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Electrically Conductive Mortar Characterization for Self-Heating Airfield Concrete Pavement Mix Design

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Abstract: The overall objective of this paper is to investigate the types and proportions of nano-carbon based conductive materials (carbon powders and fiber), the mixing procedures, and the characteristics of conductive mortar, including the heating performance, with a focus on optimizing self-heating ECON mix design with desirable electrical and mechanical properties for airfield pavement deicing applications. A state-of-the-art review on relevant literature was conducted to identify the various conductive materials that have been investigated in the past, their optimal concentration levels to achieve desirable system-level engineering properties, and the various challenges in optimizing the ECON mix design and achieving a cost-effective ECON system. In the experimental investigation, mortar specimens modified with conductive materials at different concentration levels were compared with untreated (control) specimens in terms of electrical and mechanical properties. Conductivity and strength performance assessment of the experimental results revealed that 6-mm chopped carbon fiber (CCF) utilized in this study is capable of providing improved electrical conductivity in comparison to carbon based conductive powders without loss of strength and workability. Among carbon based conductive powders, the coarsest graphite powder provides acceptable electrical conductivity improvement and lesser loss of strength and workability. Heating characteristic of conductive mortar indicates that conductive materials which can enhance ECON conductivity could provide heating performance improvement for airfield pavement deicing application.

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***Key words**: Airport pavements; Carbon fiber; Carbon powder; Heated pavements; Electrically conductive concrete; Electrical resistivity; Pavement deicing.*

Introduction

A number of studies in the past have investigated the prospect of developing electrically conductive concrete (ECON) by adding conductive materials (fibers, powders and solid particles) to conventional concrete. These studies have established, at least at the proof-of-concept level, that ECON has several innovative applications such as electrical heating for deicing of bridges, sidewalks, and pavements; sensing and monitoring; and electromagnetic interference shielding. The earliest patent on the topic of ECON was issued in 1965 [1] Since then a number of ECON recipes (i.e., mix proportions, combinations of different conductive materials, etc.) and applications have evolved [2-7].

The motivation for this paper comes from an ongoing Federal Aviation Administration (FAA) sponsored study at Iowa State University (ISU) on the development of hybrid heated airport pavement systems, of which ECON is a crucial component. One of the major issues encountered by airports currently is the maintenance of operational safety and status of the airport paved surfaces during the periods of snowfall and ice rains. The surface traction of pavement is dramatically influenced by frozen precipitation in the form of ice, snow, or slush. Traditional de-icing methods involving sand/chemical mixtures pose not only environmental concerns, but can also potentially create Foreign Object Damage (FOD) to aircraft engines. Recent research studies [8-9] have demonstrated that ECON can enable sufficient electrical conduction to facilitate the prevention of ice and snow formation when connected to a power source. These research studies serve as benchmarks for carrying out further investigations to design and develop the most effective ECON for heated airport pavement systems.

In pursuit of achieving performance optimized self-heating ECON mix design for airfield pavement deicing applications, the overall objective of this work is to investigate the types and proportions of nano-carbon based conductive materials (carbon powders and fiber) and the characteristics of conductive mortar including the heating performance.

State-of-the-art Review on Self-heating ECON for Pavement Deicing Applications

Characterizing Electrical Properties of Cement-based Systems

The electrical properties of cement-based materials have commonly been characterized in terms of electrical resistivity (a reciprocal of electrical conductivity) as described in the following equation:

$$\rho = \frac{1}{\sigma} \tag{1}$$

where, ρ is electrical resistivity and σ is electrical conductivity. The electrical resistivity describes the capability to resist the electric current flow across a specimen and can be expressed by using Ohm's law as follows:

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$$\rho = \frac{R \times A}{L},\ R = \frac{V}{I} \tag{2}$$

where, ρ is electrical resistivity, R is the electrical resistance, A is the cross-sectional area of the specimen across which the current flows through, L is length of the specimen, V is voltage across the specimen, and I is current. The electrical resistivity of concrete is significantly influenced by the porosity, relative humidity and the resistivity of the pore water containing dissolved salts (which in turn is influenced by the concrete age, origin, and type of cement) [10]. Note that, depending on the context, both electrical resistivity and conductivity have been used interchangeably in the literature to describe the electrical properties of cement paste, mortar and concrete systems.

Concrete is a multi-component, micro-porous construction material typically comprised of cement, coarse and fine aggregates, and water. Conventional or normal concrete is not electrically conductive and is primarily comprised of three phases [11]: (1) a vapor phase (pore filled with air) with about 1011 Ω-cm of electrical resistivity (i.e., extremely low conductivity); (2) a solid phase (aggregate and cementitious solids) with about 1017 Ω-cm of electrical resistivity; and (3) a fluid phase (pore filled with liquid solution including water) with about 5 to 100 Ω-cm of electrical resistivity. Since the fluid phase in concrete has relatively higher conductivity compared to that of vapor and solid phases, the conductivity measurements of concrete is higher (or resistivity is lower) when the specimen is wet or saturated with liquid solution as opposed to measurements from unsaturated specimens. Note that several factors have been identified to have influence on the electrical conductivity measurements in cementitious systems. For instance, Spragg et al. [11] reported that specimen geometry, temperature of the specimen during the test (related to the mobility of the ionic species in the pore solution), sample storage and conditioning (sealed versus saturated) are all key factors that should be considered in standardizing tests for measuring electrical resistivity/conductivity of cement-based materials.

Cement-based materials conduct electricity electrolytically through the motion of ions in pore solution of a fluid phase and electronically through the continuous contacting motion of free electrons of conductive materials in a solid phase [12]. The most commonly used methods to characterize electrical conductivity (or resistivity) of concrete are the wet and dry methods.

The wet method measures the electrical charge passed in a saturated specimen over time when a constant voltage is applied across the specimen. For normal concrete, conduction of electricity under the wet method is through electrolysis, i.e. the motion of ions in pore solution of a fluid phase. Standard test procedures that employ the wet method include the rapid chloride permeability test specified in ASTM C1202 [13], bulk resistivity method by flowing Sodium chloride (NaCl) solution in concrete specified in ASTM C1760 [14], and bulk resistivity method using plate electrodes [15]. The wet method based test procedures have predominantly been used to characterize permeability or open pore network inside concrete in terms of electrical resistivity changes to assess concrete durability.

The dry method measures the electrical charge through electrodes embedded in concrete by applying a constant voltage across the unsaturated specimen. Standard test procedures using the dry method include the bulk resistivity method by using embedded electrodes and the surface resistivity method by using the Wenner probe [16]. The bulk resistivity method using embedded electrodes has been utilized in most previous studies focusing on conductive concrete for heating applications reported since 2000s [9,17]. In the case of conductive concrete, the conduction of electricity during the dry method of the bulk resistivity test is mostly by means of electronic interaction, i.e. the continuous contacting motion of free electrons of conductive materials inside concrete.

The surface resistivity method using the Wenner probe was developed as an alternative and rapid method (a draft AASHTO procedure is under review) to assess concrete durability compared to wet method based test procedures. Recently, this methodology and the associated test device was commercialized [18] and adopted as a standard test specification by Florida Department of Transportation [19]. So far, none of the reported studies have systematically evaluated this methodology for characterizing the electrical conductivity of conductive concrete. Spragg et al. [15] reported that the surface resistivity method provides higher resistivity measurements than those obtained using the bulk resistivity method with linear correlations for normal concrete. The use of adjustment factors [15, 16, 20] have been reported to convert the surface resistivity measurements on concrete cylinder into the bulk resistivity measurements for a wide thick slab to eliminate geometrical shape effects.

Over the last several decades, studies on measuring the electrical properties of concrete mortar and mixtures have mainly focused on relating them to concrete durability. The general conclusion is that higher electrical resistivity (or lower conductivity) is an indication of higher resistance of concrete to degradation mechanisms like salt ingress and rebar corrosion.

More recent studies have focused on adding conductive materials to concrete to achieve ECON for bridge/pavement deicing, sensing and monitoring applications. Similar in its behavior to a semiconductor or a capacitor, ECON can increase its temperature and heating rate as electrical current flows through it [8, 17]. The rest of the paper, consistent with the study objectives, will primarily focus on ECON for heated pavement systems targeting deicing/anti-icing applications.

Conductive Materials

Concrete is considered as a good electrical insulator in dry condition. The electrical resistivity of air dried normal concrete ranges from 600 to 1,000 kΩ-cm [21] and oven dried normal concrete has an electrical resistivity of about 108 kΩ-cm [7]. However, the electrical resistivity of moist concrete is about 10 kΩ-cm and is therefore classified as a semiconductor [7].

Conductive materials with extremely high conductivity values (i.e., electrical resistivity values less than 0.1 Ω-cm) can be used to replace aggregate materials in normal concrete to achieve conductive concrete. Reported literature suggests that conductive materials incorporated into concrete can broadly be categorized as: (1) powders (substituting for fine aggregate in part) – carbon, graphite; (2) fibers (substituting for fine aggregate in part) – carbon fiber (CF), steel fiber (SF), steel shaving (SS), carbon nano-fiber (CNF); and (3) solid particles (substituting for coarse aggregate in part) – steel slag and marconite.

Most of the studies reported in the literature tried to experiment with various conductive materials individually or in combination, their dosage rates, and their impact on ECON mechanical properties in an effort to identify the optimized conductive material compositions and mix designs to achieve well performing ECON. Table 1 summarizes the electrical and mechanical properties of ECON investigated in the literature.

As seen in Table 1, the addition of SF alone to concrete could not provide electrical resistivity values lower than 1,000 Ω-cm which is necessary for deicing applications, although it maintained the compressive strength [12]. The addition of SS alone to concrete gave similar results as SF in terms of poorer electrical resistivity values [12]. Although the combined use of SS and SF at appropriate dosage rates provided acceptable engineering properties, field experiments revealed several concerns with respect to the use of SF and/or SS in pavements [22]: exposed SFs and SSs on pavement surfaces can rust and have the potential to damage the vehicle tires and cause delamination and concrete spalls [8]; SSs tend to produce electrical charges during the mixing process and require a specialized mixing procedure to achieve uniform dispersion within the mix; SSs acquired from industry, in general, are contaminated with oil and require cleaning.

The combined use of SFs and carbon particles to achieve ECON gave acceptable results in terms of engineering properties, but again the use of SFs in pavements have the above-mentioned concerns [8, 22]. Similar results were reported by research studies that investigated the combined use of SFs and graphite powder [9]. In addition, the use of carbon particles or graphite powder to substitute fine aggregate in part was reported to adversely affect the mix workability [8, 9]. A study of ECON with several conductive phases showed that, a lignin-derived chemical electroconductive fiber (CEF) met the requirements of conductive filler and binder for achieving conductive concrete [23].

These studies suggest that optimization of ECON mix design, to achieve high conductivity and at the same time maintain adequate mechanical properties (workability, strength, and durability), is a daunting task warranting detailed experimental investigations. It is also inferred that the use of a single conductive material type to achieve well-performing ECON has some limitations and challenges. The use of large quantities of a single conductive material required to achieve higher concrete conductivity can not only be cost-prohibitive, but can also impede the mechanical performance to some extent. These indicate that the combined use of various conductive materials in concrete has the potential to achieve cost-effective and well performing ECON with adequate electrical and mechanical properties. As per the FAA Advisory Circular (AC) No. 150/5370 on the “Airside Use of Heated Pavement Systems” for deicing applications, conductive concrete mix designs with less than 25% conductive materials (by volume) are capable of meeting the appropriate FAA material specifications for strength and durability [24].

Percolation Phenomena

In this regard, the conductivity of cementitious systems can be discussed with reference to “percolation threshold”, which refers to the volume fraction above which the conductive materials within the matrix touch one another to form a continuous electrical path [25-27]. Xie et al. [3] investigated the effect of carbon fiber content on the conductivity of cement paste and mortar systems at different water/cement or sand/cement ratios. They reported that after a certain threshold carbon fiber concentration, the addition of carbon fibers increases the conductivity of paste and mortar systems only marginally. It was further concluded that this percolation threshold is a function of the geometry of carbon fibers (length and diameter) and that the properties of non-conductive components have little influence on the overall conductivity of the system [3].

Fig. 1, which displays electrical conductivity as a function of conductive powder/fiber concentration and connectivity, can be used to explain the percolation phenomena [3]. At point 4, the conductive powders form individual clusters. As small amounts of conductive fiber is added to dense conductive powder matrix, the percolation threshold (i.e., point 2) is approached where the individual clusters come into contact with each other forming a conductive network resulting in higher conductivity. Intuitively, higher the conductive fiber length, smaller is the volume fraction of fiber needed to reach percolation [3]. Beyond the percolation threshold, addition of conductive fibers to the system has negligible effect on the conductivity.

The advantages of using a dual combination of conductive materials (i.e., powder plus fiber) as opposed to a single conductive material (i.e., powder or fiber) in improving the overall conductivity of the system is clearly seen in Fig. 1 [28]. Especially, the addition of small amounts of relatively expensive conductive fibers to large amounts of relatively cheaper conductive powder is expected to result in a cost-effective system with improved electrical conductivity [28]. Wu et al. [28] employed Scanning Electron Microscopy (SEM) to investigate the conductivity mechanisms of asphalt concrete systems containing mixed conductive materials. The SEM images revealed that the short-range contacts or connections were provided by the conductive powders while the

Table 1. Summary of Engineering Properties of Conductive Concrete Investigated by Previous Studies.

Conductive Materials	% by Volume	Electrical Resistivity, Ω-cm	Compressive Strength, MPa	Reference
Conductive Fibers	1 to 5	0.46 to 43	35 - 71	[37]
Steel Fibers (SFs)	2	5.4×10^7	54	[12]
Steel Shavings (SSs)	15 to 20	2.4×10^5 to 2.2×10^5	25 - 24	[12]
Graphite Powder	25	NA	NA	[36]
Steel Shavings/Steel Fiber	15 to 20/1.5	500 to 1,000	34	[17]
Carbon Particles/Steel Fiber	15/1.5	300 to 500	48	[8]
Graphite Powder/Steel Fiber	17.2/2.7	396	43	[9]

Note: NA – Not Available

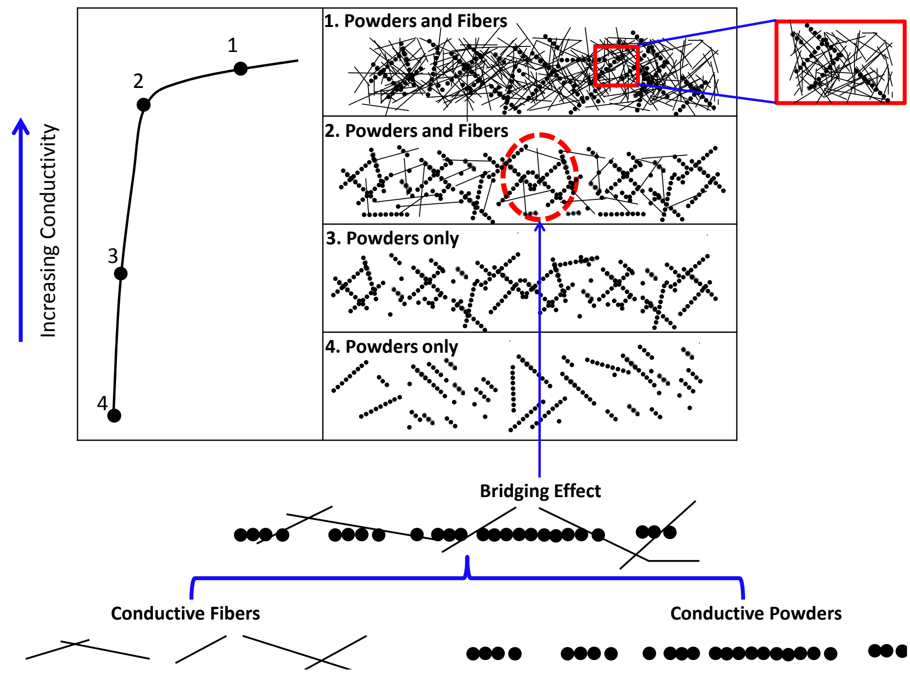


Fig. 1. Percolation Phenomena in ECON and Conductive Network Formation in Systems with Mixed Conductive Materials (Powder Plus Fiber).

conductive fibers exhibited long-range bridging effect and short-circuit effect resulting from the high aspect ratio [28]. It should be noted that even distribution of conductive fibers in the system through proper mixing is essential for achieving the conductive network formation. Typically, admixtures are used to disperse the carbon fibers.

Aggregate Properties and Cement Content

None of the reported studies indicate the need for special aggregate gradation requirements to achieve well-performing ECON. There is no special reference to strict requirements on aggregate type and size for achieving conductive concrete. Most of the studies reviewed in this paper investigated limestone mixes. Few studies experimented with the idea of either partially or fully replacing limestone aggregate with Blast Furnace Slag (BFS) along with smaller amounts of graphite powder, but were not successful in achieving desired conductive properties [9, 17]. One study [29] revealed that quartzite has greater thermal conductivity than regular aggregates such as limestone and gravel and therefore has great potential for enhancing the pavement energy harvesting properties. So far, quartzite has not been investigated in electrically conductive concrete.

Some of these studies have investigated the effects of different ratios of cement-to-sand-to-stone on the electrical and mechanical properties of conductive concrete [30-32]. Since some conductive materials (such as graphite powders) are used to partially substitute for fine aggregates in the mixture, it is expected that this can lead to volumetric changes bearing effect on workability and mechanical properties.

Mixing Technology

Although several mixing procedures have been randomly explored by previous research studies in the process of achieving conductive concrete with desirable engineering properties, there is no systematic guidance or specification available on the optimal mixing technology for conductive concrete. As mentioned previously, the reported studies do indicate that conductive fibers should be evenly distributed within the system to achieve high composite conductivity [8, 9, 22]. The degree of dispersion has a huge influence on the magnitude of electrical conductivity, especially at low conductive fiber volume fractions. Admixtures such as silica fume, polymer particles, water-based dispersions, polymer water-based solutions (methylcellulose), and silane can be used to assist in dispersing the short conductive fibers within the matrix [33]. Similar to conductive fibers, conductive powders like graphite also need to be homogeneously distributed in the concrete mix to provide good conductivity [8, 9, 22].

Other Considerations

As mentioned previously, the FAA AC No. 150/5370-17 provides guidance on the minimum performance requirements for the design, construction, inspection, and maintenance of heated airport pavements [24]. For airport pavement deicing applications, conductive concrete is recommended to be installed as a thin concrete overlay, formulated to satisfy Item P-501 (Portland Cement Concrete Pavement) specifications [34].

Cost-effectiveness is also an important ECON mix design consideration to implement ECON for heated pavement systems. However, very few studies have evaluated the cost-effectiveness of ECON based heated pavements in depth by employing economic analysis methods such as benefit-cost analysis (BCA). Yang et al. [35] presented simple cost comparison results of the currently available ECON based heated pavement systems with radiant snowmelt systems such as electrical and hydronic heating systems. The reported installation costs ranged from \$48/m^2 to \$205/m^2 for ECON based heated pavement systems and are about twice expensive than radiant snowmelt systems (\$23/m^2 to \$161/m^2). However, the unit energy costs of ECON based heated pavement system operations were reported to range from \$0.033/[m^2-cm] to \$0.075/[m^2-cm] compared to about \$0.368/[m^2-cm] in operating other snowmelt systems. Although these ballpark cost data comparisons are not enough to establish the cost-effectiveness of ECON based heated pavement system, they do demonstrate the potential of ECON for pavement deicing applications if reduction in installation costs could be achieved using innovative means, including the use of cost effective conductive material systems and economical ECON mix design optimization.

Experimental Investigation of Carbon Based Conductive Mortar Characteristics

Laboratory experimental investigation on carbon based conductive mortar characteristics was performed through evaluating trial mortar mixes consisting of carbon based conductive materials, cement, fine aggregate (sand) and water in order to:

- Identify proper mixing procedures to enable conductive materials uniformly distributed inside concrete
- Characterize types and proportions of conductive materials which can optimize engineering properties including electrical conductivity, strength, and workability

Four types of conductive carbon powder materials and one type of carbon fiber material were investigated in this study, as shown in Fig. 2. The carbon powder materials include flake graphite (FG) 3557, graphite powder (GP) A60, graphite powder (GP) 4071, and calcined coke (CC) 4335. Note that the designations listed under each material are identification numbers of commercial conductive powder materials. FG 3557 consists of 80% carbon and the other powders consist of about 99% carbon. A 6-mm long chopped carbon fiber (CCF) consisting of about 90 to 99% of Polyacrylonitrile (PAN)-based carbon was also investigated. According to the manufacturer's claim, it is able to be randomly orientated and dispersed inside the mixed materials. Note that conductive fibers investigated in previous studies on self-heating ECON for pavement deicing applications include steel shavings (SSs) or steel fibers (SFs), which have several safety concerns associated for airport pavement applications.

Fig. 3 displays the particle size distribution for each conductive powder investigated in this study. GP 4071 appears to be the coarsest and CC 4335 is next in rank. FG 3557 and GP A60 have finer gradations.

The bulk resistivity method using embedded electrodes (dry method) was utilized to characterize the electrical conductivity of conductive mortar specimens under air dry condition. Two types of embedded electrodes were evaluated for trial mortar batches: one is to insert a copper mesh into concrete and the other is to insert copper wire into concrete to measure electrical resistivity (See Fig. 4). The use of copper mesh as an electrode provided more stable measurements since it can contact larger area inside the mortar sample.

Evaluation of Mixing Procedures

Various mixing procedures were evaluated to arrive at an effective mixing procedure that enables uniform distribution of conductive materials inside mortar and consequently increase the electrical conductivity of mortar. The mixing procedures investigated in this study are briefly described below:

- Dry mixing 1: mix all particles (cement, sand, and conductive material) together in a conventional mixer (i.e., Hobart mixer) before adding water and then mix again after adding water.
- Dry mixing 2: mix cement and water in a conventional mixer and then add conductive material and sand to mix all again.
- Blender mixing: mix all particles in a blender first and then place the mixed particles in a conventional mixer to mix them with water.

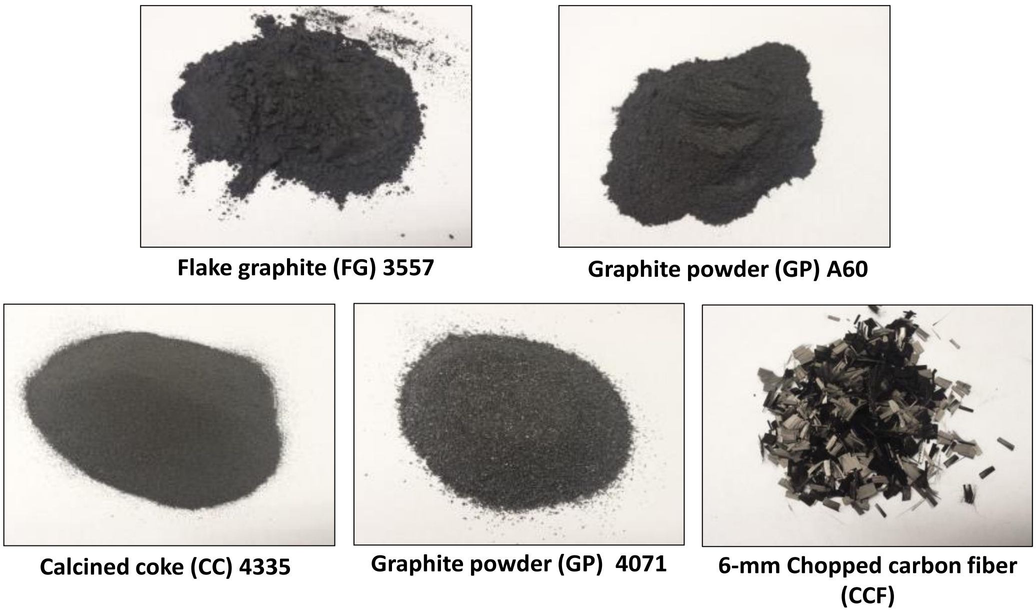


Fig. 2. Carbon Based Conductive Materials Investigated in This Study.

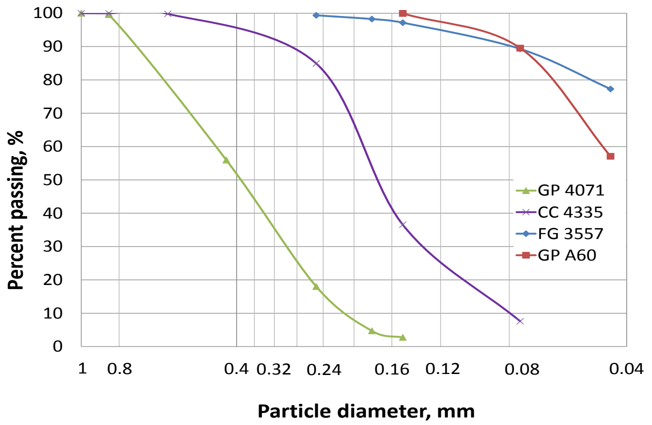


Fig. 3. Particle Size Distributions of Conductive Powders Investigated in this Study.

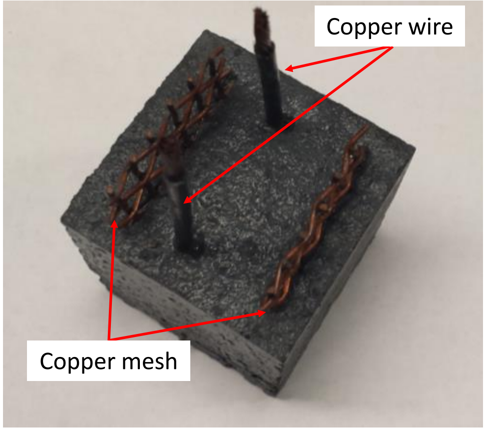


Fig. 4. Embedded Electrodes Evaluated for Electrical Resistivity Measurements.

- Stirrer mixing/Sonication mixing: use magnetic stirrer or sonication (about 30 minutes duration) to disperse conductive material in water with high range water reducer (HRWR) first and then mix the conductive material solution with cement and sand in a conventional mixer.

The conductive concrete mixing process is sensitive to particle size distribution [9]. It is more difficult to uniformly distribute the finer conductive powders during the mixing process since they absorb more water than coarser conductive powders. FG 3557 with a finer particle distribution was selected for this evaluation. To investigate the effects of mixing procedure alone on the conductivity, other variables related to the mixing procedure were kept constant: 0.45 of the water/cement ratio (w/c), 1.5 of the sand/cement ratio (s/c), and 5% by volume of conductive powder concentration. Table 2 lists the evaluated mixing procedures in the order of increasing resistivity values (i.e., the first entry corresponds to the highest electrical conductivity). Among these procedures, 'dry mixing 1' was identified as an effective mixing procedure which could provide higher electrical conductivity assuming other conditions to be identical (i.e., same materials, same mix proportion, etc.).

The use of sonication method (about 30 minutes mixing duration) in this evaluation could not provide better electrical conductivity. It is possible that this method could provide better electrical conductivity by increasing the sonication time and adding dispersant to the mixture. However, these procedures can lead to increased costs during actual construction and are not considered suitable for field implementation. Considering the relative ease and similarity of 'dry mixing 1' procedure with the conventional concrete mix procedure, 'dry mixing 1' can be considered to be a more practical, cost-effective and field-implementable method which can provide electrical conductivity values comparable to or even better than sonication mixing.

Identification of Carbon Based Conductive Materials for Engineering Properties Optimization

For comparison purposes, the experimental plan encompassed preparation and testing of six broad categories of trial mortar batches: (1) untreated mortar sample (control), (2) mortar sample treated with the FG 3557, (3) mortar sample treated with the GP A60, (4) mortar sample treated with the CC 4335, (5) mortar sample treated with the GP 4071, and (6) mortar sample treated with 6-mm CCF. In accordance with the 'dry mixing 1' procedure previously described, conductive materials at various concentrations were mixed with cement (Type I) and sand to examine their influence on the engineering properties. The conductive powder contents evaluated include 10%, 15%, and 20% by total volume. The conductive fiber contents evaluated include 0.2%, 0.4%, 0.6%, 0.8%, and 1.0 % by total volume. Higher fiber contents were not evaluated considering the chopped fiber length (6-mm) as well as higher material costs associated with the conductive fiber compared to conductive powders. The untreated (control) mortars were also tested without the addition of any conductive materials.

Table 2. Electrical Resistivity Results from Different Mixing Procedures by Using FG 3557.

No.	Mixing Method	Resistivity (Ω.cm)
1	Dry Mixing 1	1,951
2	Blender Mixing	2,145
3	Sonication Mixing	2,975
4	Dry Mixing 2	3,822
5	Stirrer Mixing	4,055

A w/c ratio of 0.45 was initially used for all trial mortar batches. However, at higher concentrations of finer conductive powders (FG 3557 and GP A60), the mortar mixtures remained dry when using a w/c of 0.45 and therefore more water was required to cast mortar specimens with uniform distribution of conductive powders. The w/c for these specimens were recalculated using the actual amount of water used to cast them. The coarser conductive powders (GP 4071 and CC 4335) and the conductive fiber (6-mm CCF) did not require additional water even at higher concentrations and therefore the w/c was maintained at 0.45. The s/c was fixed at 1.5 and a polycarboxylate based high range water reducer (HRWR) was used at a constant dosage rate recommended by the manufacturer for all the trial mortar batches. The casted mortar samples were cured in moist room. However, they were dried out under air before measuring electrical resistivity.

Table 3 summarizes the results from electrical resistivity and compressive strength tests carried out at 3rd day and 7th day from the time of casting of mortar specimens. Some practical observations regarding the results reported in Table 3 include the following:

- Both electrical resistivity and compressive strength values increased with time.
- The samples modified with 6-mm CCF have not only better electrical conductivity but also compressive strength comparable to the untreated sample (i.e., control).
- All of the samples modified with conductive powders have better electrical conductivity than the untreated sample (i.e., control), but at the cost of lower compressive strength.
- Finer conductive powders (GP A60 and FG 3557) provided higher conductivity values than coarser conductive powders (GP 4071 and CC 4335). However, a higher water demand with the use of finer conductive powders to improve the mix workability resulted in lower compressive strengths.
- Increases in finer conductive powder concentrations led to better electrical conductivity, but reduced strength gains.
- Increases in coarser conductive powder concentrations also led to better electrical conductivity without compromising the strength gains too much.

A performance assessment of engineering properties of conductive mortar specimens was carried out and the overall results are reported in Table 4. The electrical conductivity performance of each conductive material was rated using a ratio, ARER: the average ratio of electrical resistivity of conductive material treated specimens to those of control specimens. A relatively lower ARER for a conductive material indicates that it has greater potential to improve electrical conductivity in comparison to control specimen. The conductive materials were then ranked for their conductivity performance based on their ARER values as follows: 'Excellent' if 0 <ARER<0.25; 'Good' if 0.25<ARER<0.5; 'Fair' if 0.5<ARER<0.75, and 'Poor' if 0.75<ARER<1.

Similar to electrical conductivity performance ranking, the compressive strength properties were rated using a ratio, ARCS: the average ratio of compressive strengths of conductive powder treated specimens to those of control specimens. Since some decline in mortar compressive strength is unavoidable with the addition of conductive powder, a more realistic ranking of strength performance of conductive powders based on ARCS values would be as follows: 'Poor' if 0 <ARCS<0.5, 'Fair' if 0.5<ARCS<1. Workability performance was also assessed ('Poor', 'Fair') based on whether or not the addition of a specific conductive powder led to higher water demand during the casting of mortar specimen beyond the initial design w/c of 0.45.

The conductivity and strength performance assessment results summarized in Table 4 indicate that 6-mm CCF provides improved electrical conductivity in comparison to conductive powders without loss of strength and workability. Among conductive powders, GP 4071 (the coarsest conductive powder) provides acceptable electrical conductivity improvement and lesser loss of strength and workability.

Characterization of Heating Performance

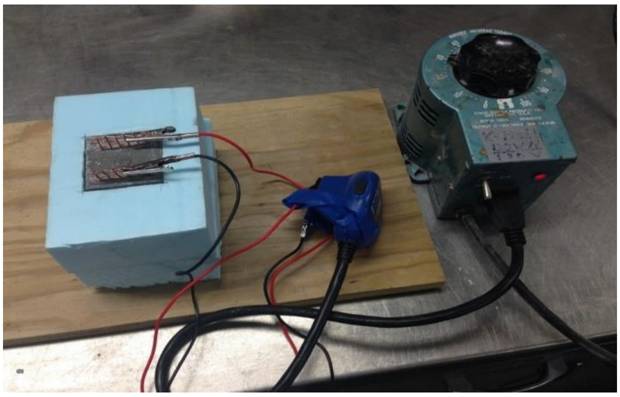
Heating performance of conductive mortar specimens were characterized to compare temperature changes in both conductive and untreated (control) mortar specimens under constant flow of electricity. The conductive mortar specimens evaluated for this purpose were the ones treated with 0.6 % of 6-mm CCF by total volume. Note that the 7-day electrical resistivity of 0.6 % of 6-mm CCF treated mortar is about four times lower than untreated (control) mortar (See Table 3). The moisture-cured specimens were evaluated at about 14th day from the time of casting of mortar specimens. However, the specimens were air-dried before conducting heating performance tests.

Table 3. Electrical Resistivity and Compressive Strength Test Results of Mortar Specimens.

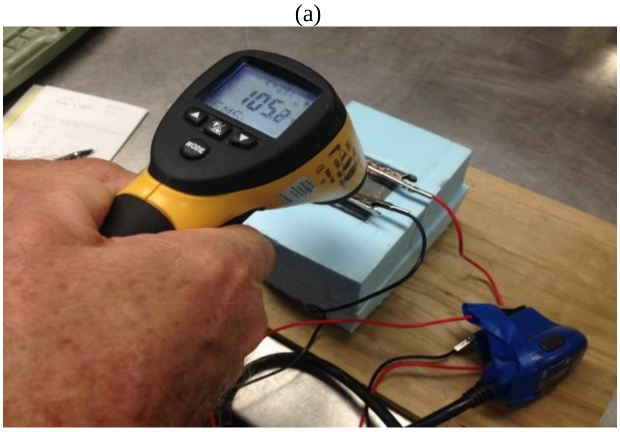
Category	Conductive Material Content (% in Vol.)	w/c	3-day Test		7-day Test	
			Resistivity (Ω·cm)	Strength (MPa)	Resistivity (Ω·cm)	Strength (MPa)
Control	0	0.45	3,143	39	3,840	51
FG 3557	10	0.45	1,675	26	1,850	26
	10	0.64	1,231	24	1,255	25
	15	0.64	796	15	936	16
	20	0.83	266	12	299	13
GP A60	10	0.64	1,094	23	1,032	30
	15	0.64	491	12	533	20
	20	0.64	169	15	194	17
CC 4335	10	0.45	2,549	42	2,813	44
	15	0.45	1,945	31	2,348	45
	20	0.45	1,792	40	1,991	50
GP 4071	10	0.45	1,477	31	1,990	31
	15	0.45	867	35	1,197	41
	20	0.45	581	30	870	29
6-mm CCF	0.2	0.45	354	38	796	48
	0.4	0.45	352	46	683	52
	0.6	0.45	241	40	985	50
	0.8	0.45	152	43	327	40
	1.0	0.45	126	47	168	51

Table 4. Conductivity and Strength Performance Evaluation Results for Carbon Based Conductive Materials Investigated in this Study.

Conductive	Conductivity		Strength	
Additive Type	ARER	Rating	ARCS	Rating
FG 3557	0.30	Good	0.45	Poor
GP A60	0.17	Excellent	0.43	Poor
CC 4335	0.64	Fair	0.94	Fair
GP 4071	0.33	Good	0.74	Fair
6-mm CCF	0.12	Excellent	1.00	Fair



(a)



(b)

Fig. 5. Mortar Heating Test Under Electricity Flow: (a) Insulated Mortar Specimen, (b) Mortar Surface Temperature Measurement Using Infrared Digital Thermometer Gun

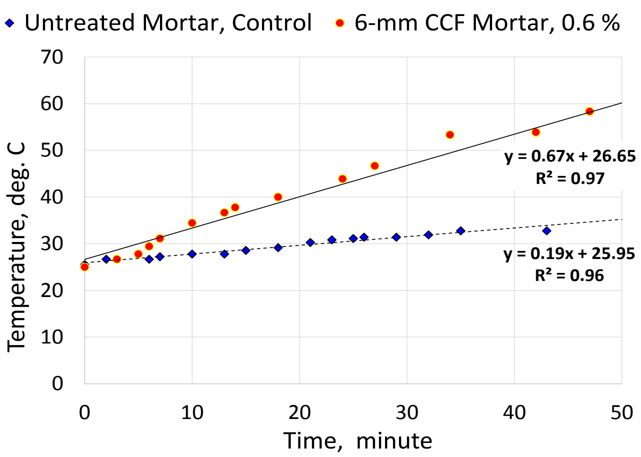


Fig. 6. Temperature Changes with Times While Supplying Electricity Flow.

Alternating current (AC) electricity flows were utilized since the sinusoidal variation of the AC voltage could provide more uniform electrical power than the direct current (DC) voltage [12]. Both conductive and control mortar specimens were tested at the same initial temperature of about 26°C (room temperature) using constant AC electricity supply of 36 volts. As shown in Fig. 5, the mortar specimen was insulated to prevent the loss of generated heat from outside while supplying electricity. The surface temperatures of mortar specimen were measured using an infrared digital thermometer gun.

Fig. 6 compares temperature-time history of tested specimens. The temperature of the conductive mortar specimen gradually increased to about 60°C at a rate of approximately 0.67°C/min, while the temperature of the untreated mortar specimen did not increase much, but remained almost constant. The current flow through the conductive mortar specimen varied from about 0.19 to 0.32A, while the current flow through the untreated mortar specimen kept constant at 0.07A. The results of this investigation demonstrates that conductive materials which can enhance ECON conductivity could provide heating performance improvement for pavement deicing applications.

Summary

The overall objective of this paper was to investigate the types and proportions of nano-carbon based conductive materials (carbon powders and fiber), the mixing procedures, and the characteristics of conductive mortar, including the heating performance, with a focus on optimizing self-heating ECON mix design with desirable electrical and mechanical properties for airfield pavement deicing applications. Findings from experimental investigations along with the state-of-the-art review on ECON are summarized below along with highlighted future recommendations to optimize the ECON mix design and achieve a cost-effective ECON system:

- Among the two most commonly used methods (wet and dry) to characterize electrical resistivity of concrete, most previous studies focusing on conductive concrete for heating applications reported since 2000s utilized the bulk resistivity method (dry) using embedded electrodes.
- The bulk resistivity method using embedded electrodes (dry method) was utilized to characterize the electrical conductivity of prepared conductive mortar specimens. The use of copper mesh, rather than copper wire, as an electrode provided more stable resistivity measurements since it can contact larger area inside the mortar sample.
- Although the combined use of steel shavings (SSs) and steel fibers (SFs) at appropriate dosage rates has been reported to provide acceptable electrical and mechanical properties, field experiments reported have revealed several concerns with respect to the use of SF and/or SS in pavements and their use is discouraged as such. Their use is to be strictly avoided especially in airport pavements.
- Among the various mixing procedures evaluated to identify the most effective one that enables uniform distribution of conductive materials inside mortar and consequently increase the electrical conductivity of the mortar system, ‘dry mixing 1’ (where all the dry materials are first mixed in a conventional

mixer before adding water) was identified as a simple, practical and effective mixing procedure which could provide relatively higher electrical conductivity.

- Mortar specimens modified with various conductive materials at different concentration levels were compared with untreated (control) specimens in terms of electrical and mechanical properties. The conductivity and strength performance assessment revealed that the 6-mm chopped carbon fiber (CCF) provided improved electrical conductivity in comparison to conductive powders without loss of strength and workability. Among conductive powders, graphite powder (GP) 4071 (the coarsest conductive powder) provided acceptable electrical conductivity improvement and lesser loss of strength and workability. Finer conductive powders including graphite powder (GP) A60 and (flake graphite) 355) provided lower electrical resistivity (or higher conductivity) values than coarser conductive powders. However, a higher water demand with the use of finer conductive powders to improve the mix workability resulted in lower compressive strengths.
- Both the temperature and current of 6-mm CCF treated conductive mortar gradually increased at a rate of approximately of 0.67^{O}C/min when subjected to constant electricity supply, while those of untreated mortar tended to remain constant.

Optimization of ECON mix design, to achieve high conductivity and at the same time maintain adequate mechanical properties (workability, strength, and durability), is a highly challenging task. Higher concrete conductivity could be achieved through the formation of a continuous electrical network of conductive materials inside concrete which does not always guarantee adequate mechanical properties. Higher conductive material concentrations are required to achieve the formation of a continuous electrical path with the use of a single conductive material type. This can either result in loss of mechanical performance at least to some extent (in the case of conductive powder) or reduced cost-effectiveness (in the case of carbon fiber). Further experimental investigations on the combined use of various conductive materials in concrete are recommended to achieve cost-effective and well performing ECON with adequate electrical and mechanical properties.

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