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Effect of compressive strain on electrical resistivity of carbon black-filled cement-based composites

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Abstract

This paper investigates the strain sensing properties of carbon black (CB)-filled cement-based composites which were prepared with 120 nm CB. A linear relationship between the fractional change in resistivity and compressive strain was observed for cement-based composites containing a large amount of CB, suggesting that this kind of composite was a promising candidate for strain sensors used in concrete structures. Tunneling effect theory and percolation theory are employed to interpret the conductivity and electromechanical properties of CB-filled cement-based composites.

Keywords: Smart materials; Electrical properties

1. Introduction

Smart structural materials have the potential to improve the durability and performance of structures in long-term service. Materials that self-monitor their stress and strain conditions are attractive for health monitoring of the civil infrastructure. In the past decade, carbon fiber reinforced concrete (CFRC) and cement mortar containing nano-size semiconductors have been found capable of sensing compressive or tensile stress both in the elastic and inelastic regimes [1–6].

Additionally, it is well known that the resistivity of CB-filled conductive polymer composites change significantly when the composites are subjected to deformation. Some research on the effects of strain on the electrical properties of CB-filled conductive polymer composites has been carried out [7–12]. It has been shown that the effect of strain on the resistivity of a conductive composite is dependent upon the polymer, CB concentration and level of strain. The effect of strain on the resistance of rubber composites is attributed to two factors. On the one hand, the strain increased (elongation) or decreased (compression) the inter-particle distance between CB particles, leading to an increment or decrement of resistivity. On the other hand, the deformation induced by the applied strain promoted rotation and translation of asymmetric CB particles in the composites, and affected the number of conductive pathways in the strain direction. Studies indicated that a linear relation held between strain and logarithm of resistance of the composites. Furthermore, the simulation results obtained by using a tunneling junction model agreed very well with the experimental data, implying that tunneling effect theory could be used to investigate the effect of strain on resistivity of composites. The results also suggested that the composites could be used to prepare strain sensors for steel frames in buildings or ships [11,12].

The deformation ability of CB-filled polymer composites was very large, whereas the concrete structures experienced only small deformation. The deformation ability of CB-filled polymer composites did not match the requirement for health monitoring for concrete structures.

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Therefore, this paper proposes the use of CB-filled cement-based composites and studies their strain sensing properties. The purpose of this study is to provide a practicable strain sensor material for long-term health monitoring of infrastructures.

2. Experimental methods

Carbon black (CB) of 120 nm came from Liaoning Tianbao Energy Co., Ltd (Liaoning, China). The specific gravity of CB was 1.98 g cm^{-3}. CB in the amount of 5%, 10%, 12%, 15%, 20% and 25% by weight of cement (i.e., 3.11%, 6.04%, 7.22%, 8.79%, 11.39%, and 13.85% by volume of composite, respectively) were used, and in this paper the corresponding mixture types were called A-5, A-10, A-12, A-15, A-20 and A-25, respectively. The cement used was Portland cement (P.O42.5) from Harbin Cement Company (Harbin, China). The water–cement ratio was 0.4 for all specimens. A water-reducing agent UNF (one kind of—naphthalene sulfonic acid and formaldehyde condensates) was used in the amount of 1.5% by weight of cement. The water-reducing agent could increase the dispersion of CB particles and facilitate the workability of the mixture. The defoamer, tributyl phosphate (made in China), was used in the amount of 0.13 vol.% to decrease the number of air bubbles.

Defoamer and UNF water-reducing agent were dissolved in water, then CB was added and stirred at high speed in a mortar mixer for 3 min. This mixture and the cement were mixed at high speed for 2 min. After this, the mix was poured into oiled molds to form prisms of $30 \times 40 \times 50$ mm for compressive testing. After pouring, an external vibrator was used to facilitate compaction and decrease the number of air bubbles. The samples were demolded after 24 h and then cured in a moist room (relative humidity 100%) for 28 days. Afterwards, the specimens were dried in an oven at 60 °C for two days to extract redundant water to eliminate the polarization effect on resistance measurement. The dried specimens were then tested at ambient temperature.

DC electrical resistance measurement was made in the longitudinal axis, using the four-probe method, in which copper nets served as electrical contacts. The copper nets were placed into the specimen when pouring the mix into molds. Fig. 1 shows the schematic of the experimental set-up. Four contacts were placed across the whole cross-section of 30×40 mm of the specimen, these were all perpendicular to the longitudinal axis and symmetrically positioned with respect to the mid-point along the height of the specimen (i.e., two contacts were in planes above the mid-point and two contacts were in planes below the mid-point). The outer two contacts (36 mm apart) were for passing current. The inner two contacts (20 mm apart) were for measuring the voltage. A FLUKE 8842A multimeter was used.

Compressive testing was performed on a 30×40 mm side of each specimen. The strain was measured by using strain gauges attached to the middle of the opposite sides of a specimen and parallel to the stress axis, as shown in Fig. 1. Compressive testing under force control was conducted using a hydraulic mechanical testing system with 120-kN maximum loading capacity. The scheme of monotonically static loading up to specimen failure was arranged. During the loading process, DC electrical resistance measurement was simultaneously made in the stress axis, using the four-probe method as described earlier. Three specimens of each type mixture were tested.

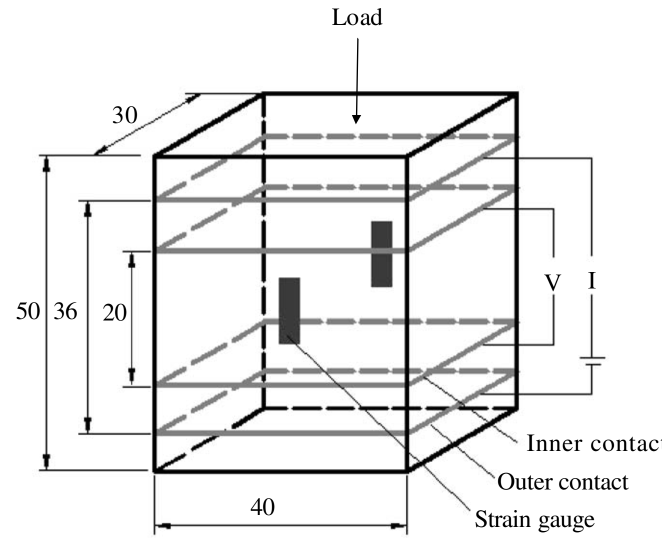

Fig. 1. Schematic of the experimental set-up (mm).

3. Results

Fig. 2 shows the resistivity (ρ) as a function of CB volume content (V) of CB-filled composites. It can be observed from Fig. 2 that the resistivity of the composites decreased dramatically with increasing CB content from 7.22 to 11.39 vol.%, i.e. from A-12 to A-20. The resistivity of the composites varied slightly outside the above range. The content range over which the resistivity varied precipitously was called percolation threshold. Therefore, in this

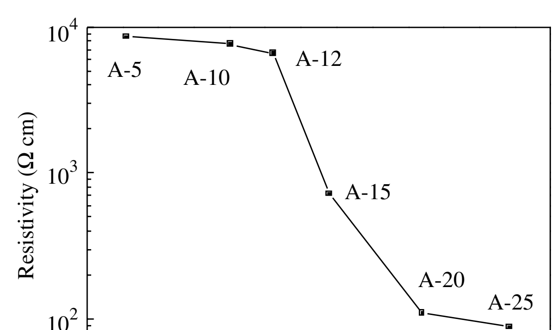

Fig. 2. Logarithm of resistivity as a function of volume content of CB.

study, the percolation threshold zone of the composites was CB in the amount of 7.22–11.39 vol.%.

Fig. 3 presents the strain–stress curves of A-15. It can be seen from Fig. 3 that the strength of the CB-filled composite could reach more than 40 MPa. Therefore, it can be used as a structural material like common concrete. Similar results have been obtained for other mixtures.

Figs. 4–6 show the fractional change in resistivity versus the compressive strain curves of A-15, A-20 and A-25, respectively. For A-5, A-10 and A-12, the resistivity varied randomly with applied compressive strain and the data of A-5, A-10 and A-12 were too noisy to be meaningful. Therefore, the results for these mixtures are not presented here. Additionally, the distance between probes was shortened during loading, which induced change in electrical resistance. However, it could be observed from Fig. 3 that the change in resistance induced by this factor was very small and negligible. The resistance was essentially proportional to the volume resistivity that was selected as a measurement in this study.

For A-15 (shown in Fig. 4), the resistivity decreased linearly with increasing compressive strain up to failure of the specimens except for a small perturbation over the strain range of (0.003–0.004) which indicated the occurrence of microcracks. The three curves for the three specimens of this mixture were almost the same, indicating that the results were repeatable. Linear fit of the experimental data showed that the relationship between the fractional change in resistivity and compressive strain was nearly linear. The fractional change in resistivity per unit strain (i.e., the strain sensitivity of the gauge factor) was 55.28 as shown in Fig. 4.

Similar results can be observed in Figs. 5 and 6 for A-20 and A-25. These curves were linear too. However, the fractional changes in resistivity per unit strain of A-20 and A-25 were, respectively, 37.71 and 51.85.

It could be concluded from the results that the CB-filled cement-based composites were suitable for strain gauges. Also, the strain sensitivity of these three types of mixtures increased in the order A-20 < A-25 < A-15.

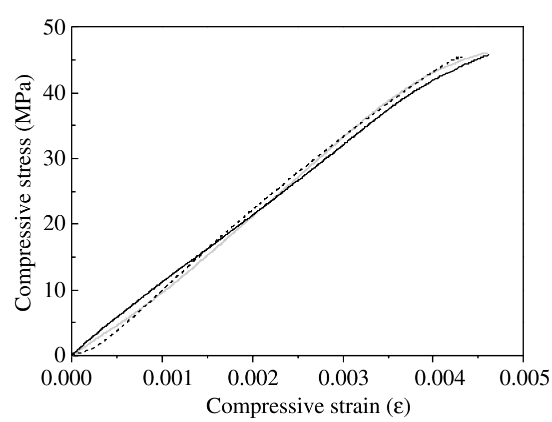

Fig. 3. Stress–strain curves of A-15.

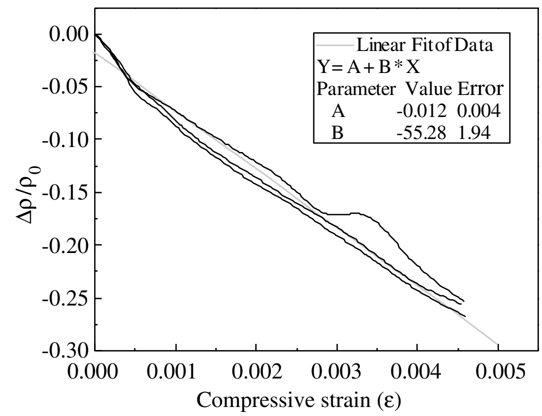

Fig. 4. Fractional change in resistivity of A-15 as a function of compressive strain.

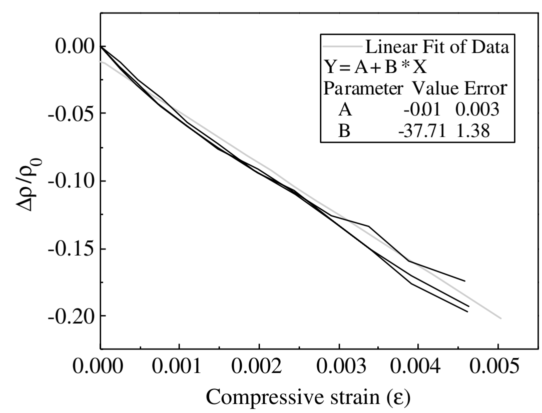

Fig. 5. Fractional change in resistivity of A-20 as a function of compressive strain.

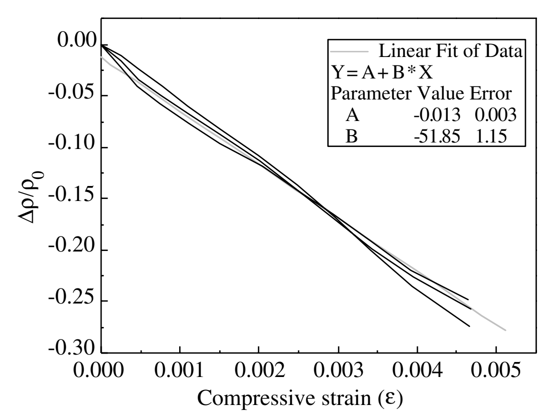

Fig. 6. Fractional change in resistivity of A-25 as a function of compressive strain.

4. Discussion

CB-filled cement-based composites were able to sense their own compressive strain. Origin of this property of the composites was very complicated.

Based on previous studies on conductivity of composites [13], percolation theory and tunneling effect theory were adopted to explain the conductivity and electromechanical properties of CB-filled cement-based composites.

According to tunneling effect theory, the natural logarithm of resistivity of composites $\ln(\rho)$ is a linear function of potential barrier width (s), i.e. the distance between CB particles. Furthermore, it is well accepted that distribution of CB particles is random and the average distance between particles is proportional to $V^{-1/3}$ [14]. Thus, $\ln(\rho)$ is a linear function of $V^{-1/3}$. For clear observation, the $V^{-1/3}$ and natural logarithm of resistivity were, respectively, nominated as abscissa and ordinate and the curve in Fig. 2 was redrawn in Fig. 7. The curve can be divided into three stages according to the variation of slope. The curve from 7.22 to 11.39 vol.% in Fig. 7 was just linear, so the tunneling effect dominated conductivity and electromechanical properties of the composites in stage II. Percolation theory could be employed to interpret the conductivity and electromechanical properties of CB-filled cement-based composites with CB content exceeding percolation threshold zone, e.g. A-20 and A-25.

Simmons [15] proposed the following equation for tunneling current density at low voltage region

$$J = [3(2m\varphi)^{1/2}/2s](e/h)^2 U \cdot \exp[-(4\pi s/h)(2m\varphi)^{1/2}] \qquad (1)$$

where m, e and h are the electron mass, charge on an electron and Planck's constant, respectively. φ, s and U are the height of tunnel potential barrier, potential barrier width and voltage applied across barrier, respectively. Eq. (1) shows that tunneling current is an exponential function of barrier width, implying a precipitous change of resistivity upon distance between CB particles. The distance between CB particles is shortened with increasing compressive strain on specimens. As a consequence, the resistivity of composites decreases with increasing compressive strain according to tunneling effect theory.

When CB content is larger than percolation threshold value, percolation theory dominates conductivity and the electromechanical properties of CB-filled cement-based composites. In this study, conductivity and electromechanical properties of A-20 and A-25 could be interpreted by percolation theory which states that an infinite percolation networks through compound formed via nearly physical contact between CB particles. Therefore, contact resistivity and the number of conductive pathways play critical roles on conductivity and electromechanical properties [13]. The number of conductive pathways increase with increasing CB content, leading to resistivity of composites decreasing, which coincides with that presented in Fig. 2 (The resistivity of A-25 is smaller than that of A-20.). Contact resistivity between CB particles decreases with increasing load [16], similar to that of carbon fiber reinforced concrete [6]. Obviously, the number of contact interfaces between CB particles and cement increases with increasing CB content. Consequently, resistivity of composites with more CB particles drops more dramatically than that with fewer CB particles when the same level of compressive strain is applied on specimens. The strain sensitivity of the gauge factor of the composites increases with increasing CB particles in percolation range, which coincides with electromechanical properties of A-20 and A-25 observed in the tests.

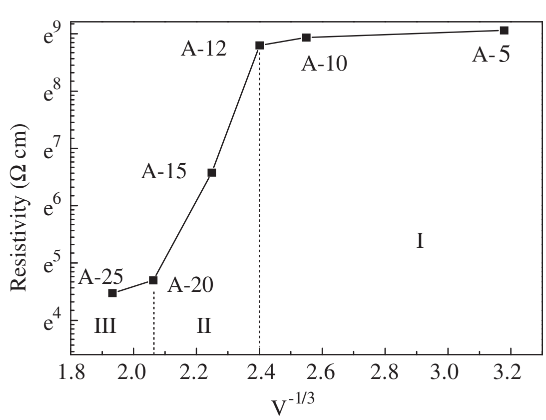

Fig. 7. Natural logarithm of resistivity as a function of $V^{-1/3}$.

Indeed, the tunneling effect and percolation phenomenon (physical contact) existed simultaneously in all specimens [17]. For A-15, the tunneling effect dominated conductivity and electromechanical properties; at the same time, contact resistivity between the CB particles and cement also decreased with increasing load. Similarly, for A-20 and A-25, physical contact dominated conductivity and electromechanical properties; at the same time, electromechanical properties were also slightly affected by the tunneling effect. However, the tunneling effect gradually faded with a shortened distance between CB particles, i.e. increasing CB content. For A-5, on the one hand, the distance between CB particles was too large to make electron transit; on the other hand, there were too few CB particles to form conductive networks. As a consequence, electric resistivity of A-5 was large and there was no occurrence of electromechanical properties for this mixture.

5. Conclusion

The following conclusions were derived from this study:

(1) The fractional change in resistivity decreased linearly with applied strain for cement-based composites with CB content in the amount of 8.79–13.85 vol.%. The strain sensitivity of the three types of mixtures increased in the order A-20 < A-25 < A-15.
(2) Both tunneling effect and percolation phenomena simultaneously played important roles in conductivity and electromechanical properties of CB-filled cement-based composites. Tunneling effect plays a dominant role when the CB content is smaller than the percolation threshold, whereas percolation phenomena play a critical role when the CB content is larger than the percolation threshold.
(3) Percolation threshold was observed for CB-filled cement-based composites. The percolation threshold zone of the CB-filled cement-based composites was

CB in the amount of 7.22–11.39 vol.%. A linear relationship between natural logarithm of resistivity and $V^{-1/3}$ was observed over the percolation zone, indicating that the tunneling effect played a critical role in conductivity and electromechanical properties when CB content was smaller than the percolation threshold.

(4) The CB-filled cement-based composites containing CB in the amount of 11.39–13.85 vol.% were in the post-percolation zone. The contact resistivity played a dominant role in conductivity and electromechanical properties in this case.

Acknowledgements

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