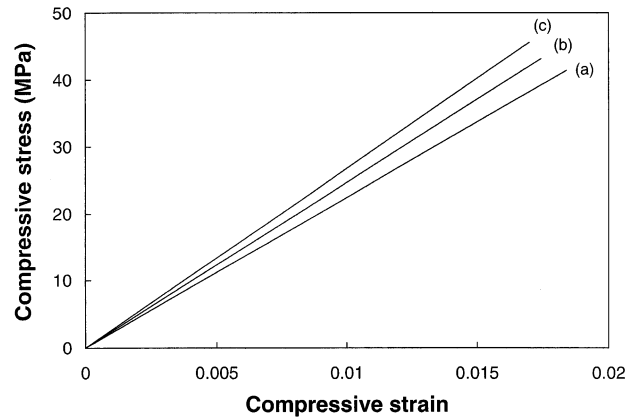


Fig. 2. Stress versus strain during compressive testing up to failure at loading rates of (a) 0.144, (b) 0.216 and (c) 0.575 MPa/s.

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.

### 3. Results and discussion

Fig. 1 shows the fractional change in resistivity in the stress direction versus the strain in the stress direction during compressive testing up to failure at three different loading rates. The resistivity increased monotonically with strain and stress, such that the resistivity increase was most significant when the strain or stress was low compared to the strain or stress at fracture. Similar curvature of the resistivity curve (Fig. 1) was observed for all three loading rates. At fracture, the resistivity abruptly increased, as expected. Fig. 2 shows the stress versus strain at different loading rates. The stress–strain curve is a straight line up to failure for any of the loading rates, indicating the brittleness of the failure. The higher the loading rate, the lower was the fractional change in resistivity at fracture and the higher was the compressive strength, as shown in Table 1. The modulus and ductility essentially did not vary with the loading rate in the range of loading rate used in this work, although the modulus slightly increased and the ductility slightly decreased with increasing loading rate, as expected.

Table 1  
Effect of strain rate on compressive properties

| Loading rate (MPa/s) | Strain rate ( $10^{-5}$ /s) | Strength (MPa) | Modulus of elasticity (GPa) | Ductility (%) | Fractional change in resistivity at fracture |
|----------------------|-----------------------------|----------------|-----------------------------|---------------|--|
| 0.144                | 5.3                         | $41.4 \pm 1.6$ | $1.83 \pm 0.17$             | $1.9 \pm 0.2$ | $1.78 \pm 0.24$                              |
| 0.216                | 8.8                         | $43.2 \pm 1.0$ | $1.85 \pm 0.14$             | $1.8 \pm 0.2$ | $1.10 \pm 0.13$                              |
| 0.575                | 23.3                        | $45.7 \pm 2.1$ | $1.93 \pm 0.17$             | $1.8 \pm 0.3$ | $0.81 \pm 0.16$                              |

The electrical resistivity is a geometry-independent property of a material. The gradual resistivity increase observed at any of the loading rates as the stress/strain increased indicates the occurrence of a continuous microstructural change, which involves the generation of defects that cause the resistivity to increase. The microstructural change is most significant in the early part of the loading. At any strain, the extent of microstructural change, as indicated by the fractional change in resistivity, decreased with increasing loading rate. In addition, the amount of damage at failure, as indicated by the fractional change in resistivity at failure, decreased with increasing strain rate. Hence, the loading rate affects not only the failure conditions, but also the damage evolution, all the way from the early part of the loading. A higher loading rate results in less time for microstructural changes, thereby leading to less damage build-up.

#### 4. Conclusion

The electrical resistivity of cement mortar increased monotonically with compressive strain/stress up to failure, such that the increase was more significant in the early part of the loading. An increase in the strain rate caused the resistivity at any strain level to decrease, in addition to causing the resistivity at failure to decrease. This means that the microstructure changed continuously during loading, such that the change was most significant in the early part of the loading. Furthermore, at any strain level, the extent of microstructural change decreased with increasing strain rate, thereby causing the compressive strength to increase with increasing strain rate.

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