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Electrically induced temperature difference and deformation in hardened cement pastes

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Abstract

Electromechanical effect of hardened cement paste beam is investigated in this paper. When an external electrical current is applied to the electrodes attached to opposite surfaces of a cement beam, it is found that temperature on the positive electrode is always higher than that on the negative electrode. The sign of electrically induced temperature difference is determined by the direction of applied electrical current. Electrically induced temperature difference makes the beam bend towards the surface with a higher temperature. Both electrically induced temperature difference and electroosmosis lead to electromechanical effect of hardened cement paste. Finally, electromechanical effect becomes more obvious by adding NaCl to cement paste.

Keywords: Cement paste; Electromechanical effect; Electrically induced temperature difference; Flexual deformation

1. Introduction

Smart civil structures capable of nondestructive performance monitoring and self - adaptation in real time are of increasing importance due to the needs to maintain the functions of critical civil infrastructure systems, such as bridges and dams. For the past ten years, structural materials such as cement-based materials and fiber reinforced polymer composites have been used as sensors and actuators to construct smart concrete structures [1,2]. And this method has been proved to be promising and practical in the future. Cement-based materials with small content of conductive microfiber, carbon fiber and steel fiber, can sense strain, stress and damages based on piezoresistivity effect [3]. They can also be used to melt snow and ice for pavements based on Joule effect [4]. This paper focuses on electromechanical effect of hardened cement paste, that is, deformation is induced under the applied electrical field, which is helpful to develop smart concrete structures having the ability to adjust their deformation.

F.H.Wittmann et al. [5,6] has first studied the electromechanical coupling effect in a bar of hardened cement paste under bending; a stress dependent voltage and a voltage dependent displacement were measured. A voltage was observed when an external load was applied to the specimen. Conversely, when an external voltage was applied to the electrodes attached to opposite surfaces of the bar, the bending happened at once. If the direction of the applied electrical field was reversed, the direction of bending changed as well. This phenomenon was due to electroosmosis, that is, porous water transports with ions under the action of an electric field. In 1995, Jie-Fang Li et al, Lijian Yuan et al. [7,8] reported the electromechanical behavior of hardened Portland cement paste as a function of measurement frequency, dc electrical bias, moisture content and water to cement ratio. They found that the electromechanical response decreased dramatically with increasing measurement frequency. And no strain was induced below critical moisture content. Above the critical moisture content, the induced strain increased rapidly with small increments in moisture.

In 2002, the first author of this paper proposed both electroosmosis and Joule effect to be the origins of electromechanical effect of carbon fiber reinforced cement composite. And it was estimated that thermal expansion due to Joule effect

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was the minor factor within the above two effects [9]. We have also observed the voltage induced by axial compressive stress in hardened cement paste and carbon fiber reinforced cement composites [10]. Wen and Chung have examined variations of dielectric constant with compressive stress in cement paste, steel fiber reinforced cement, and carbon fiber reinforced cement, and taken advantage of them to assess average piezoelectric voltage constants and average piezoelectric charge constants [11].

In this paper, a novel phenomenon about electro-thermal–mechanical interactions in hardened cement pastes is reported. When an external electrical current is applied to the electrodes attached to opposite surfaces of the cement beam, temperature difference between the upper surface and the lower surface of the beam is generated. Temperature difference can lead to the bending of the beam. Therefore, the appearance of temperature difference induced by the applied electrical current plays an important role in the electromechanical effect of hardened cement pastes. To our knowledge, by now none has reported this phenomenon exhibited in hardened cement paste.

2. Experimental procedure

2.1. Sample preparation

P 42.5 ordinary portland cement (Huaxing Cement Co., Huangshi City, P R China) was hydrated at a water to cement mass ratio of 0.35. Cement and water were mixed for 2 min. The paste was then cast into the mold (2 cm × 0.5 cm × 16 cm) and vibrated to eliminate air bubbles for 2 min. Specimens were precured for 24 h at a relative humidity (rh) of 70%. They were then cured in air (about 70% rh). Another type of specimens was prepared using NaCl (1.0 wt.%) water solution. They have the same ratio of water to cement and curing as the first type of specimens.

2.2. Measurement method

The electrically induced deformation was measured by an inductance technique. A schematic of the measurement system is shown in Fig. 1. Specimen is supported on two points with a span of 12 cm. In the middle of the beam, two thin layers made with silver paint (SPI Supplies, USA.) were painted at two opposite surfaces, which were used as electrical contacts. The area of coating was 4 cm × 2 cm. The bending displacement in the mid-point of the beam was measured with a linear variable differential transformer (LVDT). A circular ceramic patch (10 mm in diameter, and 1 mm in thickness) was inserted between the sample and the rod of LVDT for insulation. The sample was electrically excited by Keithley 2400 power. Two Pt100 thermistors were attached to the surface of electrodes with silicone. In this paper, temperature measured by the upper thermistor is defined as T_{Upper}, while temperature measured by the lower thermistor is defined as T_{Lower}. T_{Upper} minus T_{Lower} is defined as temperature difference (ΔT), that is,

$$\Delta T = T_{\mathrm{Upper}} - T_{\mathrm{Lower}}$$

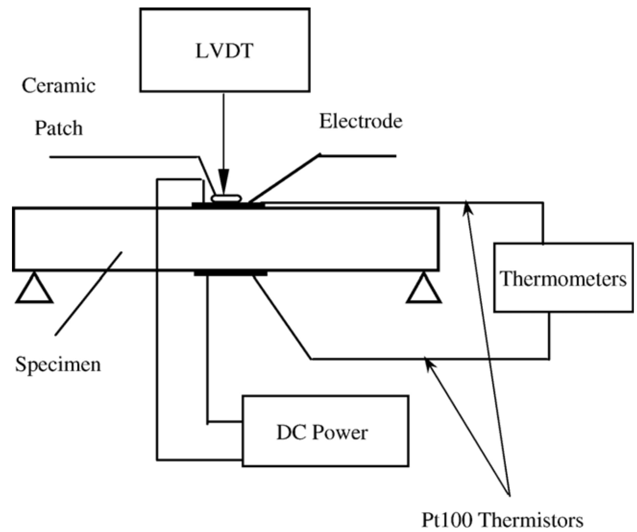

Fig. 1. The experimental setup.

During the test, electrical current, voltage, temperature and deflection as a function of time were recorded. In this paper, we have used the convention in which current flowing from the lower electrode to the upper electrode corresponds to positive value of current and voltage, whereas current flowing from the upper electrode to the lower electrode corresponds to negative value of current and voltage. As beam bends upwards, bending deflection is supposed to be a positive value.

3. Results and discussions

As electrical current of +20 mA and −20 mA was applied to the specimen, changes of T_{Upper}, T_{Lower}, ΔT, bending deflection of the midpoint and voltage as a function of time were examined. As shown in Fig. 2(a), when the applied current is +20 mA, T_{Upper} is smaller than T_{Lower}, ΔT is negative, and the beam bends downwards. In Fig. 2(b), as the direction of current changes, T_{Upper} is larger than T_{Lower}, ΔT is positive, and the beam bends upwards. Therefore, temperature on the positive electrode of the beam is always higher than that on the negative electrode. So, temperature difference through the thickness of the beam is generated.

In the area out of electrodes, temperature increases slightly. As current is switched off, the electrically induced deformation decreases, and it is reversible. In Fig. 2, although the current makes no change, voltage increases with time due to the polarization effect in cement [12]. Three specimens with the age of 3 days were tested. Similar phenomena were also found in specimens with the age of 28 days.

Sun et al. [13], Wen and Chung [14] have reported the Seebeck effect of cement-based materials. Seebeck effect is referred to the fact that temperature difference produces thermoelectric force in cement-based materials. However, none has reported the reverse effect of Seebeck effect, that is, electrical current can generate temperature difference, called as Pletier effect. Depending on the Pletier effect, thermoelectric materials like Bi_2Te_3, $CoSb_3$ can be used to manufacture

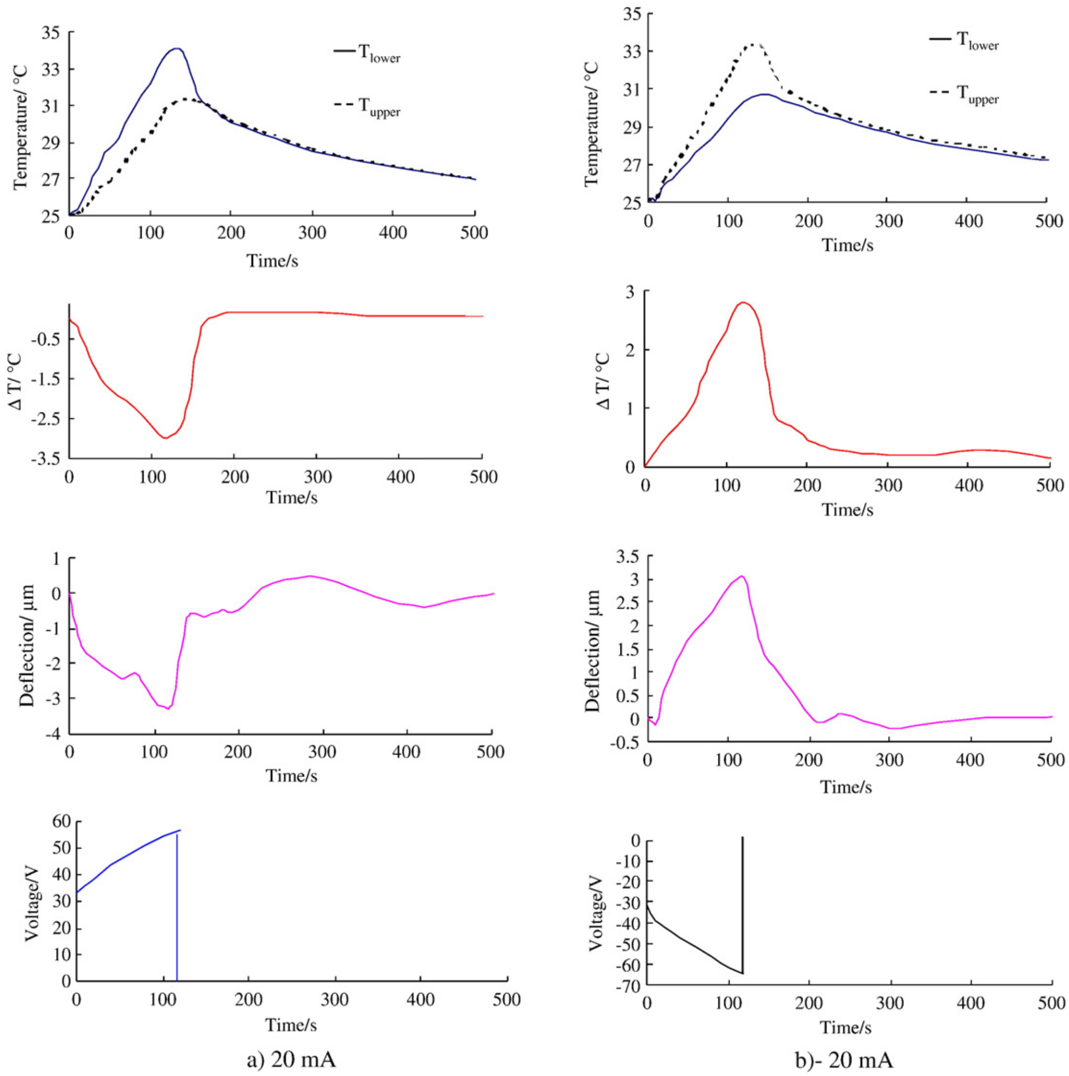

Fig. 2. Temperature of upper surface and lower surface (T_{Upper}, T_{Lower}), temperature difference (ΔT), deflection of the midpoint of the beam and voltage as a function of time.

cooling devices. In our test, temperature on two electrodes is higher than air temperature, the cooling effect has not been found. This is because ordinary hardened cement paste has high electrical resistance, heat produced by the applied electrical current makes temperature of the area between two electrodes increase.

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 [15]. 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^{+}, Na^{+}, K^{+}, OH^{-} etc.) in the pore solution, is considered as the main source of concrete conduction [16]. 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. Fig. 3 is the schematic of double electrical layer and ionic distribution in hardened cement. As shown in Fig. 3, the surface charge of the C–S–H is of negative sign. Therefore the first absorbed layer is predominantly positively charged thus forming an intermediate layer. On the top of this intermediate layer there exists a diffuse layer with a net negative potential, called as Gouy diffuse layer. S. Chatterji et al have also measured the charge density of Gouy diffuse

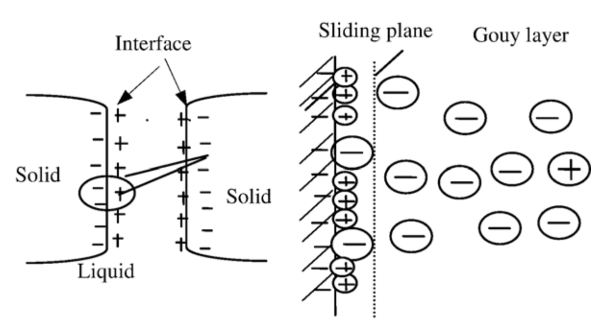

Fig. 3. Schematic of solid–liquid interface electrical double layer and ionic distribution in hardened cement paste.

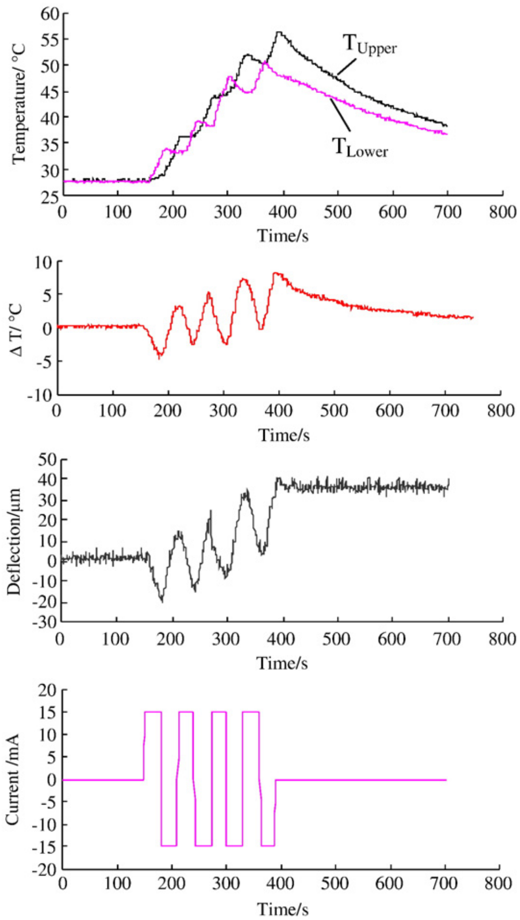

Fig. 4. Temperature of upper surface and lower surface (T_{Upper}, T_{Lower}), temperature difference (ΔT), deflection of the midpoint of the beam adding 1% NaCl to the water-cement mixture applied alternatively positive and negative current.

layer, −2.5 μC/cm^2 [17]. The distribution of ion in diffuse layer is determined from the thermal movement and the Coulomb attraction. When electrolytic solution is driven to move, there is a still liquid layer with the thickness of several molecules near the surface of solid. The outer boundary of this liquid layer is called as the sliding layer, and the potential of the sliding layer is called as Zeta-potential.

As an external electrical field is applied, the transport of ions in Gouy diffuse layer, mainly negative ions, can drag water into gel pores, leading to the shape change of hardened cement paste [6,7]. On the other hand, negative ions moving towards the positive electrode can also bring heat to the positive electrode. Therefore, temperature near the positive electrode is higher than temperature near the negative electrode. So, in Fig. 2 the sign of electrically induced temperature difference is determined by the direction of applied electrical current. Further, temperature difference between the upper surface of the beam and the lower surface can make the beam bend towards the surface with higher temperature. Therefore, electromechanical effect in hardened cement paste results from both electrically induced temperature difference and electroosmosis behavior of electrolyte solvent in the porous cement matrix. Further studies are required to find the weight of these two factors. It can also be seen in Fig. 2 that temperature on the positive electrode decreases immediately after the current is turned off, while temperature on the negative electrode continues to increase for about 10–20 s after the current is switched off. This is because that negative ions accumulating near the positive electrode, which has higher temperature, will transport towards the negative electrode as the current is switched off. Then, heat is brought back to the negative electrode, so temperature on the negative electrode increases shortly after the current is switched off.

In another test, specimens mixed with NaCl (1.0 wt.%) water solution was tested. Electrical current of +15 mA and −15 mA was applied to the specimen alternatively, changes of T_{Upper}, T_{Lower}, ΔT and bending deflection of the midpoint as a function of time were recorded using an automated data sampling system, which is given in Fig. 4. As shown in Fig. 4, when the applied current is +15 mA, T_{Upper} is smaller than T_{Lower}, ΔT is negative, and the beam bends downwards. When the applied current is −15 mA, T_{Upper} increases while T_{Lower} decreases, so the upward deflection is generated. The curve of ΔT vs. time is similar with that of deflection vs. time. During each cycle, the negative current has made higher temperature increasing than the positive current. Correspondingly, the negative current has made larger deformation than the positive current. Thus, baselines of ΔT vs. time and deformation vs. time have a trend of raise. In fact, although the applied electrical current is smaller than that used in Fig. 2, temperature difference and deformation are larger than that in Fig. 2, indicating that the addition of NaCl has strengthened electromechanical effect in hardened cement paste. Thus, electromechanical effect becomes more obvious by adding NaCl to cement paste.

4. Conclusions

The main conclusions derived from this study are as follows:

(1) When an external electrical current is applied to the electrodes attached to opposite surfaces of a cement beam, it is found that temperature on the positive electrode is higher than that on the negative electrode.
(2) The sign of electrically induced temperature difference is determined by the direction of applied electrical current.
(3) Temperature difference is generated through thickness of the beam, which makes the beam bend towards the surface with higher temperature. Both electrically induced temperature difference and electroosmosis behavior are supposed to be the source of electromechanical effect of hardened cement paste.
(4) Electromechanical effect becomes more obvious by adding NaCl to cement paste.

Acknowledgments

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