Piezoresistive Cement-based Sensors for Local Compressive Stress/Strain Monitoring of Concrete Structures

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ABSTRACT:

Piezoresistive cement-based materials have such characteristics as high sensitivity coefficient, low price, good durability and compatibility with concrete so that they can be made into embedded piezoresistive cement-based sensors (PCS) suitable for local compressive stress/strain monitoring of concrete structures. In this paper, the measuring and making methods of PCS are studied and the properties of a kind of standardized PCS are measured. The results indicate that the direct-current four-pole method based on embedded gauze electrode is suitable for measuring the resistance of PCS. The combination of carbon fiber and carbon black can improve the piezoresistivity of cement-based materials to endow PCS with favorable sensitivity, linearity and repeatability.

1. INTRODUCTION

Concrete structures constitute a large portion of civil infrastructures, but their reliability is relatively low because of wide material discreteness and complex application environment [1, 2]. Consequently, the security of concrete structures is an important problem being paid attention to at all times in civil engineering. Although engineering accidents occurring during the service period of concrete structures can be avoided by reasonable structural design, the complex service condition and the probable unexpected extreme situation are still threatening the safety of concrete structures and imperiling people's lives and possessions. Therefore, it is necessary to take reasonable measures to monitor the state of concrete structures [3- 5].

Local monitoring is needed for ensuring the health and safety of concrete structures during their service periods. It is conventionally realized by embedding in or attaching to structures sensors, such as optical fibers, electric-resistance strain gauges and piezoelectric strain sensors etc. However, the durability and the compatibility with concrete of these sensors are general problems that limit their application in engineering [6].

Cement-based materials containing conductive fillers (carbon fiber, carbon black and black lead, etc.) have superior ability to sense their own stress/strain, which can be used for retrofits or new installations, including strain-sensing coating, corrosion monitoring of rebar, traffic monitoring and weighing in motion and so on[7-10]. The embedded piezoresistive cement-based sensors (PCS) can be made of these sensing cement-based materials. Such sensors for local stress/strain monitoring of concrete structures can make up for the shortcomings of sensors mentioned above. Compared to intrinsically concrete structures made of sensing cement-based materials, PCS can be installed on the key positions of concrete structures, which can enhance the efficiency of monitoring and better meet the requirement of monitoring on condition that construction cost is not obviously increased and current construction technology is not changed.

In this paper, the measuring and making methods of PCS are studied and the properties of a kind of standardized PCS are measured.

2. MATERIALS AND EXPERIMENTAL METHOD

Main raw materials include Portland cement (type I) from Harbin cement factory, silica fume, dispersant (methylcellulose), defoamer (tributyl phosphate), water-reducing agent (sodium salt of a condensed naphthalenesulphonic acid), carbon black of 120nm from Fushun Carbon Black Co.,Ltd and carbon fiber of 6mm from Jilin Carbon Co.,Ltd. The electrode materials used are copper gauze.

A mortar mixer is used to mix the raw materials containing carbon fiber, carbon black, dispersant, water-reducing agent and water for about 3 min, and then this mixture is mixed with silica fume and cement for another 3 min. After pouring the mixture into the oiled molds, a vibrator is used to reduce the amount of air bubbles. The specimens are prepared and demolded after 1 day, and then they are cured at standard fogroom for 28 days.

3. RESULTS AND DISCUSSIONS

3.1 Measuring method of resistance of PCS

The electrode of piezoresistive cement-based materials is commonly set in the two-pole layout and the four-pole layout [9, 11]. And consequently the embedded gauze electrode can also be set in these two layouts. The measuring methods corresponding to these two layouts are the direct-current two-pole method and the direct-current four-pole method respectively. In the direct-current two-pole method, the two poles are both current electrode and voltage electrode, whereas the inner two poles and the outer two poles are voltage electrode and current electrode respectively in the direct-current four-pole method.

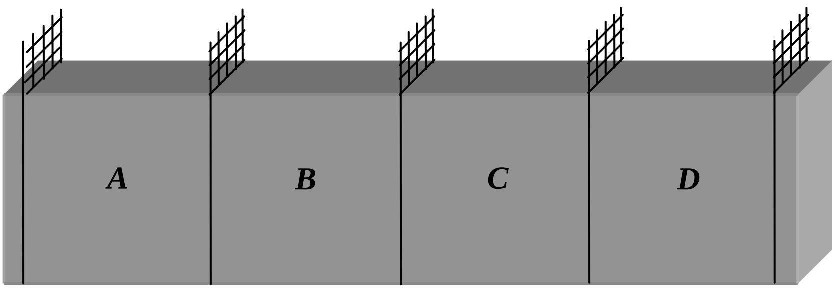


Fig.1. Sketch map of the specimen used to compare the direct-current two-pole method with the direct-current four-pole method

In order to compare the direct-current two-pole method with the direct-current four-pole method, specimens with electrode layout as shown in Fig.1 are prepared. The resistance of specimen B, C and B+C in Fig.1, which is measured by these two methods respectively, is listed in Table 1. It shows that the resistance measured by the direct-current four-pole method is all smaller than that measured by the direct-current two-pole method. Comparing the resistance summation of B and C with the resistance of B+C, the resistance measured by the direct-current two-pole method does not meet the series relationship, but that measured by the direct-current four-pole method does. It is proved that the direct-current four-pole method can eliminate the contact resistance between electrode and piezoresistive cement-based materials [12].

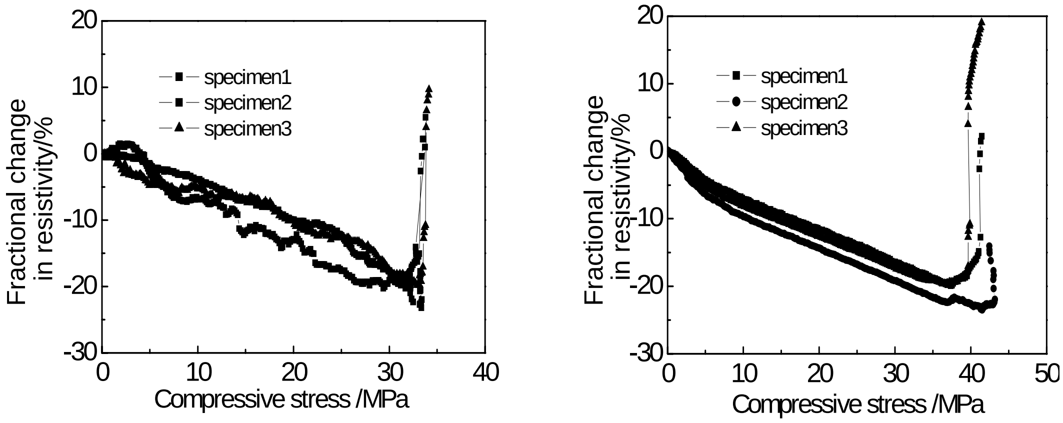
Table 1. Resistance of specimens measured by different methods

Measuring method	Resistance /Ω		
	B	C	B+C
Direct-current two-pole method	2.37	2.42	3.15
Direct-current four-pole method	0.86	0.84	1.90

Therefore the the direct-current four-pole method based on embedded gauze electrode is suitable for measuring the resistance of PCS.

3.2 Improvement of piezoresistivity of PCS

The stable properties (mechanical property, electrical property and piezoresistivity etc) of piezoresistive cement-based materials, especially the repeatability of piezoresistivity is necessary for making PCS.



(a) With carbon fiber only (b) With carbon fiber and carbon black

Fig.2. Fractional change in resistivity of cement-based materials with carbon fiber only and with carbon fiber and carbon black under compressive load

Fig.2 illustrates the piezoresistivity of cement-based materials with carbon fiber and carbon black has higher repeatability and linearity than that of cement-based materials with carbon fiber only. It shows the repeatability and the linearity of piezoresistivity of cement-based materials can be improved by simultaneously adding carbon fiber and carbon black within them.

Piezoresistivity results from the variation in the contact electrical resistivity between conductive fillers themselves (carbon fiber and carbon black) and between conductive filler and cement-based materials under compressive load. The variation in contact electrical resistivity is due to the contacting and tunnelling conduction effect [13, 14]. The combination of carbon fibers and carbon black particles, which provides charge transport over large and small distances respectively, enhances the contacting and tunnelling conduction effect [15,16]. As a result, the response of contact electrical resistivity to force-field is sensitive and stable.

In addition, when making PCS, the fraction of carbon fibers and carbon black need be adjusted to ensure the sensitivity, mechanical and electrical properties etc of PCS.

3.3 Properties of PCS

Based on the above research results about the measuring and making methods of PCS, a kind of PCS are made and shown in Fig.3. The data acquisition system developed according to the measuring method of PCS is given in Fig.4. Compressive experiment under load control is performed by using a material testing system (MTS). The resistivity and the strain along the stress axes of specimens are measured by the data acquisition system and strain gages respectively during this experiment.

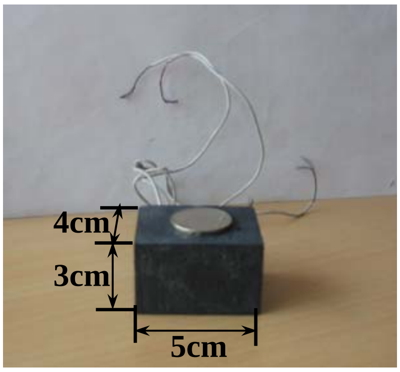


Fig.3. Photograph of PCS

Fig.4. The developed data acquisition system

Fig.5 and Fig.6 show that the fractional change in electrical resistivity varies linearly and reversibly with stress/strain under repeated compressive load. The relationship between compressive stress/strain and the fractional change in electrical resistivity of PCS can be expressed as Equation (1), and then the properties of PCS are listed in Table 2.

$$\Delta\rho = -1.313\sigma \quad \text{or} \quad \Delta\rho = -0.0221\varepsilon \qquad (1)$$

Where σ is the compressive stress (MPa), ε is the compressive strain ($\mu\varepsilon$) and $\Delta\rho$ is the fractional change in electrical resistivity (%).

The results indicate that PCS have high sensitivity, linearity and repeatability. The sensitivity of PCS is 0.0138%/με (meaning their gage factor is 138), which indicates PCS are well above those associated with traditional metal strain gages (gage factors of 2 to 3). It results from the reversible variation in the contact electrical resistivity between conductive fillers themselves (carbon fiber and carbon black) and between conductive filler and cement-based materials under elastic loading of PCS.

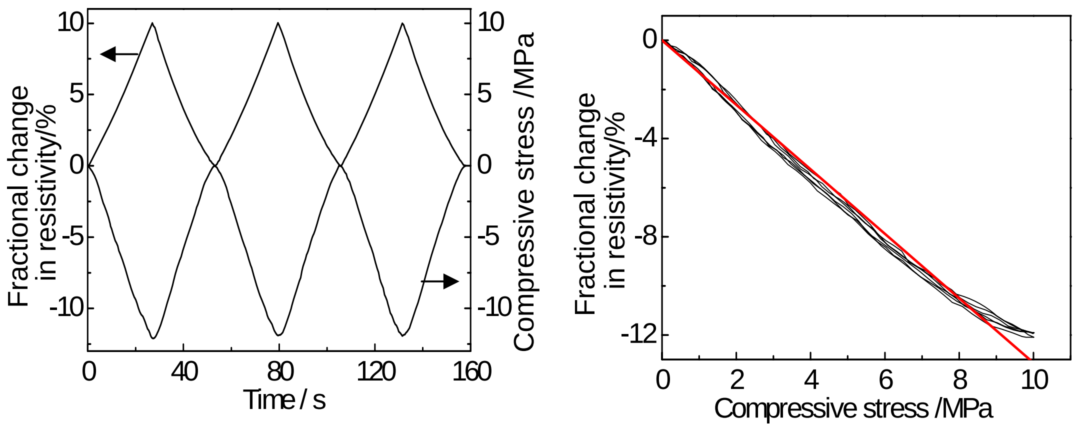


Fig.5. Compressive stress and fractional change in electrical resistivity of PCS under repeated compressive load

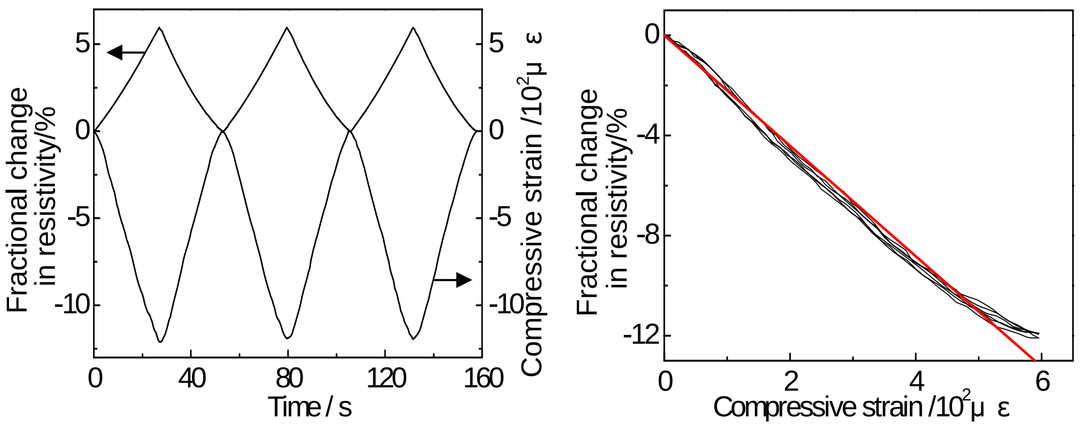


Fig.6. Compressive strain and fractional change in electrical resistivity of PCS under repeated compressive load

Table 2. Properties of PCS

Parameters	Index values	
	Stress sensors	Stain sensors
Input range	0～10MPa	0～595με
Output range	0～11.97%	0～11.97%
Sensitivity	1.313%/MPa	0.0221%/με
Linearity	0.996	0.995

4. CONCLUSIONS

The measuring method and the making method of PCS have been discussed in this study. It is found that the direct-current four-pole method based on embedded gauze electrode is suitable for measuring the resistance of PCS beacause it can eliminate the contact resistance between electrode and piezoresistive cement-based materials. The combination of carbon fiber and carbon black, which enhances the contacting and tunnelling conduction effect of piezoresistive cement-based materials, can provide cement-based materials with desirable piezoresistivity suited for making PCS.

The proposed PCS based on the piezoresistivity of cement-based materials for local stress/strain monitoring of concrete structures are successfully made. Such sensors have high sensitivity and favorable linearity and repeatability.

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