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Sensors and Actuators A 138 (2007) 294–298
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

Embedded piezoresistive cement-based stress/strain sensor

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Received 25 October 2006; received in revised form 28 March 2007; accepted 8 May 2007
Available online 18 May 2007

Abstract

In order to develop one type of embedded piezoresistive cement-based stress/strain sensor (PCSS) to monitor the local compressive stress/strain of concrete structures, we explore the piezoresistivity of cement-based material with carbon fiber and carbon black under single compressive loading and repeated compressive loads at different loading amplitudes, and find it is reversible and stable within the elastic regime. This justifies the use of cement-based material with carbon fiber and carbon black in the manufacture of embedded PCSS. PCSS based on the piezoresistivity of cement-based material with carbon fiber and carbon black is tested with compressive stress/strain in the range 0 MPa (0 $\mu\varepsilon$) to 8 MPa (476 $\mu\varepsilon$) for performance evaluation. Results indicate that PCSS can be used to achieve a sensitivity of 1.35% MPa^{-1} (0.0227% $\mu\varepsilon^{-1}$, gage factor of 227), linearity of 4.17% (4.16%), repeatability of 4.05% (4.06%) and hysteresis of 3.61% (3.62%), and the relationship between its input (compressive stress/strain) and output (fractional change in electrical resistivity) is $\Delta\rho = -1.35\sigma$ ($\Delta\rho = -0.0227\varepsilon$). These findings suggest that this newly developed sensor can be used as one of the alternatives to monitor the compressive stress/strain of concrete structures.

Keywords: Sensor; Cement-based material; Piezoresistivity; Stress/strain; Monitoring

1. Introduction

Concrete structures constitute a large portion of civil infrastructures, but their reliability is relatively low because of wide material discreteness and complex service environment [1,2]. Consequently, the safety of concrete structures is an important problem being paid attention to at all times in civil engineering field. Although the engineering accidents occurring during the service period of concrete structures can be avoided by reasonable structural design, some probable unexpected extreme situations are still threatening the safety of concrete structures. Therefore, it is necessary to take reasonable measures to monitor the state of concrete structures [3,4].

In order to monitor the performance and state of concrete structures during their service periods, the information reflecting structural state need be obtained by appropriate monitoring technologies [5,6]. Now local monitoring for concrete structures is usually achieved by embedding such sensors as electric-resistance strain gauges, optic sensors, piezoelectric ceramic, shape memory alloy and fiber reinforced polymer bar in key structural positions [7–11]. However, these sensors have such drawbacks as poor durability, low sensitivity, high cost, low survival rate and unfavorable compatibility with concrete structures [12,13].

Cement-based material containing electrical fillers (carbon fibers or carbon black), which has favorable piezoresistivity to sense stress/strain in it [14–16], great durability and good compatibility with concrete structures, etc., and it can therefore be used to develop retrofits or new installations, including traffic monitoring, weighing in motion [17], corrosion monitoring of rebar [18], strain-sensing coating [19]. However, the study on embedded piezoresistive cement-based stress/strain sensor (PCSS) (Fig. 1), which is made of piezoresistive cement-based material with carbon fiber and carbon black, has not received much attention from the research community, although it has the potential to overcome some drawbacks of other sensors mentioned above, and achieve a higher monitoring efficiency, lower construction cost and simpler construction technology than intrinsically smart carbon fiber concrete structures since PCSS is embedded only in key positions of concrete structures. In this paper, we discuss the piezoresistivity of cement-based material with carbon fiber and carbon black under compressive load, make PCSS and measure their static performance parameters.

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doi:10.1016/j.sna.2007.05.011

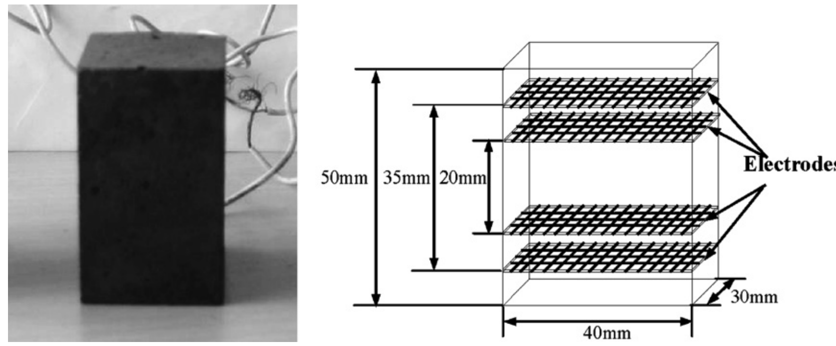

Fig. 1. PCSS and their electrode arrangement.

2. Materials and experimental method

2.1. Preparation

Raw materials we used to produce PCSS are mainly Portland cement purchased from Harbin cement factory, silica fume, dispersant agent (methylcellulose), defoamer agent (tributyl phosphate), water-reducing agent (sodium salt of a condensed naphthalenesulphonic acid), carbon black purchased from Fushun Carbon Black Co. Ltd., carbon fiber of 6 mm long purchased from Jilin Carbon Co. Ltd., and copper gauze (with opening of 2.03 mm × 2.03 mm) for making electrode.

We mixed and stirred carbon fiber, dispersant agent (0.2% by weight of cement), water-reducing agent (1.5% by weight of cement) and water in a mortar mixer for about 3 min, added carbon black, silica fume (15% by weight of cement), cement and defoamer agent (0.05% by weight of cement) and stirred the mixture for another 3 min, poured the mixture into a number of oiled moulds, embedded the gauze electrode, used a vibrator to remove air bubbles, removed the specimens from the moulds in 24 h, and cured them in a standard fog room at 20 °C and 100% relative humidity for 28 days, dried the specimens at 50 °C for 2 days before they were tested.

2.2. Measurement

A compressive experiment with load control was performed with PCSS using a material testing system (MTS) as shown in Fig. 2 at a temperature of 20 °C and a relative humidity of 39%.

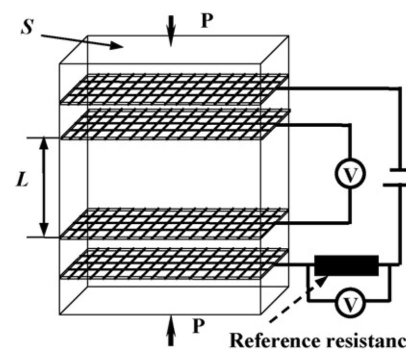

Fig. 3. Principle map of measurement circuit for resistance signal.

The electrical resistivity $\rho(t)$ of PCSS can be expressed as

$$\rho(t) = \frac{U_p(t)S}{I(t)L} \quad (1)$$

where $U_p(t)$ is the voltage of PCSS, S the sectional area of PCSS, L the space between two voltage poles and $I(t)$ is the current in circuit [20] shown in Fig. 3 which can be described as

$$I(t) = \frac{U_p(t)}{R_p(t)} = \frac{U_r(t)}{R_r} \quad (2)$$

where $R_p(t)$ is the resistance of PCSS, and $U_r(t)$ is the voltage of reference resistance with constant resistance R_r.

From Eqs. (1) and (2):

$$\rho(t) = \frac{U_p(t)}{U_r(t)}\frac{SR_r}{L} \quad (3)$$

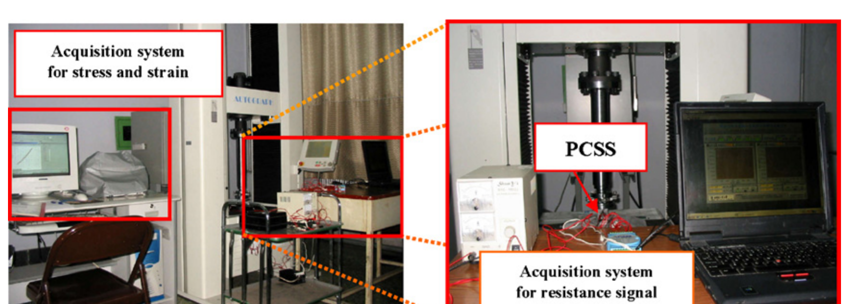

Fig. 2. Testing equipments for PCSS.