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EFFECT OF TEMPERATURE ON ELECTRICAL PROPERTY OF CARBIN BLACK-FILLED CEMENT-BASED COMPOSITES

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Abstract

Cement-based composites filled with 120nm carbon black in the amount of 15% (A-15) and 25% (A-25) were found to be the promising strain sensor material candidates. This paper investigates the effects of temperature on the electrical property of A-15 and A-25. Encapsulated with epoxy was a practical way to insulate the composites from water. Study on temperature effect showed that resistivity of A-15 or A-25 was temperature dependence, however, the strain sensing the ability of them were independent from temperature. Experimental results suggested that A-15 or A-25 was a promising candidate for strain sensor used in concrete structures.

INTRODUCTION

Health monitoring in civil infrastructure needs a durable strain sensor. It is well known that the resistivity of carbon black (CB)-filled conductive polymer composites change significantly when the composites are subjected to deformation. It is suggested that the composites could be used to prepare strain sensors for steel frames in buildings or ships [1-3]. However, the deformation ability of CB-filled polymer composites is very large, whereas the concrete structures only experienced small deformation. The deformation ability of CB-filled polymer composites didn’t match the requirement of health monitoring for concrete structures. Therefore, electrical property of CB-filled cement-based composites has been explored [11], Experimental results showed that resistivity of A-15 and A-25 changed linearly upon strain, and the strain gauge factor was 55 and 52 respectively. So A-15 and A-25 were promising strain sensor materials for long-term health monitoring for infrastructures. In addition, carbon fiber reinforced concrete (CFRC) and cement mortar containing nano-sized semiconductors have been found capable sensing compressive or tensile stress, both in the elastic and inelastic regimes for their volume resistance, changing with applied stress [4-7]. Due to their durability and promising performance in long-term service, smart structural materials that can monitor stress and strain themselves have been more and more attractive in health monitoring. But past research mainly focus on the effect of strain on the resistivity of materials, the effect of moisture or temperature was rarely considered.

However, the environmental temperature is variable, which will affect the temperature of cement-based composites. For the purpose of using smart concrete sensors in real engineering, this paper was to study the effect of temperature on the property of A-15 or A-25, and explored the mechanism.

MATERIALS AND METHODS

Carbon black (CB) of 120nm came from Liaoning Tianbao Energy Co., Ltd (Liaoning, China). The specific gravity of CB was 1.98g/cm^3. CB in the amount of 15% and 25% by weight of cement (i.e., 8.79% and 13.85% by volume of composite, respectively) were used, and in this paper the corresponding mix types were called A-15 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 mix. 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, and then CB was added and stirred at high speed in a mortar mixer for 3 minutes. This mixture and the cement were mixed at high speed for 2 minutes. After this, the mix was poured into oiled molds to form prisms of 30×40×50mm. After pouring, an external vibrator was used to facilitate compaction and decrease the number of air bubbles. The samples were demolded after 24h and then cured in a moist room (relative humidity 100%) for 28 days. Specimens of A-15 and A-25 were encapsulated with epoxy after being dried at 60℃ for 48 hours. Additionally, temperature couples were fixed inside the center of some specimens when molding, to measure the temperature of specimens.

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 the mix into molds. Fig.1 shows the schematic of experimental set up. Four contacts were placed across the whole cross-section of 30×40mm 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 (36mm apart) were for passing current. The inner two contacts (20mm apart) were for measuring the voltage. A data acquisitive system was used to measure the resistance in real time, as shown in Fig.1. The series reference resistor (R_r) was fixed and known. Presume that the voltage of reference resistor was U_r and the voltage between two inner contacts was U_i, the resistance of specimen between two inner contacts (R_i) could be obtained as $R_i = U_i \cdot R_r / U_r$, therefore, the resistivity of the specimen could be easily calculated. U_i and U_r were acquired with a data acquisition board.

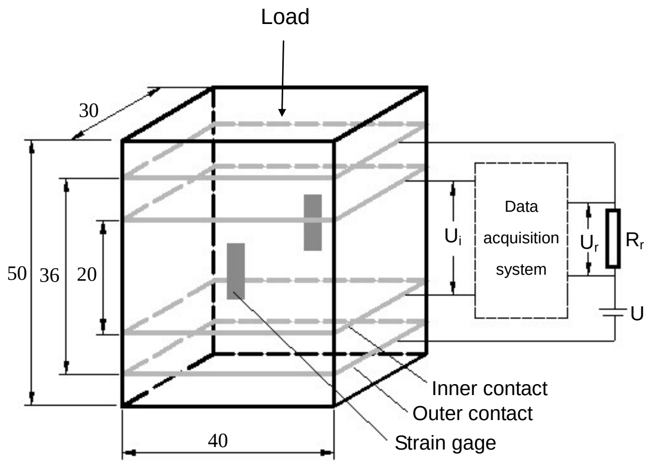


Figure 1. Schematic of the experimental set-up (all dimensions in mm).

To study the effect of temperature on the resistivity of composites, a temperature controller was used to control the temperature of specimens in the regime from -10℃ to 100℃. During the temperature change process, DC electrical resistance was measured with a four-probe method. The strain gauges were attached to the middle of the opposite sides of a specimen to measure the strain of composites caused by temperature.

Temperature on the strain-sensing property of A-15 and A-25 was studied. Compressive testing was conducted using a mechanical testing system. Compressive testing was performed on a 30×40mm side of each specimen. Before applied loading, the temperature of specimen was controlled to –10, 20 and 50℃ respectively with a temperature control box of the MTS, a reference specimen fixed with a temperature couple was beside the test specimen to help measure the temperature as shown in Fig.2. The scheme of monotonically static loading up to specimen failure was arranged. The strain was measured by using strain gauges attached to the middle of the opposite sides of a specimen. The strain gauges were parallel to the stress axis. During the loading process, DC electrical resistance measurement was simultaneously made in the stress axis, using the four-probe method as described earlier.

RESULTS AND DISCUSSION

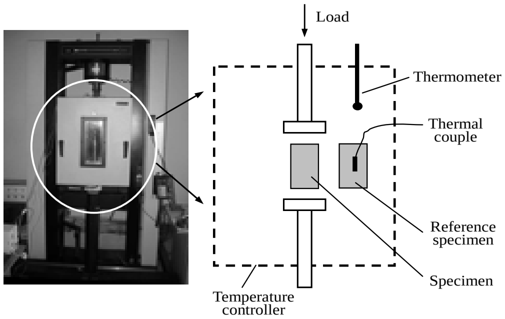


Figure 2. Schematic of experimental setup.

Thermal expansion of CB-filled composite can change the width between CB particles, and as a result, the resistivity of the composite changes [9]. Therefore, effect of temperature on the resistivity of CB-filled composites includes two sides: (Ⅰ)Resistivity changes as a consequence of thermal expansion; (Ⅱ) Except for the effect of thermal expansion, change of resistivity resulted from temperature. In this study, the linear expansion factor of A-15 and A-25 was measured as 1.65×10^5 and 1.62×10^5 respectively. And the percent fractional change in resistivity of A-15 and A-25 per micro-strain was 0.0055% and 0.0052% respectively. So the effect of factor (Ⅰ) was obtained and removed from the effect of temperature, then the effect of factor (Ⅱ) was obtained for temperature compensation when using used the composite as a strain sensor.

Fig.3 shows the effect of temperature on the resistivity of A-15. Curve (a) includes factor (Ⅰ) and factor (Ⅱ), curve (b) includes only factor (Ⅱ). The curves are described in the form of fractional change in resistivity upon temperature and the resistivity of the specimen at 0℃ was taken as the reference resistivity. Curve (a) could be separted into two stages. From -10℃ to about 50℃, the resistivity of the composites decreased linearly with temperature, and with further increase in temperature, the resistivity of the composites turned to increase. If there was no expansion of specimen, the effect of temperature would be represented as curve (b). The resistivity decreased nearly linearly from -10℃ to about 50℃, and then decreased gradually. The highest fractional change in resistivity in curve (b) was about 10%.

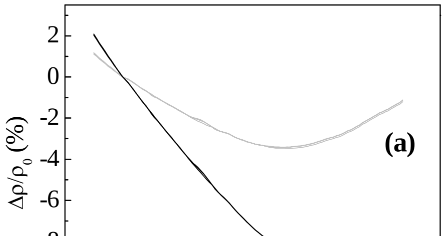


Fig.3. Variation of the fractional change in resistivity of A-15 with temperature. Curve (a) includes effect of factor (Ⅰ) and factor (Ⅱ), curve (b) includes only effect of factor (Ⅱ).

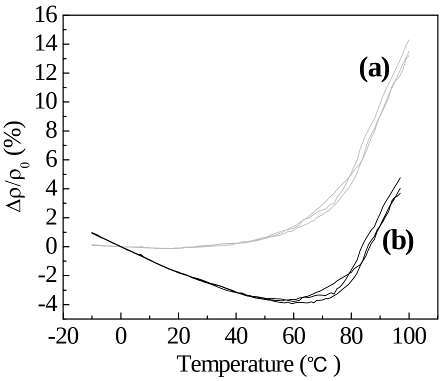
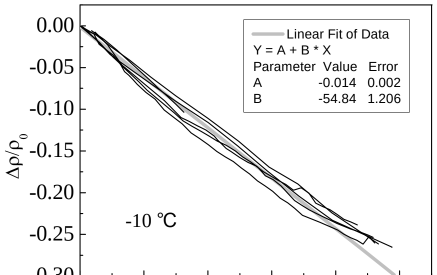


Fig.4. Variation of the fractional change in resistivity of A-25 with temperature. Curve (a) includes effect of factor (Ⅰ) and factor (Ⅱ), curve (b) includes only effect of factor (Ⅱ).

Fig.4 shows the effect of temperature on the resistivity of A-25. Curve (a) includes factor (Ⅰ) and factor (Ⅱ), curve (b) includes only factor (Ⅱ). The curves are described in the form of fractional change in resistivity upon temperature and the resistivity of the specimen at 0℃ was taken as the reference resistivity. Both curve (a) and curve (b) from -10℃ to about 50℃, the resistivity of the composites changed with temperature more slowly than that of A-15. With further increase in temperature, the resistivity of the composites increased abruptly. The highest fractional change in resistivity in curve (b) was about 4%.



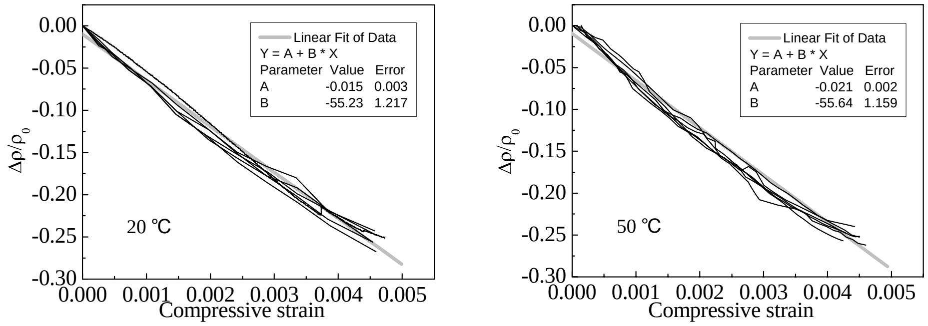
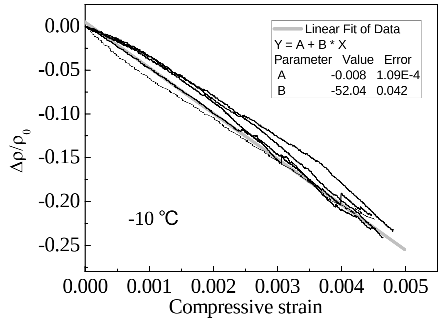


Fig.5. Fractional change in resistivity as a function of compressive strain of A-15 at various temperatures.

For A-15, conduction is dominated by electron tunneling across small barriers separating large conduction regions. And, the tunneling can be essentially regarded as between two bulk conductors. According to early research [8], there are two possible sources of the electric field on the tunneling junction, one is obviously the externally applied field. As for the second source, since the tunnel junction is situated in a thermal bath, there will inevitably be thermal fluctuations leading to voltage difference across the junction. An equation was proposed to explain the temperature dependence of conductivity of composites:

$$\sigma = \sigma_0 \exp[-T_1 /(T + T_0)] \qquad (1)$$

Where σ_0, T_1 and T_0 are the constants related to the property of composites. From the equation we know that the resistivity of A-15 was an exponential function of temperature and decreased with temperature. This was in agreement with our experimental results as shown in curve (b) of Fig. 3. For A-25, the concentration of CB was large and the conduction network was continuous, the material exhibits graphitic conductivity. The resistivity was related to the charging of energy that was required to remove an electron from a neutral aggregate. At higher temperatures, the continuous conduction network would be damaged by thermal expansion, the resistivity of A-25 increased with temperature as shown in curve (b) of Fig. 4.



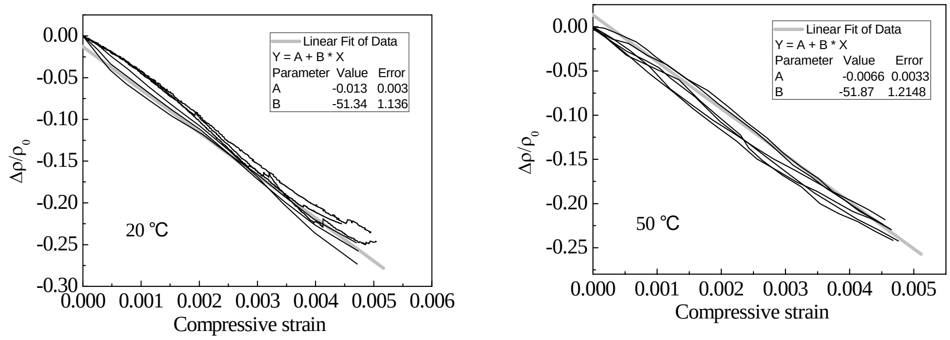


Fig.6. Fractional change in resistivity as a function of compressive strain of A-25 at various temperatures.

Fig.5 shows the strain-sensing property of A-15 under various temperatures. And Fig.6 shows the strain-sensing property of A-25 under various temperatures. Corresponding to the general environmental temperature of structures, the strain-sensing property of A-15 or A-25 was conducted at –10℃, 20℃ and 50℃ respectively. Fig.5 and Fig.6 show that resistivity of composite change linearly upon compressive strain, the strain gauge factor of A-15 or A-25 under various temperatures were the same. The results indicate that temperature had nearly no influence on the strain-sensing ability.

CONCLUSIONS

The following conclusions were derived from this study.

1. (1) The resistivity of A-15 and A-25 were temperature dependent, temperature compensation should be considered when using A-15 or A-25 as a sensor.
2. (2) Within the general environmental temperature scope, the strain-sensing property of A-15 and A-25 were nearly not influenced by temperature.

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