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Conductivity of ionically-conductive mortar under repetitive electrical heating

R.H. Zhao [a], C.Y. Tuan [b,*], A. Xu [a], D.B. Fan [a]

[a] International Cooperation in Science and Technology Demonstration Bases for Structural Wind Resistance and Structural Safety, Guangzhou University, China
[b] Department of Civil Engineering, University of Nebraska-Lincoln, USA

HIGHLIGHTS

- Conductivity of mortar decreases in a 28 d period, but decreasing rate drops significantly after 28 d.
- Higher DC voltage enhance redox reaction inside ionically conductive mortar.
- Repetitive electrical heating would not change apparent properties of mortar.
- Conductivity of mortar was significantly improved by replenishing electrolyte.

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ABSTRACT

Ionically-conductive mortar may be used for indoor radiant heating floor tiles and partition walls. In these applications, mortar blocks are soaked in electrolyte solutions. The surfaces of the block are coated with sealant afterwards to prevent evaporation. The mortar block becomes a heating element due to ionic conduction if a voltage is applied to the two electrodes in the block. The ability of the ionically-conductive mortar to maintain its conductivity under repetitive electric-heating cycles is of great importance to successful applications. Two batches of specimens were prepared using 4.8% CuSO4 and 9.1% FeSO4 solutions, respectively, and were energized at 10 and 50 V under both direct current (DC) and alternating current (AC) to evaluate the electrical resistivity over the specimen's age (days since casting). The experimental results showed that resistivity of the ionically-conductive mortar increased with age, but the increase gradually diminished after 28 days. Under 10 V AC, the mortar temperature rose very slowly after 2 h. However, the resistivity dropped significantly after 2 h under 50 V AC with noticeable increase in temperature. The resistivity was even lower under 50 V DC due to the "redox reactions" in the ionically-conductive mortar. To assess the impact of repetitive electric-heating cycles on the hydration of the mortar, SEM was used to observe the morphology of the hydration products. It was evident that the hydration products and internal structures of the specimens were unaffected by the repetitive heating and the ionically-conductive mortar maintained stable electrical conductivity.

1. Introduction

Conductive concrete is made by adding electrically conductive materials to concrete, so that concrete would change from a poor conductor into a good conductor for use in applications such as electric-heating [1], electromagnetic shielding [2], structural monitoring [3], and cathodic protection for reinforcing steel bars [4]. Traditional conductive concrete is made by adding steel fibers, carbon fiber, graphite and the like into concrete, and the electric circuit formed by the conductive materials through lap joints [5] enables conduction of electricity within the concrete. For this reason, traditional conductive concrete has drawbacks such as flocculation of fibers, difficult dispersion of carbon black and rusty steel components [6–8]. To resolve these issues, an innovative conductive cementing material, ionically-conductive mortar, has been developed. Conductivity of ionically-conductive mortar is dependent on the directional migration of free ions in the mortar in an electric field [9–12], which is different from the traditional conduction mechanism [5]. A literature review shows that ions can directionally migrate in cement-based composites, making the composites electrically conductive. Whittington et al. [13] proved that there was free moisture containing a variety of ions in concrete, and the directional migration of ions made the concrete con-

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* Corresponding author.
E-mail address: ctuan1@unl.edu (C.Y. Tuan).

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ductive. The directional migration of ions in concrete has been observed by many researchers and used in concrete permeability evaluation and chloride ion erosion [14–16]. Most of these researches aimed at reducing the amount and the sizes of voids inside the cement-based composite to reduce permeability. The ionically conductive mortar, however, attempts to harness the free moisture available in the mortar by increasing the amount and sizes of the voids to enhance the electrical conductivity.

Ionically conductive mortar is particularly suitable for floor tiles and partition walls construction for radiant heating. Although the ionically conductive mortar is a porous material, its compressive strength is about 10–16 MPa, which is higher than that of common concrete hollow blocks [17]. The ionically conductive mortar is primarily intended for non-load-bearing structures. However, epoxy-coated steel bars or glass fiber reinforced polymer (GFRP) rebar may be used for load-bearing walls to mitigate potential galvanic corrosion of steel reinforcing bars due to electrolyte solution. The porosity of ionically conductive mortar is in the range of 20–35%. Higher porosity indicates there is significant amount of air voids in the mortar which causes lower thermal conductivity compared to that of concrete blocks. Preliminary studies have been conducted to explore the fabrication procedures [9], factors affecting its physical properties [10], permeability of ion-based conductive mortar [11], and the ion-based conductive mortar shows good heating performance [12].

Stable conductivity under repeated electric-heating is crucial for ion-based conductive mortar to be useful in practical applications. This study investigated the changes in electrical resistivity of mortar specimens with age, the changes in resistivity under alternating current (AC) and direct current (DC) power with variable voltage. Changes in physical properties of cement-based materials at elevated temperature have been studied [18–20], including strength variation, composition of hydration products, porosity of the mortar structure and thermal cracking. These changes take effect gradually at different temperature stages, and are related to the water cement ratio [18–20]. These experimental results provide a basis for studying the influence of repeated heating on the properties of ion-based conductive mortar specimens. Ionically conductive mortar relies mainly on directional migration of ions to conduct electricity, and how this process is affected by temperature and hydration process has been studied herein.

Based on the results of the previous experiments [12], ionically conductive mortar specimens with good electric-heating properties were selected to study the impact on the porosity and hydration products in the specimens due to long-term repetitive electric-heating. The electric-heating properties of the ionically conductive mortar under various voltage of AC as well as DC power were further analyzed. The changes in the microscopic pores in the mortar under repeated electric-heating were investigated based on morphologic analysis using scanning electron microscope (SEM). The experimental results show that the pore structure and hydration products in the ionically conductive mortar remained relatively unchanged under repeated electric-heating, thus being suitable for radiant heating applications.

2. Tests

2.1. Materials for test specimens

All the materials used to fabricate the test specimens are shown in Table 1.

Aluminum (Al) powder was used to generate tiny gas bubbles in the cement to increase the number of interconnected voids in the specimens [21]. These voids facilitate the electrolyte solution to permeate within the specimens. The surfaces of the specimens were coated with epoxy resin to ensure sustainable ionic conduction in the mortar.

Table 1
Material properties.

Materials	Material properties
Cement	P.O 42.5R cement; 3-day compressive strength: 30.6 MPa; initial setting time: 135 min; alkali content: 0.6% (mass ratio, alkali: cement * 100%)
Sand	Normal river sand; sand with grain size $\leq$ 0.25 mm accounts for 50% of the total mass; mean grain size: 0.25 mm-0.5 mm
galvanized steel electrode	Diameter: 1 mm; mesh size: 5 mm × 5 mm; being processed into 40 mm × 30 mm sheets
Copper electrode	Red copper, diameter: 1 mm; mesh size: 5 mm × 5 mm; being processed into 40 mm × 30 mm sheets
Al powder	Analytical reagent; content $\geq$ 99%
$FeSO_4$	Analytical reagent; content $\geq$ 99%
$CuSO_4$	Analytical reagent; content $\geq$ 99%
Epoxy resin (ER)	Epoxy resin consists of adhesive A and adhesive B, mixed at 1:1 ratio;Benefits: waterproofing, anticorrosive, and acid and alkali resistant

Note: 1 MPa = 145 psi; 1 in. = 25.4 mm.

2.2. Specimen preparation

The dimensions of the specimens were 40 mm × 40 mm × 40 mm and the mix proportion (weight ratio) was water: cement: sand = 0.5: 1: 3 in accordance with the Chinese specification (ISO 679:1989) [22]. Aluminum powder was added according to an Al/cement weight ratio of 0.075% [20]. The fabrication process is summarized as follows: (1) the quantities of cement and sand were mixed in a mixer; (2) tap water was added into the mixture and mixing for 2–3 min; (3) Al powder was added and mixing for 1–2 min; (4) the mixture was cast into a mold and vibrated on a vibrating table for about 1 min; and (5) the surface of the specimen was finished with a steel trowel. The electrodes tend to shift in the mold during the vibration, and the shape of the electrodes was modified as shown in Fig. 1.

The specimens were taken out of the mold after about 12 h and put into a curing box of 20 °C (68 °F) and 98% humidity[22]. The specimens were weighed after curing. Groups of three specimens were immersed in electrolyte solutions of two electrolyte solutions, 4.8% $CuSO_4$ and 9.1% $FeSO_4$, respectively. The specimen designations are shown in Table 2. Specimens labeled with CC and CF had copper and galvanized steel electrodes, respectively, and were soaked in water. After being immersed for 96 h, the mortar specimens were wiped dry and coated with a 1-mm thick layer of epoxy resin. Fig. 2 shows a typical test specimen.

2.3. Measurement of electrical resistivity

The resistivity of specimens was measured using a multi-meter according to the circuit shown in Fig. 3. The experiments were carried out at room temperature of 25 °C. The power source used in the experiments was either AC or DC, according to the designations in Table 2. The electrical resistivity of a specimen was calculated by Eq. (1),

$$R = \frac{U}{I} \cdot \frac{A}{L} \tag{1}$$

where U is the voltage between the two ends of the specimen, I is the current in the circuit, A and L are the cross sectional area and length of the specimen, respectively. The resistivity, R, includes