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Piezoelectric effect of hardened cement paste

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Abstract

The piezoelectric effect of hardened cement paste was studied in this paper. As compressive stress was applied on the specimen, an electrical current was observed. The electrical current increases nonlinearly with compressive stress. The average sensitivity constant reached is 1.0×10^{-8} A/MPa. Through investigation of the variation of piezoelectric effect with absorbed water content in specimens, the mechanism of this phenomenon was analyzed. Piezoelectric effect of hardened cement paste is related to the transportation of mobile ions along with water in the hydrated cement product under stress.

Keywords: Hardened cement paste; Piezoelectric effect; Electrokinetic phenomenon

1. Introduction

Civil engineering structures are now playing very important roles in the human society. Important civil engineering structures include dams, bridges and nuclear power plants etc. Because of corrosion and fatigue, structures will undergo degradation as the internal and external defects emerge. Therefore, structural health monitoring (SHM) of structures has been attracting much attention in recent years. SHM systems (SHMS) can detect the extent and location of defects so that repairs and treatments can be punctually performed. Piezoelectric materials such as lead zirconate titanate (PZT) and polyvinylidene fluoride (PVDF), which exhibit simultaneous actuator/sensor behavior, have attracted great attention from researchers in SHM of civil engineering structures [1–6].

However, there exist differences in the properties between PZT or PVDF and the host structures. For example, the acoustic impedance, temperature coefficient, shrinkage, and creep characteristics of PZT and PVDF are quite different from those of concrete, which is the most popular material in civil structures. To develop piezoelectric materials suitable for building construction and infrastructure, Li et al. [7] and Zhang et al. [8] studied cement-based 0–3 piezoelectric (PZT) composite, which has smaller acoustic impedance than PZT and has good compatibility with Portland cement concrete. Cement-based 0–3 piezoelectric composite is shown to have a slightly higher piezoelectric factor and electromechanical coefficient than those of 0–3 PZT/polymer composite with a similar content of PZT particles [7,8]. But they have ignored piezoelectric effect of the cement matrix itself. In this paper, hardened cement paste is regarded as a piezoelectric material. In SHMS of civil engineering structures, the use of a structural material as sensor and actuator can help to eliminate or reduce the need for embedded or attached devices, which are expensive and limited in durability. In addition embedded devices can cause degradation of the mechanical properties of structures themselves. Further, the energy conversion of mechanical energy to electrical energy, or electrical energy to mechanical energy in concrete structures can be realized based on piezoelectric effect of hardened cement paste. Even if the efficiency of the energy conversion is not high, the large volume of concrete structures may make the effect significant enough for technological use.

Related literatures are listed here. Wittmann first measured a stress dependent voltage and a voltage dependent displacement in a very small bar of hardened cement paste under small bending moment [9,10]. Li et al. and Yuan et al. studied the deformation induced by the applied electrical field in thin discs of hardened

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cement paste [11,12]. Sun et al. measured the voltage induced by axial low compressive stress in cubic specimens of hardened cement paste and carbon fiber reinforced cement [13]. They also reported the deformation induced by the applied electrical field in carbon fiber reinforced cement [14]. Wen and Chung examined variations of dielectric constant with compressive stress in cement paste, steel fiber reinforced cement, and carbon fiber reinforced cement, and took advantage of them to estimate theoretically average piezoelectric voltage constants and average piezoelectric charge constants [15,16].

However, previous experimental studies on piezoelectric effect of hardened cement paste have not provided the clear mechanical–electrical relationship. In this paper, the electrical current induced by loads is recorded. The mechanism of piezoelectric effect is discussed further. These studies are the basis for a kind of new SHM technology for civil engineering structures.

2. Experimental procedures

Type 425 portland cement was used (Huaxin Cement Co., Hubei Province, PR China). The ratio of water to cement was 0.25. Cement and water were mixed in the mixer for 2 min. After pouring the mix into oiled molds, a vibrator was used to decrease the amount of air bubbles. The specimens were demolded after 1 day, and then allowed to cure at room temperature in air for 28 days after covering with a wet cloth. Six specimens were made from each mix. The size of specimen was $40\times40\times40$ mm.

The specimens were kept in air for a year before testing. The experimental system is shown in Fig. 1. The loading device is an INSTRON1341 system. The measurement system, consisting of resistor R_L, voltage amplifier and computer, can collect the experimental data automatically. A specimen, after being polished on every surface by using fine sand paper, is sandwiched by two 0.1 mm thick copper foil of 50×50 mm at an initial pressure of 0.4 MPa. The copper foil serves as electrodes for measurement. Two pieces of plastic membrane were used to separate the electrodes from the steel plate of the testing machine.

The piezoelectric effect of cement paste stems from the streaming current, which is an interface electrochemical concept [10–12]. When the streaming current needs to be measured, a resistor is chosen to connect with the sample in parallel, and resistance of the resistor must be far smaller than that of the sample [17]. It can be explained using the effective electrical circuit model shown in Fig. 2. In Fig. 2, R_0 is the resistance of the specimen, C is the capacitor of specimen, R_L is an outward connected resistor, and i_s stands for the electrical current produced. When $R_0 \gg R_L$, electrical current through R_L is approximately equal to i_s. The change of R_0 under loading makes little influence on the electrical current measurement. In the experiment reported here, the resistance of cement samples is above 1 MΩ while R_L is 500 Ω.

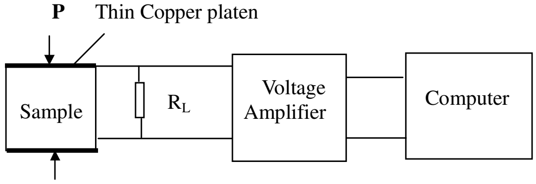

Fig. 1. The experimental system.

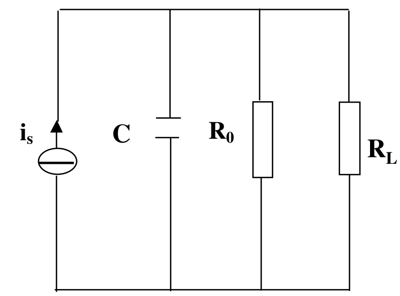

Fig. 2. The effective electric circuit of measurement.

In Fig. 1, if the amplification coefficient is B, and voltage recorded is U under a certain stress, then the electrical current can be calculated as below:

$$i_s = \frac{U}{B \cdot R_L}$$

3. Test results and discussion

Fig. 3 shows electrical current and the applied stress during repeated compressive loading of hardened cement paste. Electrical current increases nonlinearly with compressive stress. The average sensitivity coefficient is

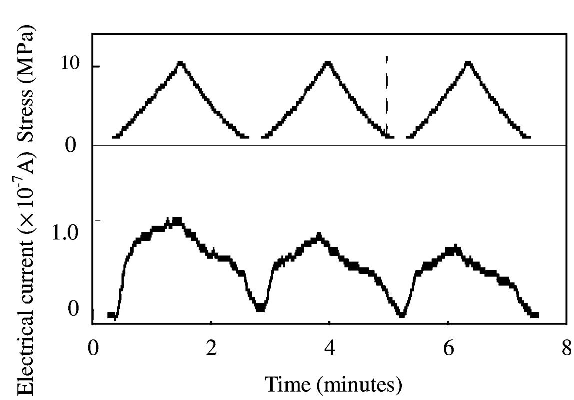

Fig. 3. Compressive stress and electrical current vs. time.

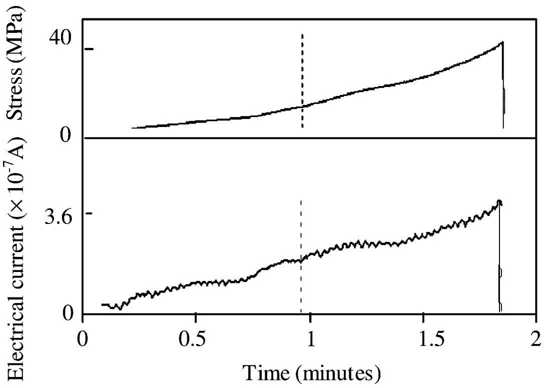

Fig. 4. Compressive stress, electrical current vs. time till the breaking stress.

about 1.0×10^{-8} A/MPa. The maximum electrical current of the first loading cycle is slightly larger than the second and third loading cycle; the amplitudes of the second and third loading cycle are similar (it is noted that the initial value at the beginning of the second loading cycle is slightly higher than that at beginning of the third loading cycle). Fig. 4 shows stress and electrical current vs. time when the applied stress is up to the breaking stress. Electrical current is observed to increase with increasing stress; and it decreases when the specimen fractures; this is because of the widespread cracking accompanied with fracture. When the applied stress is kept stable (see Fig. 5), electrical current decreases quickly at the start, then it decreases slowly.

The mechanism of piezoelectric effect in hardened cement paste is different from that in other piezoelectric materials such as piezoelectric ceramics. Hardened cement paste is assumed in the general case to comprise three components from the volumetric standpoint, viz. (a) hydration product, (b) capillary pores and (c) unreacted cement. The water present in the paste is categorized as evaporable or nonevaporable, the latter being defined as that retained on D-drying (the sample is equilibrated with ice at −79 °C by continuous evacuation with a rotary pump through a trap cooled in a mixture of solid CO_2 and ethanol [18]). Evaporable water is considered to reside partly in the capillary pores and partly in so-called gel pores within the hydration product. And the ionic conduction, due to the motion of ions (Ca^{2+}, Na^{+}, K^{+}, OH^{-}, SO_4^{2-}, etc.) in the pore solution, is considered as the main source of concrete conduction [19]. It is emphasized that in any solid-electrolyte system there is a specific liquid region in contact with the solid surface, referred to as electrical double layer or diffuse layer. Ions in solution are absorbed on to the solid surface. Similarly, the opposite charges line up in the solid side. Many researchers have proposed the electrical double layer model to explain formation of cement microstructure and AC impedance spectroscopy of cement paste [20,21]. When compressive stress is applied, water is forced through microchannels because of extrusion. So ions in the mobile part of the electrical double layer flow along micropores, which causes an electrical current, that is, the streaming current. The accumulation of ions sets up an electric field with an electrokinetic potential called the streaming potential. This streaming field generates another electrical current, called the conduction current, which is opposite to the streaming current.

In Fig. 3, the reason why the amplitude of electrical current during the first loading cycle is larger is because redistribution of water in pores takes place after the first loading. When the load is kept constant as in Fig. 5, the declination of electrical current is due to the opposite conduction current.

To prove that piezoelectric effect of hardened cement paste is related to the transportation of mobile ions along with water under stress, the influence of water content on stress-induced electric current is also studied in this paper. First, specimens were dried in the oven under 70 °C for 48 h. It was found that the hardened cement paste hardly exhibited any piezoelectric effect after this treatment. The specimens were then stored in a humid environment, and observed. The variation of absorbed water with time is shown in Fig. 6. After the specimens are weighed, electrical current under the same

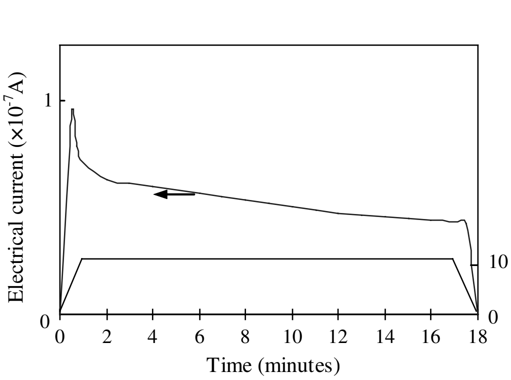

Fig. 5. Compressive stress, electrical current vs. time under the sustained loading.

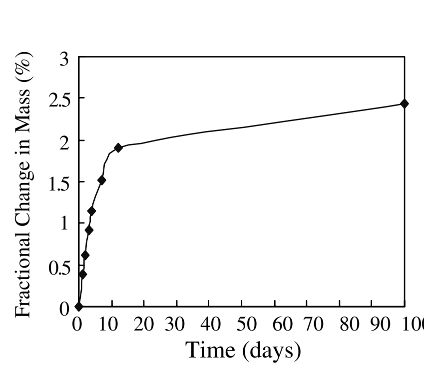

Fig. 6. Variation of the mass with time in the wet air after drying treatment for 48 h.

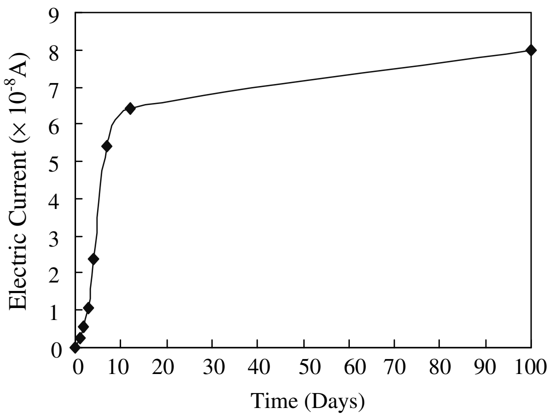

Fig. 7. Variation of electric current with time in the wet air after drying for 48 h.

compressive stress of 10 MPa was examined, then unloaded. The procedure was repeated after every few days. Fig. 7 shows the variation of electric current with time. From Figs. 6 and 7, it can be seen that electric current increases as the absorbed water increases. As the water content increases, it is advantageous to the ionic transportation under stress, so electrical current flow increases.

4. Conclusions

Hardened cement paste can be regarded as a piezoelectric material. In this paper, electrical current induced by compressive stress is observed. Results show that electrical current increases nonlinearly with compress stress. The average sensitivity constant reaches 1.0×10^{-8} A/MPa. The amplitude of electrical current in the first loading cycle is slightly higher than that of the following cycles because redistribution of water in the pores takes place after the first loading. In the process of the sustained loading, electrical current decreases gradually. Piezoelectric effect of hardened cement paste is related to the transportation of mobile ions along with water in the hydrated cement product under stress.

Acknowledgement

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