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Ionically Conductive Mortar for Electrical Heating

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An innovative conductive composite, ionically conductive mortar, is developed in this study. The directional migration of ions under external voltage makes the mortar conductive. The electrical resistance of the mortar causes the mortar to generate heat, which is used for deicing. To ensure conductivity, the number of free ions and the moisture content in the mortar must stay relatively high. The specimens were soaked in electrolyte solutions for 96 hours to saturation and coated with epoxy resin. Subsequent electrical heating tests showed that the specimens could achieve a heating rate of 19.7°C (35.5°F) in 120 minutes under 30 V AC. This heating performance would improve with increasing applied voltage.

Keywords: electrical conductive concrete; ice and snow melting; ionic conduction; radiant heating.

INTRODUCTION

Electrically conductive concrete is a composite material made by adding electrical conductive materials to the traditional cement-based mixture. The research on electrically conductive concrete began in the 1930s in France, America, and Germany. The mixture may be used for heating and piezo-resistive applications.^{1,2} It has multiple applications such as snow melting and deicing, indoor heating, health monitoring, and electromagnetic shielding.³⁻⁶ In the 1990s, conductive concrete was used for the deck of the Roca Spur Bridge in Nebraska for snow melting. This is the first time conductive concrete was used in a real structure.³

The most commonly used conductive materials in traditional conductive concrete include steel fiber, steel slag, carbon fiber, and nano-carbon black.⁷⁻⁹ The mechanism of conduction through the concrete made by these materials can be categorized as: 1) conductive circuits due to interconnection of conductive materials with each other; and 2) electronic conduction.¹⁰⁻¹² Therefore, the conductivity of these conductive concretes depends on the electrical properties of conductive materials and their distribution in the mixtures. There are many drawbacks in these types of conductive concrete. For example, the resistivity of the conductive concrete made by steel fiber or steel slag would increase tens of times if the steel fiber or steel slag is rusty.¹³ The carbon fibers tend to twine around each other or flocculate, and uniform dispersion in the mixture is difficult. The non-uniform dispersion of conductive materials causes uneven distribution of temperature and cracks due to thermal stress.¹⁴ The small size of the nano-conductive material makes it difficult to form conductive circuits, unless a large amount of admixtures is batched, which significantly increases the cost.⁹

An innovative conductive composite—ionically conductive mortar—is developed in this study. The directional

migration of ions under external voltage makes the mortar conductive, which is different from the traditional conduction mechanism. Whittington et al.¹⁵ proved that there was free moisture containing a variety of ions in concrete, and the directional migration of ions made the concrete conductive. The directional migration of ions in concrete has been observed by many researchers and used in concrete permeability evaluation and chloride ion erosion.¹⁶⁻¹⁸ ASTM C1202 specifies a method using the coulomb electric flux as an electrical indication of the ability of normal concrete to resist chloride ion penetration.¹⁹

The literature review shows that ions can directionally migrate in cement-based composites, making the composites electrically conductive. However, the main purpose of the existing research was investigating the permeability and compactness of the cement-based composite based on its conductivity. Most of these researches aimed at reducing the amount and the sizes of voids inside the cement-based composite to reduce permeability and increase compactness. The ionically conductive mortar developed in this study, 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.

The effectiveness of epoxy surface coating to prevent moisture evaporation from inside the mortar was investigated in terms of mortar conductivity. The effect of curing time on the conductivity was also investigated. Based on the results, having an epoxy coating and a curing time of 28 days are essential for the mortar specimens to be ionically conductive. A series of ionically conductive mortar specimens with different type and concentration of electrolyte solutions, as well as with different electrode materials, were made. The electrical conductivities of these specimens were compared. The heating performance of the ionically conductive mortar specimens was evaluated in a laboratory setting, and the specimens showed stable conductivity and good heating performance.

RESEARCH SIGNIFICANCE

An innovative cementitious mortar that conducts electricity through electrolyte was developed in this study. Unlike the traditional conductive cementitious composites, the “ionically conductive mortar” takes advantage of directional migration of ions in the free moisture of the

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Table 1—Material properties

Materials	Material properties
Cement	PO 42.5R cement; 3-day compressive strength: 30.6 MPa; initial setting time: 135 minutes; alkali content: 0.6%
Sand	Normal river sand; sand with grain size ≤ 0.25 mm accounts for 50% of total mass; mean grain size: 0.25 to 0.5 mm
Galvanized steel electrode	Diameter: 1 mm; mesh size: 5 x 5 mm; being processed into 40 x 30 mm sheets
Copper electrode	Red copper, diameter: 1 mm; mesh size: 5 x 5 mm; being processed into 40 x 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: waterproof, anticorrosive, acid- and alkali-resistant

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

composite. As a result, this concrete development bypasses several drawbacks of the traditional electrically conductive concrete. The ionically conductive mortar can be used for indoor radiant heating as well as for ice and snow melting of sidewalks and driveways.

TESTS

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 gas and, thus, to increase the porosity of specimens and the number of interconnected voids in specimens.²⁰ These voids facilitate the electrolyte solution to permeate within the specimens. The epoxy resin was adopted to coat the surface of part specimens for ensuring sustainable ionic conduction in the mortar, and some of specimens were uncoated for proving effectiveness of epoxy resin.

Specimen Preparation

The designations of the specimens in all the experiments are given in Table 2. The dimensions of the specimens were 40 x 40 x 40 mm (1.6 x 1.6 x 1.6 in.) and the mixture proportion (weight ratio) was water:cement:sand = 0.5:1:3 in accordance with the Chinese specification ISO 679:1989.²¹ Aluminum powder was added according to the 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 followed by mixing for 2 to 3 minutes; 3) aluminum powder was added followed by mixing for 1 to 2 minutes. The mixing time is determined by the quantity of materials, according to the Chinese specification ISO 679:1989.²¹ For a large amount of materials, the stirring time was extended until all materials were mixed uniformly by visual inspection; 4) for each specimen, the mixture was cast into a mold in three lifts. One-third of the mold was filled with mixture in each lift and vibrated on a vibrating table at a frequency

of 2860 cycles/min with an amplitude of 0.3 to 0.6 mm for approximately 10 seconds; and 5) the surface of the specimen was finished with a steel trowel.

The shape of traditional electrode is usually rectangle. If the rectangular electrode was used, the electrodes would tend to shift in the mold during vibration, consequently causing uncertain spacing between two electrodes. To resolve this issue, the shape shown in Fig. 1 was used for electrodes. The top of the electrode was bent on the mold, and the flat bottom of the electrode kept the electrode in place during vibrating.

The specimens were taken out of the mold after approximately 12 hours and put into a curing box of 20°C (68°F) and 98% humidity.²¹ All the specimens were cured for 28 days except those specimens made specifically for different curing times. In those cases, the specimens were cured for 7, 28, and 60 days, respectively, as shown in Table 2. After curing was complete, the specimens were weighed and subject to a series of tests, according to the Chinese standards for testing the performance of building mortar (JGJ/T70-2009).²² The results are presented in Table 3. The size and shape of void inside specimen can be seen in the discussion of the experiment ‘Influence of Curing Time on the Resistivity of Ionically Conductive Mortar’.

The specimens were immersed in electrolyte solutions of different concentrations to allow the solutions to soak into the specimens. Two electrolyte solutions, CuSO₄ (the CS group) and FeSO₄ (the FS group), and the different concentrations used, are given in Table 2. Control specimens were immersed in pure water (designated as the C group) for baseline. The specimens were taken out of the solution or water, wiped dry, and weighed every 12 hours. The specimens were considered saturated when the difference in weights was less than 1% between two successive measurements. The longest immersion time in the experiments was 96 hours, which would be long enough to saturate all specimens. The saturated surface-dry (SSD) specimens were coated with a 1 mm (0.0394 in.) thick layer of epoxy resin using a brush. Figure 2(a) shows a typical test specimen with epoxy resin. Some specimens were not coated with epoxy for comparison purposes, as summarized in Table 2.

Measurement of electrical resistivity

The resistivity R of specimens was measured using a multi-meter according to the circuit shown in Fig. 2(b). The electrical resistivity of a specimen was calculated by Eq. (1).

$$R = (U/I)(A/L) \quad (1)$$

where U is the voltage between the two ends of the specimen. A 30 V AC (alternating current) power source was used for testing. I is the current of the circuit, and A and L , as shown in Fig. 1, are the cross-sectional area and length of the specimen, respectively.

The time lapsed of the experiments, defined as the length of time an experiment was conducted since a specific specimen has finished curing, is presented in the various tables. The test temperature was controlled by an air-conditioner and set at 30°C (86°F).

Table 2—Designations of specimens

Experiment	Designation	Type and mass fraction of electrolyte solution	Epoxy resin	Type of electrodes	Curing time	
Influence of epoxy resin coating on resistivity of ionically conductive mortar	ER-FS-01	FeSO ₄ 4.8%	Coated	Galvanized steel	28 days	
	ER-FS-02	FeSO ₄ 9.1%				
	ER-FS-03	FeSO ₄ 13%				
	ER-FS-04	FeSO ₄ 16.7%				
	ER-FS-05	FeSO ₄ 20%				
	NER-FS-01	NER-FS-01	FeSO ₄ 4.8%	Uncoated	Galvanized steel	28 days
		NER-FS-02	FeSO ₄ 9.1%			
		NER-FS-03	FeSO ₄ 13%			
		NER-FS-04	FeSO ₄ 16.7%			
		NER-FS-05	FeSO ₄ 20%			
Influence of curing time on resistivity of ionically conductive mortar	D7-C	Pure water	Coated	Galvanized steel	7 days	
	D7-FS-01	FeSO ₄ 4.8%				
	D7-FS-02	FeSO ₄ 9.1%				
	D7-FS-03	FeSO ₄ 13%				
	D7-FS-04	FeSO ₄ 16.7%				
	D7-FS-05	FeSO ₄ 20%				
	D28-C	D28-C	Pure water	Coated	Galvanized steel	28 days
		D28-FS-01	FeSO ₄ 4.8%			
		D28-FS-02	FeSO ₄ 9.1%			
		D28-FS-03	FeSO ₄ 13%			
		D28-FS-04	FeSO ₄ 16.7%			
	D28-FS-05	FeSO ₄ 20%				
	D60-C	D60-C	Pure water	Coated	Galvanized steel	60 days
		D60-FS-01	FeSO ₄ 4.8%			
		D60-FS-02	FeSO ₄ 9.1%			
D60-FS-03		FeSO ₄ 13%				
D60-FS-04		FeSO ₄ 16.7%				
D60-FS-05	FeSO ₄ 20%					
Influence of electrolyte solution and concentration on resistivity	C	Pure water	Coated	Galvanized steel	28 days	
	FS-01	FeSO ₄ 4.8%				
	FS-02	FeSO ₄ 9.1%				
	FS-03	FeSO ₄ 13%				
	FS-04	FeSO ₄ 16.7%				
	FS-05	FeSO ₄ 20%				
	CS-01	CuSO ₄ 4.8%				
	CS-02	CuSO ₄ 9.1%				
	CS-03	CuSO ₄ 13%				
	CS-04	CuSO ₄ 16.7%				
CS-05	CuSO ₄ 20%					
Influence of different electrodes on resistivity of ionically conductive mortar	C-Cu	Pure water	Coated	Copper	28 days	
	CS-01-Cu	CuSO ₄ 4.8%				
	CS-02-Cu	CuSO ₄ 9.1%				
	CS-03-Cu	CuSO ₄ 13%				
	CS-04-Cu	CuSO ₄ 16.7%				
CS-05-Cu	CuSO ₄ 20%					

Notes: Mixture proportion (weight ratio) was water:cement:sand = 0.5:1:3; solubility of different solutes should be determined according to solubility table; solutions presented in the table were based on solubility at 30°C (86°F); mass fraction = (mass of solute/mass of solution) × 100%; for each code, five specimens were fabricated and all results given are average testing values of them.

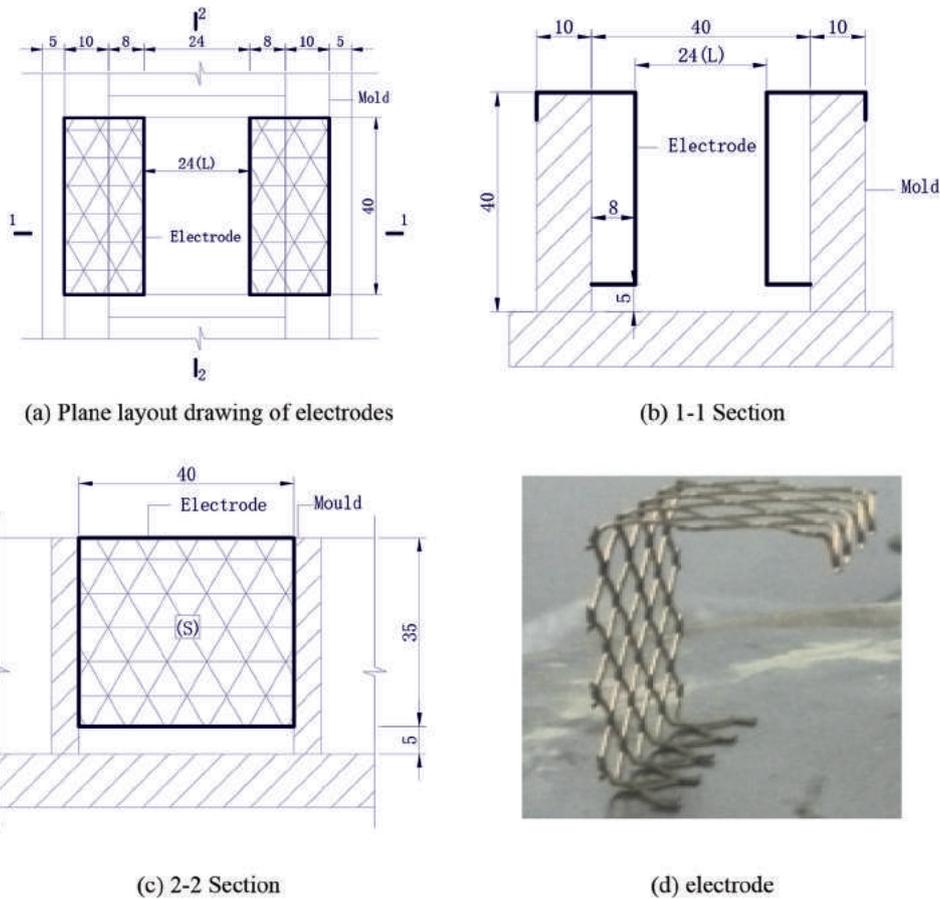


Fig. 1—Electrode configuration, in mm. (Note: 1 mm = 0.0394 in.)

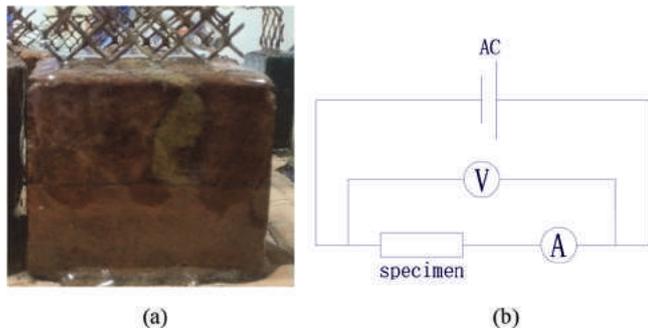


Fig. 2—(a) Specimen coated with epoxy resin; and (b) testing circuit.

RESULT AND ANALYSIS

Influence of epoxy resin coating on resistivity of ionically conductive mortar

Traditional conductive concrete does not have an epoxy coating on the surface. Due to concrete hydration and moisture evaporation from inside, the resistivity of conductive concrete would increase rapidly with age. For this reason, epoxy coating was applied on the surface of the ionically conductive mortar. The coating would not only ensure stable ionic conduction within the mortar, but also provide insulation to enhance electrical safety when the conductive mortar is energized. The epoxy resin coating can be used not only in the ionically conductive mortar but also in other traditional conductive concrete due to its effectiveness of preserving the moisture inside the concrete.

Table 3—Properties of 28-day specimen

Compressive strength	Density	Porosity	Water penetrating time	Osmotic pressure
32.4 MPa	2331 kg/m ³	35.23%	72 hours	0.4 MPa

Notes: Mixture proportion (weight ratio) was water:cement:sand = 0.5:1:3, curing time of 28 days; water penetrating time means time for which specimen saturated by the water; 1 MPa = 145 psi.

A total of 50 specimens was fabricated in two groups; the ER group and the NER group. The specimens coated with epoxy resin are denoted as the ER group and those that were not are denoted as the NER group. Five specimens were immersed into electrolyte solutions of different concentration as shown in Table 2. The resistivity of each specimen was measured under 30 V AC at 1, 3, 7, 14, and 28 days of age. The resistivity was measured on the day the specified curing was complete. The changes in resistivity with age were compared between the ER group and the NER group, while keeping other parameters the same. The results from the FS group are presented in Table 4 and Fig. 3. It can be seen that the resistivity of the NER specimens increased significantly with time. For instance, the resistivity of FS-03-NER increased 262% in 28 days, while that of FS-03-ER only increased 144%. Good ionic conduction in the mortar relies on the electrolyte, while the moisture was consumed during the hydration process. The hydration products also continued filling in the interconnected voids as the mortar aged, resulting in gradual reduction in the number of voids.²³ When the spec-

Table 4—Resistivity ($\Omega\cdot\text{m}$) of specimens

Time lapsed, days	FS-01		FS-02		FS-03		FS-04		FS-05	
	ER	NER								
1	54.35	96.08	48.54	111.61	54.78	112.42	69.37	107.25	86.61	113.01
3	56.76	125.59	50.51	147.86	57.59	150.79	70.79	132.70	88.70	150.91
7	72.24	214.94	67.34	262.80	80.06	277.46	93.36	225.43	120.12	275.44
14	86.97	273.13	86.21	337.30	102.50	349.97	112.87	294.37	147.60	350.43
28	106.38	323.93	114.95	385.90	133.42	407.41	138.18	339.37	177.01	393.16

Table 5—Properties of specimens with different curing time

Curing time, days	Compressive strength, MPa	Porosity, %	Water penetrating time, hours
7	20.9	40.59	72
28	32.4	35.23	72
60	38.9	34.85	72

Notes: Mixture proportion (weight ratio) was water:cement:sand = 0.5:1:3; water penetrating time means time for which specimen saturated by water; 1 MPa = 145 psi.

imens were stored at 30°C (86°F), free moisture evaporated and caused crystallization of electrolyte. The crystallization caused a sharp decrease in free ion concentration inside the mortar. Moreover, the crystals filled the voids in the mortar and impede the movement of free ions. Consequently, the resistivity of the mortar increased. Because specimens in the ER groups were only affected by the hydration reaction, the increase in resistivity was much less.

It can also be seen from Fig. 3 that the resistivity-increase trend of both ER and NER groups was almost parallel to each other from 14 days to 28 days. This indicates that evaporation of water causing increase in the resistivity of the NER specimens took place during the first 14 days. The rest of the increase was mainly due to the hydration reaction in the specimens. Therefore, the epoxy coating is necessary for ensuring sustainable ionic conduction in the mortar.

Influence of curing time on resistivity of ionically conductive mortar

The voids in the specimens would be gradually filled by calcium-silicate-hydrates (C-S-H) due to hydration. Moisture content of the specimens was affected by the humidity, temperature, and the time of curing. The permeability tests showed that porosity of the specimens and the electrolyte concentration dictate the permeation rate as well as the concentration of free ions in the specimens.²⁴ The results showed that specimens with larger porosity had faster permeation rate. On the contrary, the specimens immersed in higher electrolyte concentration showed slower permeation rate. The ion concentration and moisture content are the most influential parameters on the conductivity. The impact of the curing time on the resistivity of the mortar specimens was investigated.

Test specimens from each batch were divided into three groups for 7, 28 and 60 days of curing time,²¹ which were respectively designated as D₇, D₂₈, and D₆₀, as shown in Table 2. The properties of the specimens cured for 28 days

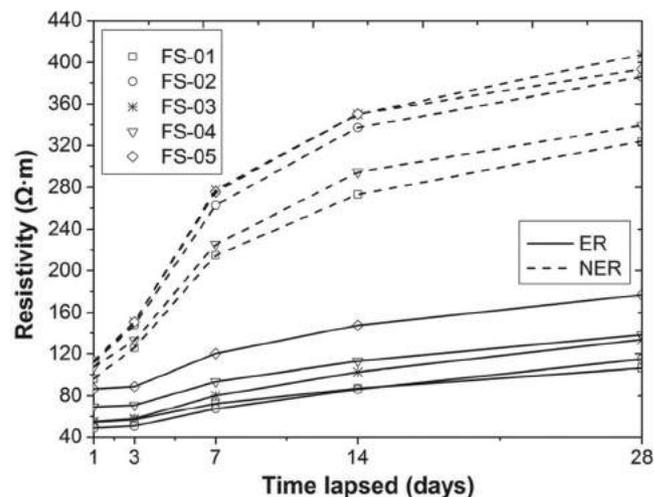
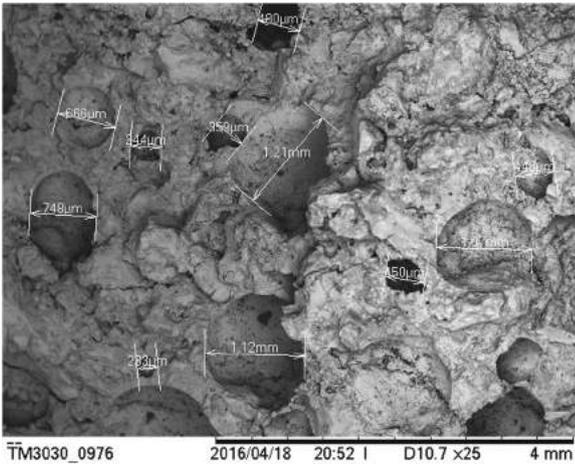


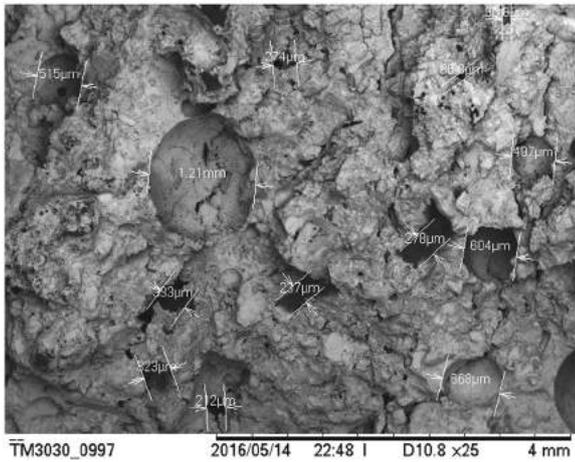
Fig. 3—Changes in resistivity with time elapsed: (a) 7 days (25 times); (b) 28 days (25 times); and (c) 60 days (30 times).

are presented in Table 5. A scanning electron microscope was used to take micro-photographs to show the size and shape of voids in the mortar, as shown in Fig. 4. The resistivity under 30 V AC was respectively measured at 1, 3, 7, 14, 28, 60, and 90 days. The results from the FS specimens are presented in Table 6 and in Fig. 5.

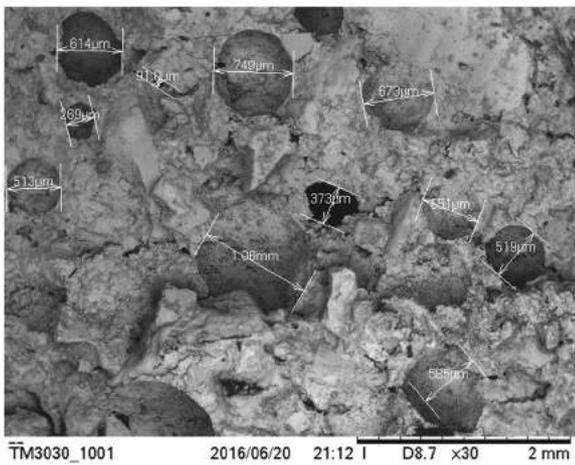
The moisture content of the specimens was relatively high when tested at 1 and 3 days, and the resistivity mainly depended upon the moisture content. D₇ groups had high moisture content because the hydration process was not yet complete. It takes approximately 14 days for the hydration products to fill interconnected voids in ordinary portland-cement paste with a water-cement ratio (*w/c*) of 0.5.²⁵ Accordingly, D₇ groups had the highest number of interconnected voids at the beginning, shown in Fig. 4, and there were more ions available to permeate into these specimens during the same time period.²⁶ Conductivity increases with increasing ion concentration.²⁷ Due to high ion concentration and high moisture content, the resistivity of D₇ specimens was lower than the other groups. The resistivity of D₆₀ specimens was low as well due to the high moisture content resulting from long curing time after hydration was complete. When curing time was more than 14 days, the influence of ions concentration on the resistivity was less significant. The resistivity of the FS specimens was in the order of D₇ < D₂₈ < D₆₀, increasing with time elapsed. With increasing curing time, D₆₀ groups had the lowest number of free ions due to completed hydration, and most voids were



(a) 7d (25times)



(b) 28d (25times)

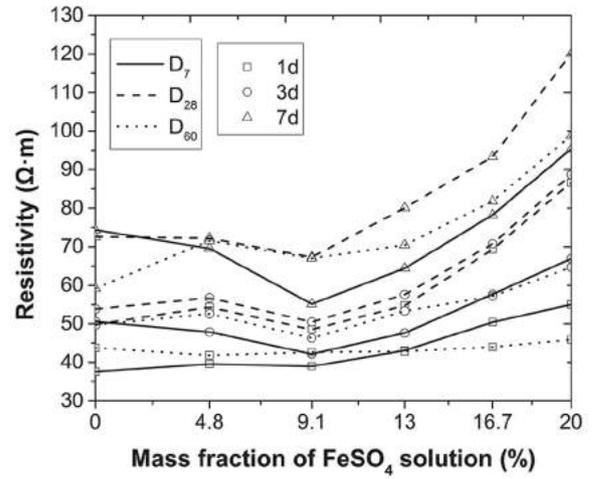


(c) 60d (30times)

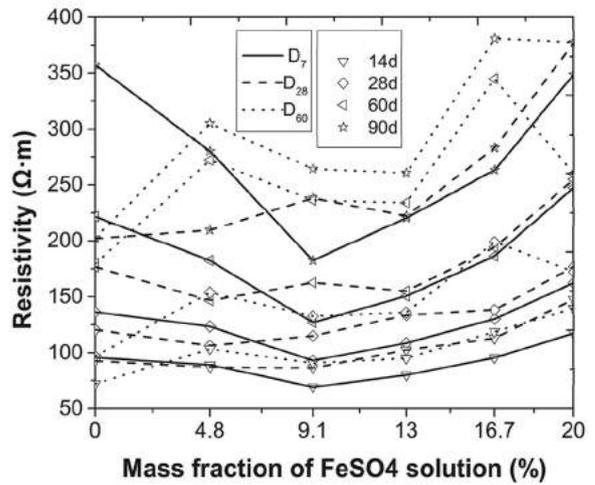
Fig. 4—Size and shape of voids inside mortar with various curing times.

filled by CSH. On the contrary, D₇ groups had most free ions while hydration was still in progress.

The resistivity of D₇ groups increased rapidly versus time at a rate much faster than those of D₂₈ and D₆₀ groups.



(a) Changes in resistivity with electrolyte concentration (day 1 through day 7)



(b) Changes in resistivity with electrolyte concentration (day 14 through day 90)

Fig. 5—Changes in resistivity with various curing times.

Within the D₇ groups, the resistivity of the FS specimens was smaller than that of the C specimens (that is, control specimens were immersed in pure water), indicating that the free ions in the specimens played an important role in the electrical conduction in the mortar. For high-concentration electrolyte solution, crystallization took place inside specimens and blocked the penetration of ions. As a result, the resistivity of specimens increased.

Figure 5 shows that the resistivity of D₂₈ and D₆₀ specimens in the C groups was smaller than that in the FS groups due to different permeability. Penetration tests showed that pure water had a rate approximately two times higher than that of the solutions at a 4.8% concentration. The penetration rate decreased with increasing concentrations.²⁴

It was found that the D₇ groups had a higher concentration of ions than in the D₂₈ and D₆₀ groups. However, the mechanical strengths of the D₇ groups may not be adequate due to incomplete hydration, according to Table 4. The D₆₀ groups had poor permeability of ionic solutions and, thus, the electrical conductivity of the mortar may not be adequate. To ensure good mechanical strength and electrical

Table 6—Resistivity ($\Omega\cdot m$) of specimens receiving different curing times

Time lapsed, days	Group No.	Resistivity					
		C	FS-01	FS-02	FS-03	FS-04	FS-05
1	D ₇	37.58	39.59	38.99	43.05	50.46	55.05
	D ₂₈	49.85	54.35	48.54	54.78	69.37	86.61
	D ₆₀	43.72	41.81	42.64	42.81	43.95	45.87
3	D ₇	50.61	47.89	42.16	47.62	57.66	66.89
	D ₂₈	53.87	56.76	50.51	57.59	70.79	88.70
	D ₆₀	49.72	52.65	46.30	53.32	57.20	64.66
7	D ₇	74.36	69.56	55.11	64.42	78.26	95.39
	D ₂₈	72.60	72.24	67.34	80.06	93.36	120.12
	D ₆₀	59.20	71.56	66.99	70.48	81.84	98.78
14	D ₇	95.71	89.06	69.14	79.84	95.57	117.42
	D ₂₈	92.72	86.97	86.21	102.50	112.87	147.60
	D ₆₀	71.96	103.39	90.70	95.04	118.57	139.39
28	D ₇	136.07	123.19	93.10	108.63	129.90	162.47
	D ₂₈	120.44	106.38	114.95	133.42	138.18	177.01
	D ₆₀	96.93	153.86	132.43	135.61	199.01	172.49
60	D ₇	221.50	182.33	126.61	150.66	186.40	247.51
	D ₂₈	176.81	146.52	162.70	155.04	194.26	254.79
	D ₆₀	179.49	272.12	236.43	234.12	344.83	259.74
90	D ₇	357.37	279.99	182.41	220.42	263.16	348.48
	D ₂₈	202.02	209.43	238.40	222.22	283.18	376.77
	D ₆₀	202.79	305.17	264.27	260.49	380.69	377.36

Table 7—Resistivity ($\Omega\cdot m$) of specimens in FS groups

Time lapsed, days	Resistivity					
	C	FS-01	FS-02	FS-03	FS-04	FS-05
1	65.87	47.94	36.10	43.17	46.49	60.06
3	79.07	59.16	44.02	54.73	62.43	87.41
7	95.23	74.15	57.20	76.03	91.59	133.61
14	108.09	82.22	68.77	101.72	111.20	144.66
28	131.53	107.82	93.29	139.14	149.73	200.51

conductivity, the specimens were cured for 28 days before conducting subsequent experiments.

Influence of electrolyte solution and concentration on resistivity

Specimens made of regular cementitious mortar were soaked in the solutions of FeSO₄ and CuSO₄, respectively, with various concentrations as given in Table 2. The resistivity of the specimens under 30 V AC was then measured at 1, 3, 7, 14, and 28 days. The results from the FS and CS groups are presented in Tables 7 and 8 and Fig. 6 and 7, respectively.

As shown in Table 7 and Fig. 6, the resistivity of the FS specimens decreased with concentration to 9.1% and then increased with the concentration up to 20%. The conduc-

Table 8—Resistivity ($\Omega\cdot m$) of specimens in CS groups with galvanized iron electrodes

Time lapsed, days	Resistivity					
	C	CS-01	CS-02	CS-03	CS-04	CS-05
1	65.87	45.69	51.96	56.15	71.50	91.72
3	79.07	55.38	68.46	75.28	94.43	124.33
7	95.23	72.04	94.14	116.00	143.84	164.83
14	108.09	86.73	120.28	144.95	193.98	215.39
28	131.53	111.04	158.14	185.64	261.90	281.79

tivity increases with the increase of ions concentration.²⁷ However, there is an upper bound beyond which the ionic conduction will be limited by the solubility of the chemicals.²⁸ The precipitated crystal would gradually occupy the voids in the specimen, thus increasing the resistivity of the specimen. The higher the concentration of the solution, the more pronounced this phenomenon will be. From Table 8 and Fig. 7, the upper bound of the concentration of the CuSO₄ solution appeared to be 4.8%.

At 30°C (86°F), the solubility of CuSO₄ is smaller than that of FeSO₄, and hence the electrical resistivity of CS group is always greater than that of FS group. Therefore, the solubility and the concentration of the solutions had a strong influence on the conductivity of the ionically conductive mortar.

Table 9—Resistivity ($\Omega\cdot\text{m}$) of specimens in CS groups with copper electrodes

Time lapsed, days	Resistivity					
	C-Cu	CS-01-Cu	CS-02-Cu	CS-03-Cu	CS-04-Cu	CS-05-Cu
1	40.60	50.82	52.81	60.22	67.50	77.49
3	46.44	64.12	69.70	82.50	95.93	117.01
7	61.39	92.60	100.99	115.69	128.51	158.77
14	71.45	106.14	106.44	132.36	158.99	212.48
28	105.83	127.79	135.43	172.64	207.58	288.03

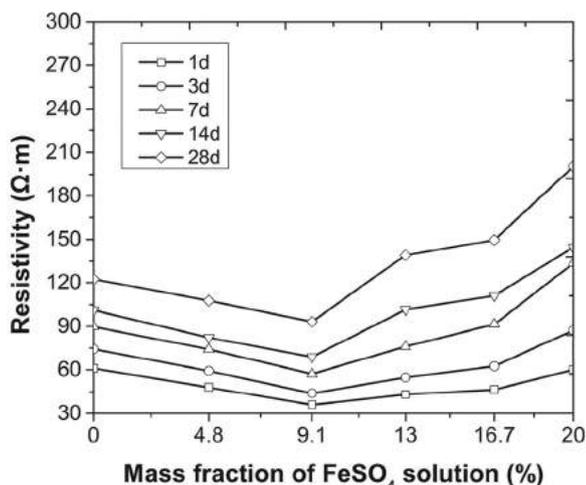


Fig. 6—Changes in resistivity of specimens in FS groups.

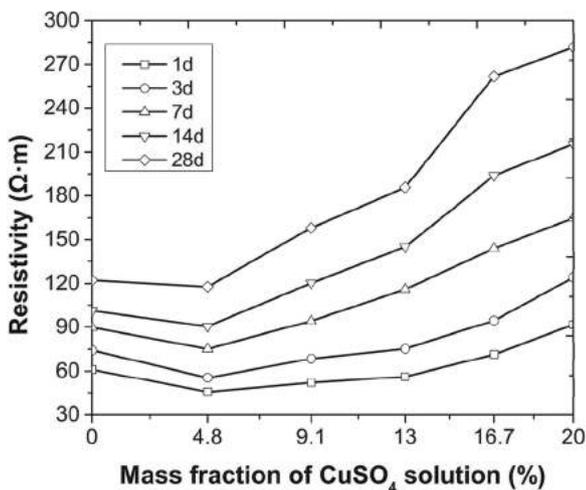


Fig. 7—Changes in resistivity of specimens in CS groups.

Influence of different electrodes on resistivity of ionically conductive mortar

The electrical charges carried by ions in the electrolyte form an electrical circuit between the electrodes when a voltage is applied to the electrodes. The degree of polarization is directly related to the type of electrodes. Further, some metal electrodes may even react with the electrolyte solution without being energized. To investigate the influence of different electrodes on the resistivity, copper electrodes were used for 30 specimens, as shown in Table 2. These specimens were immersed into the CuSO_4 solution. Both galvanized iron electrodes and copper electrodes were tried for testing the specimens in the CuSO_4 solution. A 30 V AC was

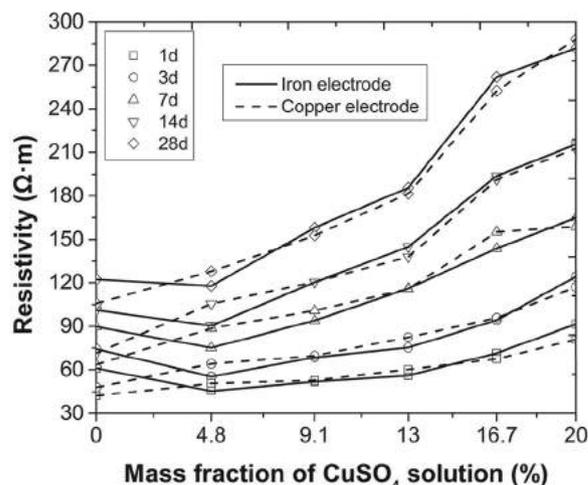


Fig. 8—Effect of different electrodes on resistivity.

applied to the electrodes at 1, 3, 7, 14, and 28 days after the specimens were cured, coated with epoxy, and placed in a room at 30°C (86°F). The results from using the galvanized iron electrodes are presented in Table 8, while those from using the copper electrodes are presented in Table 9. The test results from Tables 8 and 9 are compared in Fig. 8.

When the mass fraction of the solution was 0%, the resistivity specimens with the galvanized iron electrodes were higher than that with copper electrodes. However, the opposite was true when the mass fraction of the solution was 4.8%. This is due to different ionization potentials of the metal electrodes in the electrolyte solutions. Copper and zinc have the same ionization potential in same solutions, while iron has a lower potential of about five to nine orders of magnitude smaller than those of copper and zinc.²⁷ Thus, using iron electrodes in electrolyte solutions would activate polarization more readily under the same electric field. Even though galvanized iron electrodes are coated with a layer of zinc film (generally 3 to 5 μm thick), the zinc would dissolve quickly due to chemical reactions and the exposed iron would become the electrodes. Copper electrodes could only cause polarization in CuSO_4 solution. As a result, the resistivity of the specimens with copper electrodes was always higher when mass fraction of the solution was 4.8%.

When the concentration of solution was in the range between 9.1% and 16.7%, the resistivity of the specimens with iron electrodes was higher. As the concentration of CuSO_4 solution increases, the iron electrode surface would be covered by the copper ion “deposits”; thus, the effect of two different electrodes became less significant. Further, the water contents in the specimens decrease with age, causing

Table 10—Temperature versus heating time

Designation	Time lapsed, days	Initial temperature, T_0	Temperature of 60 minutes T_{60}	Temperature of 120 minutes T_{120}	Temperature difference, $T_{120} - T_0$	Average current, mA	Electrical power, W
FS-02	7	28.9	45.7	48.6	19.7	27.5	0.807
	14	29.5	42.1	44.2	14.7	21.4	0.642
	28	29.5	39.9	42	12.5	17.2	0.516
	60	29.5	39.2	41.6	12.1	16.9	0.507
	90	29.6	39	41.5	11.9	16.7	0.501
CS-01-Cu	7	29.5	37.8	40.3	10.8	14.2	0.426
	14	29	36.8	38.1	9.1	12.1	0.363
	28	29.2	36	37.4	8.2	10.8	0.324
	60	29.1	35.9	37.1	8	10.5	0.315
	90	29.2	35.3	37	7.8	10.2	0.306

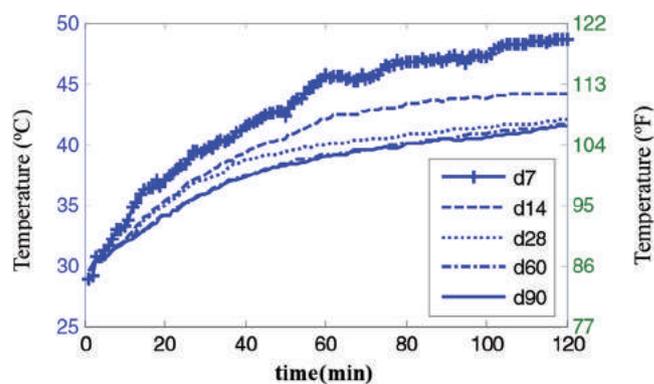
Note: °F = 32 + 1.8 × °C.

higher concentration or near saturation to slow down the “deposits.” Thus, the iron electrodes would enhance the polarization if they have not been fully covered by copper. When the mass fraction of the solution reached 20%, the resistivity between the specimens with the two different electrodes were approximately the same. Due to the high concentration of electrolyte solution, the chemical reaction was quick to cause the steel electrode covered by copper in a short time. This is why the steel electrode specimens exhibited the same performance as the copper electrode specimens.

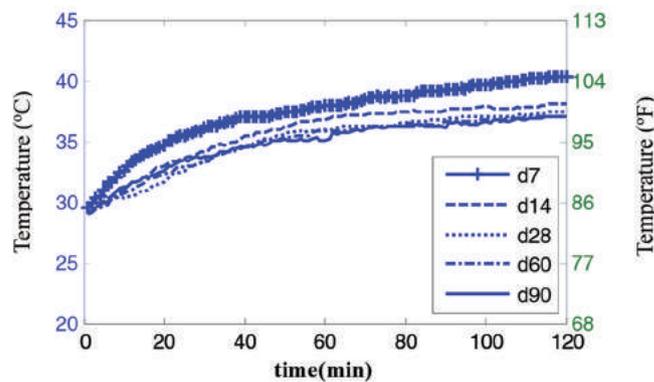
The test results indicated that the type of electrolyte solution and the ionization potential of the electrodes has significant influence on the resistivity of ionically conductive mortar. Metals that react with electrolyte solutions should not be used for electrodes. Although the replacement reaction between iron electrodes and CuSO_4 solution helped to alleviate the polarization, it weakened the strength of the electrodes because the iron electrodes were loosely covered by copper deposits. As a result, the reliability and durability of conductivity of ionically conductive mortar cannot be assured. On the other hand, metals having high ionization potential should be selected for electrodes. It is desirable that the electrodes and the ions in the electrolyte solution are made of the same metallic element. The service life of the electrodes would be prolonged, as the ionic chemical reaction is reversible. The higher the ionization potential of the metal, the more difficult for the electrodes to cause polarization effect, which helps to reduce the resistivity of ionically conductive mortar.

Heating performance of ionically conductive mortar

Conductive concrete is mainly used for deicing and snow melting as well as indoor heating,^{29,30} so it is necessary to study the electric heating performance of ionically conductive mortar. Specimens FS-02 and CS-01-Cu, which showed the best conductivity in the tests, were subsequently subject to the heating test. These specimens were tested under 30 V AC for 120 minutes, and the surface temperature was recorded at every minute by using an infrared temperature



(a) Temperature rise vs. Time – FS-02



(b) Temperature rise vs. Time – CS-01-Cu

Fig. 9—Heating rate of specimens.

sensor. The heating tests were conducted at 1, 3, 7, 14, 28, 60, and 90 days after the specimens were coated with epoxy and placed in a room at 30°C (86°F). The testing circuit was previously shown in Fig. 2(b). The surface temperature and the average current during the experiment are presented in Table 10 and Fig. 9.

During the tests, the temperature of the ionically conductive mortar rose sharply in the first 60 minutes, followed by a gradual increase during the next 60 minutes. This trend appeared to be independent of specimen’s age and the elec-

trolyte solutions. The maximum heating rate of 19.7°C (35.5°F) in 120 minutes indicates that the ionically conductive mortar has good electric heating performance. The heating tests were conducted under a voltage of 30 V, which is safe to human body. The heating performance of ionically conductive mortar should improve with increasing applied voltage.

The FS group had a faster heating rate than the CS group. When the tests were conducted 7 days after applying the epoxy coating, the FS group had a maximum temperature rise of 19.7°C (35.5°F), while the CS group had 10.8°C (19.4°F). There was plenty of free moisture in the specimens at 7 days, and the FS group had higher ion contents than the CS group. As the specimens aged, the free moisture in the specimens gradually diminished and the Fe²⁺ ions in the FS specimens precipitated and crystalized, and were gradually oxidized to Fe³⁺ crystal. This could be observed from the fracture surface of the specimens, as the inside of the specimens gradually turned to red. The CS specimens did not experience the aforementioned changes with time. As a result, the two groups showed comparable heating rates. When the heating tests were conducted at 90 days, the FS group had a maximum temperature rise of 11.9°C (21.4°F), while the CS group had 7.8°C (14°F).

As shown in Fig. 9, the heating rate of the specimens would decrease with age due to hydration in progress before 28 days. However, the heating rates of the specimens became stabilized after 28 days.

CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn:

1. An ionically conductive mortar concept was developed and its electrical conductivity was investigated. The ionically conductive mortar has some advantages over the traditional conductive concrete, such as the dispersion and degradation of the conductive materials.

2. Moisture contents in the specimens was one of the most important factors influencing the resistivity of the conductive mortar. Epoxy coating is essential to prevent evaporation of the moisture. The results showed that the resistivity of the ER specimens was far less than that of the NER specimens. The resistivity of the NER specimens at the age of 28 days was approximately three times higher than that of the ER specimens.

3. Curing time had significant influence on the porosity and the hydration process in the mortar, and subsequently on the permeability and concentration of electrolyte solution in the mortar. The results showed that the shorter the curing time, the better the permeability of the mortar. However, inadequate curing time would compromise the mortar's mechanical strengths. To ensure good permeability and the mechanical strength, the optimum curing time is 28 days.

4. The conductivity of ionically conductive mortar would increase with the increase of ion concentration in the electrolyte solution. However, there is an upper bound beyond which the ionic conduction will be limited by the solubility of the chemicals.

5. Different electrolyte solutions have different ranges of mass fractions for achieving minimum resistivity of the mortar. This is because different salts used in the electrolyte have different solubility. Salts with good solubility should be used for the electrolyte solution.

6. The type of electrolyte solution and the ionization potential of the electrodes has significant influence on the resistivity of ionically conductive mortar. Metals that react with electrolyte solutions should not be used for electrodes. Metals having high ionization potential should be selected for electrodes. It is desirable that the electrodes and the ions in the electrolyte solution are made of the same metallic element. The service life of the electrodes would be prolonged, as the ionic chemical reaction is reversible.

7. Ionically conductive mortar has good electric heating performance and could achieve a heating rate of 19.7°C (35.5°F) in 120 minutes under 30 V AC. The heating performance of ionically conductive mortar should improve with increasing applied voltage.

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