Strain sensing property of carbon black filled cement-based composites

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ABSTRACT: Effect of strain on the resistivity of carbon black (CB) filled cement-based composites were studied in this paper. The composites were prepared with CB of 120nm size. A linear relationship between the fractional change in resistivity and compressive strain was observed for cement-based composites filled with large content of CB, suggesting that this kind of composites was a promising candidate for strain sensor used in concrete structures. The straining sensing properties of the composites were affected by tunneling effect and percolation phenomena.

1 INTRODUCTION

Smart structural materials that can monitor stress and strain themselves have been more and more attractive in health monitoring for civil infrastructure due to their durability and promising performance in long-term service. In the past decade, Chung D.D.L *et al*. (1998) and Li *et al* (2004) found that carbon fiber reinforced concrete (CFRC) and cement mortar containing nano-size semiconductors have been found to be available to sense compressive or tensile stress both in elastic and inelastic regimes for their volume resistance changing with applied stress.

Additionally, it is well known that the resistivity of carbon black (CB) filled conductive polymer composites changed significantly when the composites were subjected to deformation. A number of researches of the effects of strain on the electrical properties of CB-filled conductive polymer composites have been carried out, which have been summarized by G. Schwartz *et al* (2000) and Simmons J G (1963). It has been found that the effect of strain on the resistivity of a conductive composite was dependent upon the polymer, CB concentration and the level of strain. The effect of strain on the resistance of rubber composites was 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, affecting 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 applied to investigate the effect of strain on resistivity of composites. The results also suggested that the composites could be used to prepare strain sensors that could be applied to steel frames in buildings or ships.

The deformation ability of CB-filled polymer composites was very large, whereas the concrete structures could only experience small deformation. The deformation ability of CB filled polymer composites didn’t match the requirement of health monitoring for concrete structures. Therefore, this paper proposed the CB filled cement-based composites and studied their strain sensing properties. The purpose of this study was to provide a practicable strain sensor material for long-term health monitoring for infrastructures, the material would be sensitive to strain, and this sensing ability would be insensitive to temperature.

2 EXPERIMENTAL METHODS

Carbon black (CB) of 120nm was from Liaoning Tianbao Energy Co., Ltd (Liaoning, China). CB in the amount of 5%, 10%, 15%, 20% and 25% by weight of cement (i.e., 3.11%, 6.04%, 8.79%, 11.39%, and 13.85% by volume of composite, respectively) were used, and in this paper the corresponding mix type were called A5, A10, A15, A20 and A25 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 help the dispersion of CB particles and facilitate the workability of mix. The defoamer, tributyl phosphate (made in China), was used in the amount of 0.13 vol.% to decrease the amount of air bubbles.

Defoamer and UNF water-reducing agent were dissolved in water, and 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 size 30×40×50mm for compressive testing. After pouring, an external vibrator was used to facilitate compaction and decrease the amount of air bubbles. The samples were demolded after 24h and then cured in a moist room (relative humidity 100%) for 28 days.

DC electrical resistance measurement was made in the longitudinal axis, using the four-probe method, in which copper net served as electrical contacts. The copper nets were placed into the specimen when pouring mix into molds. Four contacts were across the whole cross-section of 30×40mm of the specimen that 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 (36mm apart) were for passing current. The inner two contacts (20mm apart) were for measuring the voltage. A FLUKE 8842A multimeter was used.

Compressive testing was performed on a 30×40mm side of each specimen. The strain was measured by using strain gages attached to the middle of the opposite sides of a specimen. The strain gages were parallel to the stress axis. 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 loading process, DC electrical resistance measurement was simultaneously made in the stress axis, using the four-probe method as described earlier.

3 RESULTS

Figure.1 showed the resistivity (*ρ*) as a function of CB volume content (*V*) of composites filled with CB. It could be observed from Figure.1 that the resistivity of the composites decreased dramatically with increasing CB content from 10% to 20%, i.e. A10, A15 and A20. Over other content ranges, the resistivity of the composites decreased slightly with increasing CB content. The content range over which the resistivity varied dramatically was called percolation threshold. In this study, the percolation threshold zone was CB in the amount of 10%~20% by weight of cement, nominated stage II in Figure.1. It should be noted that though the resistivity looked decreased slightly from A15 to A20. But in fact the fractional change in resistivity per unit content for section from A15 to A20 was 0.85 that near the 0.90 for section from A10 to A15. Therefore, we partitioned stage Ⅱ as from A10 to A20.

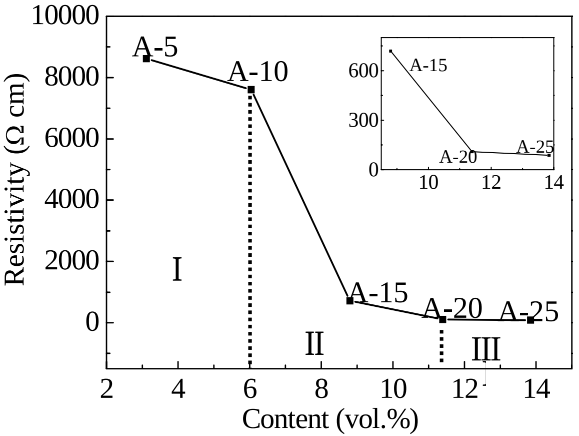

Figure.1. Resistivity of composites as a function of CB content

Figures.2~4 showed the fractional change in resistivity versus compressive strain curves of A15, A20 and A25, respectively. At least three specimens of each type were tested. For A5 and A10, the resistivity varied randomly with applied compressive strain. The data of A5 and A10 were too noisy to be meaningful. Therefore the results for these cases didn't present here. Additionally, the distance between probes was shortening during loading, which induced change in electrical resistance. However, the change in resistance induced by this factor was too small and could be neglected. The resistance was essentially proportional to volume resistivity that was referred to as measurement in this study.

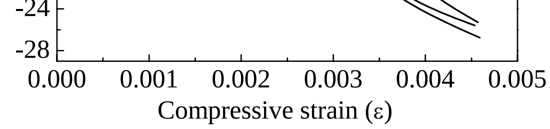

Figure.2. Fractional change in resistivity of A15 as a function of compressive strain.

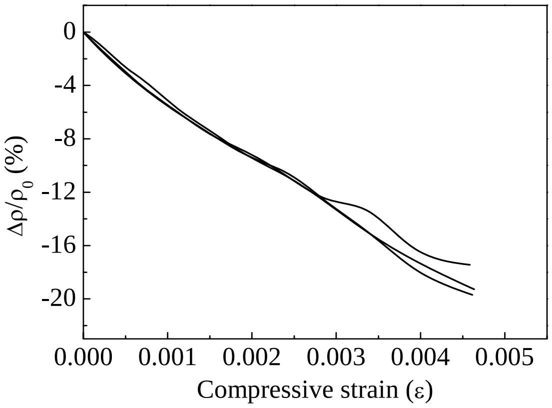

Figure.3. Fractional change in resistivity of A20 as a function of compressive strain.

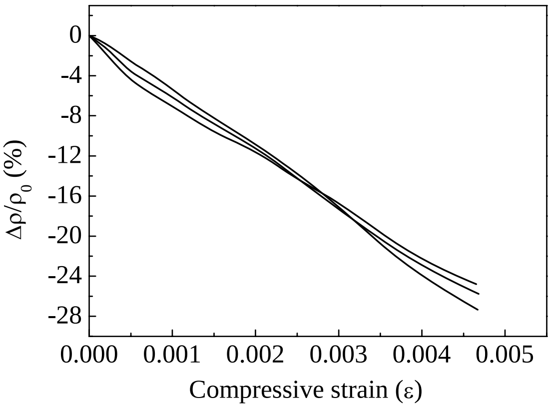

Figure.4. Fractional change in resistivity of A25 as a function of compressive strain.

For A15 (shown in Figure.2), the resistivity decreased linearly with increasing compressive strain up to failure of the specimens except small perturbation over the strain range of [0.003~0.004] which indicated the occurrence of microcrack. The three curves for three specimens of this mixture were almost the same, indicating 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, and the fractional change in resistivity per unit strain (i.e., the strain sensitivity of the gage factor) was 5525.7 as shown in Figure.2.

The similar results could be observed in Figures 3 ~4 for A20 and A25. The data of them were linear too. However, the fractional change in resistivity per unit strain of A20 and A25 were respectively 3770.5 and 5185.4.

It could be concluded from the results that the cement-based composites filled with CB were available to be strain gauges. And the strain sensitivity of the three types of mixtures increased in the order A20<A25<A15.

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, percolation theory and tunneling effect theory were adopted to explain the conductivity and electromechanical properties of CB filled cement-based composites.

Simmons proposed the following equation of tunneling current density at low voltage region

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

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

When CB content is larger than percolation threshold, percolation theory dominated conductivity and electromechanical properties of CB filled cement-based composites. In this study, conductivity and electromechanical properties of A20 and A25 could be interpreted by percolation theory. According to percolation theory, an infinite percolation networks through compound formed via nearly physical contact between CB particles. Therefore, contact resistivity and the number of conductive pathways played critical roles on conductivity and electromechanical properties. The number of conductive pathways increased with CB content, leading to resistivity of composites decreasing, which coincided with that presented in Figure. 1 (The resistivity of A25 is smaller than that of A20). Contact resistivity between CB particles decreased with increasing load, similar with that carbon fiber reinforced concrete. Obviously, number of contact interface between CB particles and cement increased with increasing CB content. Consequently, resistivity of composites with more content of CB particles dropped more dramatically than that with smaller content of CB particles when the same level of compressive strain was applied on specimens. The strain sensitivity of gauge factor of the composites increased with increasing CB particles, which coincided with electromechanical properties of A20 and A25.

In deed, tunneling effect and percolation phenomenon (physical contact) existed simultaneously in all specimens. For A15, tunneling effect dominated conductivity and electromechanical properties, at the same time contact resistivity between CB particles and cement also decreased with increasing loading. For A20 and A25, physical contact dominated conductivity and electromechanical properties, at the same time electromechanical properties were also affected slightly by tunneling effect. However, the tunneling effect became faintly with shortening distance between CB particles, i.e. increasing CB content. For A5, on the one hand, the distance between CB particles was too large to transit for electrons; on the other hand, CB particles were too few to form conductive networks. As a consequence, electric resistivity of A5 was large and no occurrence of electromechanical properties for this mixture.

5 CONCLUSIONS

The following conclusions were obtained from this study.

1) The fractional change in resistivity decreased linearly with applied strain for cement-based composites with large CB content. The strain sensitivity of the three types of mixtures increased in the order A20<A25<A15.

2) Both tunneling effect and percolation phenomena played important roles in conductivity and electromechanical properties of CB filled cement-based composites at the same time. Tunneling effect played a dominant role for some cases, however, percolation phenomena played a critical role for other cases.

3) Percolation threshold was observed for cement-base composites filled with CB. The percolation zone for CB content was in the amount of 10%~20% by weight of cement. Tunneling effect played a critical role in conductivity and electromechanical properties when CB content was close to percolation threshold.

4) The cement-based composites with CB content of 20~25% by weight of cement were in post-percolation zone. The contact resistivity played a dominant role in conductivity and electromechanical properties for this case.

6 AKNOWLEDGEMENTS

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