Electrically conductive asphalt concrete: Towards a theory of practice

Mohammad Ali Notani

Iowa State University

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Electrically conductive asphalt concrete: Towards a theory of practice

by

Mohammad Ali Notani

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil, Construction and Environmental Engineering

Program of Study Committee:
Halil Ceylan, Major Professor
Sunghwan Kim
Mani Mina
(Jiehua) Jay Shen

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2019

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DEDICATION

This thesis is dedicated to my parents for their unconditional love and endless support.
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ACKNOWLEDGMENTS

First and foremost, I thank God almighty for giving me the strength, knowledge, ability, and opportunity to undertake this research study and to persevere and complete it successfully. Without his blessing, this achievement would not have been possible.

I would like to express my sincere gratitude to my major advisor Professor Halil Ceylan, for the continuous support of my M.Sc. study and related research, for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I owe my deepest gratitude to Dr. Sunghwan Kim for his invaluable guidance that continuously improved my knowledge and understanding.

I am fortunate to have Dr. Kasthurirangan Gopalakrishnan advice through the whole of my study at ISU. His feedback and comments on my works have always been of huge help through my study. In addition, I would like to thank Dr. Ali Arabzadeh for his great advice through this research. His invaluable guidance is much appreciated. I would like to thank other committee members, Dr. Mani Mina and Dr. Jay Jiehua Shen for their guidance and insightful comments throughout this thesis. I am very grateful to Mr. Theodore (Ted) Huisman, and Mr. Paul Ledge for their kindly and endless support through laboratory works and providing a very friendly environmental at the lab.

In addition, I would also like to thank my friends and colleagues; Sajjad Satvati, Ali Arabzadeh, Amir Malakooti, Alireza Sassani, Sharif Gushgari, Yang Zhang, Joseph Podolsky, Ayoub Kazemiyan Zadeh, and Vahid Barzegar for being such a good friend for the whole time I had in ISU. And also, I would like to express my thanks to the department faculty and staff for making my time at Iowa State University an enjoyable experience. I want to also offer my
appreciation to those who were willing to participate in my surveys and observations, without whom this thesis would not have been possible.

This research was supported by the Federal Aviation Administration (FAA) Air Transportation Center of Excellence (COE) for PEGASAS and the support provided by FAA and ISU is greatly appreciated.

My mother and father are the source of happiness in my life, and I would like to express my deepest love to them for endless supports and love. I would like to thank my brothers and sister for their great support and encouragement.
Ice and snow on paved surfaces have always been considered a source of concern for transportation agencies and users. On airfield pavements, slippery surfaces double concerns in terms of flight delays or cancellation. Currently, while mechanical approaches like snow plowing and using deicing chemicals are widely used to facilitate more favorable conditions for transportation agencies and users, neither mechanical approaches nor deicing materials can provide sufficiently acceptable ice and snow surfaces during harsh wintertime. Fortunately, techniques using resistive heating of pavement material can be used to free pavement surfaces from ice and snow using a heated pavement system fabricated with electrically-conductive asphalt concrete (ECAC) with embedded electrodes connected to an electrical power source.

This study set out to fabricate an ECAC mixture with high electrical conductivity able to melt ice and snow. Given this goal, asphalt mixture was dosed with conductive additive-carbon fiber (CF)- using a promising mix design to provide a homogeneous composite material. The electrical characteristics of such a mixture was investigated both through volume resistivity measurements and active infrared thermography (IRT). To provide scientific insight, the mechanisms of creating heating and the resulting patterns are discussed in terms of electrical theory applied to an HPS system fabricated from ECAC material. In addition to the determining functional performance of ECAC material, its mechanical performance was evaluated to ensure that such a specific mixture can deal with stress and strain applied through environmental and mechanical loading. The results of this study revealed that the fabricated ECAC material could successfully provide enough thermal energy to melt ice and snow at very low temperatures, and also showed that the fabricated mixture had better mechanical performance than a conventional asphalt mixture.
CHAPTER 1. INTRODUCTION

General Overview

Ice and snow on paved airfield areas can result in hazardous conditions that can lead to airplane incidents or even accidents, as described in FAA AC 150/5200-30D. Moreover, snowstorms often decrease airport traffic volume by causing flight delays or cancellations, or, in a worst-case scenario, airport closures. To alleviate such winter-related problems, an airport operator can adopt an appropriate time-saving approach to minimize cost and effort associated with ice and snow removal from surfaces of runways, taxiways, aprons, etc. The use of deicing chemicals or deployment of snow removal equipment are the conventional methods for winter maintenance of airfield paved areas, and both are typically costly and time-consuming. It has been proven that such common solutions often do not provide a sufficiently dry surface to ensure that transportation delays or flight cancellations will not happen.

Emerging technologies, however, make it is possible to overcome both financial and time-related winter-maintenance problems; for example, it has been proven that spray deposition of ice-phobic coatings on areas paved with asphalt concrete or Portland cement concrete (PCC) can help decrease the bond developed between a pavement surface and ice/snow. Using even newer technology, a heated pavement system (HPS), it is possible to raise the surface temperature of a paved area sufficiently to melt ice and snow.

A HPS system can provide an effective and practical approach to providing ice- and snow-free surfaces for airfield pavement using a Joule heating concept, i.e., converting electrical energy into thermal energy is the primary mechanism of such a system. To achieve this, a HPS should be fabricated from electrically-conductive asphalt concrete (ECAC) in which significant current is allowed to flow. To implement such a mechanism, there are several matters to be
addressed, including: making a common insulative asphalt mixture being electrically conductive, providing a heating mechanism with appropriate pattern on the HPS pavement surface, and determining the influence of conductive additive properties on overall mechanical and functional performance of HPS.

**Objectives**

This study pursued the following objectives:

- To develop a promising mix design for fabricating ECAC able to provide a satisfactory level of mechanical and functional performance both in terms of heat generation efficiency and mechanical resistance to related cracking potential.
- To determine the properties of carbon fiber most significant influencing the ECAC functional performance.
- To understand the heat generation mechanism and pattern at micro-level
- To examine the effect of the main source of electrical power (electrode) on the overall performance of HPS

The overall goal of this research is to provide a fabrication procedure suitable for providing ice/snow-free surfaces for transportation infrastructures. It is to be hoped that the findings and discussions of this study could be used as a scientific foundation for future applications of smart pavement.
Thesis Organization

This thesis, written in the journal paper-based format, is organized as follows:

Chapter 1 provides general background, research objectives, and dissertation organization.

Chapter 2 presents a comprehensive literature review on the current state of the art

Chapter 3 presents a promising mix design procedure that yields an acceptable homogenous composite material and examines the effect of carbon fiber properties on the asphalt mixture’s functional and volumetric properties.

Chapter 4 presents significant insights into theoretical and practical heating mechanisms and heating patterns incorporating some fundamental concepts applied to reality validated using modeling. Functional and mechanical performance of ECAC is also evaluated and discussed in detail.

Chapter 5 presents a thesis summary along with conclusions and recommendations for future studies.
CHAPTER 2. LITERATURE REVIEW

This section devotes to present state of the art related to the recent endeavors on providing ice/snow free heated pavement system (HPS) along with describing comprehensive literature related to potential conductive additives for reducing electrical resistivity of an asphalt mixture. It should be noted that, in addition to the material provided in this section, each chapter presented in this thesis will include related literature review relevant to the particular aim and scope of that chapter.

A great deal of money is dedicated annually to winter maintenance problems occurring in cold regions and related to removing ice and snow from roadway surfaces [1]. In the air transportation system, presence of ice and snow can cause slippery pavement surfaces that sometimes inhibit landing and take-off operations. Such conditions can affect both operating efficiency of the air transportation system and threaten air passenger safety. In current practice, a mechanical approach such as snow plowing and deicing chemical materials have often been used to alleviate such concerns, but these approaches often do not produce acceptable surface conditions in a sufficiently timely manner that does not interrupt air transportation plans [2].

Conventional asphalt mixture is formed of mineral aggregates and asphalt binder, neither of which is electrically conductive, so their combination in fabricating asphalt concrete will result in an electrically-insulating material of electrical resistivity greater than $10^{10}$ Ω.cm [3]. Therefore, the first challenge would be to produce electrically-conductive conventional asphalt concrete. This can be done by transforming the asphalt mixture into an ECAC that takes advantage of compatible conductive additives that can be classified into different categories relate to their intrinsic structural properties: a) powder such as graphite and carbon black, b) fibers, i.e., carbon fiber, steel fiber, or carbon nanotube fiber, c) shavings, d) solid particles such
as slag, and Marcionite [4]. In producing a conductive asphalt mixture, it is essential to give attention to the compatibility of the additives with asphalt material, so, during the selection process, the dosage of conductive material and its cost should be given attention [5].

Although previous studies have described several fabrication procedures, there is as yet no promising and standard procedure for producing ECAC. Pan, et al., [6] stated that a promising mix design for such an asphalt concrete should have a uniform distribution of conductive agents within its asphalt matrix, and also that a promising mix design should not require high asphalt binder content or high mixing and compacting temperatures. To this end, two mixing procedures have been introduced: dry mixing and wet mixing [6]. In the former method, the conductive material is directly added with dry aggregate before adding hot asphalt binder, and attempts have been to directly add a conductive agent during mixing of the mineral aggregate with the asphalt binder [7]. In the wet mixing procedure, on the other hand, the asphalt binder is first modified by adding conductive additives, then the modified asphalt is used to fabricate the asphalt mixture [7].

Direct measurement of electrical resistivity has been widely used to quantify the electrical conductivity of an asphalt mixture, with the volume resistivity measured using a two-probe method [3], [8], [9]. An exploration of the literature reveals that measurement of electrical resistivity of conductive asphalt mixture has been measured at different temperatures [3], [8], suggesting idea that its conductivity is temperature dependent. ECAC capable of melting ice and snow should therefore have low electrical resistivity at low temperatures.
**Electrical Properties Evaluation Method**

**Electrical Resistivity**

Electrical resistivity is an intrinsic material property reflecting the capability of a material to resist against electric current, and Ohm’s law can be used (Eq.1) to obtain this property,

\[ \rho = \frac{RS}{L} \]  

(1)

Where,

\( \rho \) = electrical resistivity (\( \Omega \).cm)

\( R \) = resistance (\( \Omega \))

\( S \) = electrode conductive area (cm²)

\( L \) = distance between two potentials or electrodes

There are two types of electrical resistance defined in the composite material under study: composite resistance and contact resistance [10]; the former is defined as the resistance of individual conductive particles that depend on material properties and the latter defined as the barrier between two conductive particles through which an electron should pass from one fiber to another.

Resistivity is the reciprocal of conductivity [11-14]. Wu, et al., [9] conducted a study on electrical conductivity of an asphalt mixture containing graphite in which a stainless-steel disk-shaped electrode was chosen to apply voltage potential within the material. The graphite was used to fill voids between this electrode and the asphalt concrete and ensure that the contact resistance would be less than 1Ω. Garcia, et al., [14] also fabricated an electrically-conductive asphalt specimen containing a nickel electrode, and graphite was used to fill the voids between the electrode and the asphalt material to increase the self-healing capability of the asphalt mixture. This study showed that the contact resistance resulting from such an approach is lower.
than 0.1 $\Omega$. In this study, a multimeter was used to measure the electrical resistance of specimens [14], similar to the study of Wang, et al., [15] that also used a two-probe technique to measure electrical resistance of conductive asphalt mixture. In that study, good contact between the electrode and the asphalt mixture was provided by silver paint used to stick a copper plate to each side of the asphalt specimen.

**Percolation Threshold**

Percolation theory can be employed to determine how given positioned sites are intercommuned in three-dimensional space [16]. This concept can be applied to ECAC in the context of volume electrical resistivity to describe the transitional behavior of an insulator-to-conductor phase of a material composed of a mixture of conductive materials and an insulating matrix (asphalt mixture) [17]. Arabzadeh, et al., [11] indicated that electrically-conductive asphalt mastic containing carbon fiber attains its transition zone at a CF content between 0.75% and 1% by total volume of asphalt mastic [11]. It was also shown that incorporating carbon black in addition to CF in asphalt mastic reduces the lower threshold to 0.5% by volume of total asphalt mastic [11]. Another study found that incorporating of CF into asphalt mixture affects volume resistivity at a minimum dosage of 0.75% by total volume of composite material (See Figure 2-1) [18].
There is a wide array of conductive materials that can be used in asphalt mixtures, including carbon fiber, carbon black, steel fiber, steel wool, graphite, aluminum chips, steel slag, etc. Carbon fiber, because of its high aspect ratio and its adaptability to asphalt binder, is a highly conductive material that can be used to make an asphalt mixture electrically-conductive. The high melting point of carbon fiber represents another considerable advantage, the possibility of producing asphalt mixtures at a higher mixing temperature [19]. Using carbon fiber in an asphalt mixture not only decreases the electrical resistivity but also can reinforce the mixture and improve its tensile strength [20], [21]. It has been proven that CF-reinforced asphalt mixture has a longer fatigue life than conventional asphalt mixture [22]. Although the high aspect ratio of CF makes it a good conductive agent for asphalt mixture, achieving good dispersion of CF throughout the asphalt mixture composition is a challenging task, and if is poorly dispersed within the asphalt matrix, a good three-dimensional network of conductive paths cannot be created within the asphalt matrix [13].
While steel fiber and steel wool both have been widely utilized in Portland cement concrete, the use of such additives in an asphalt mixture creates mixing concerns. Liu, et al., [23] reported that incorporation of steel wool into an asphalt mixture reduces the mixture's electrical resistivity, and their study also showed that the percolation threshold using incorporated steel wool occurs at volume contents of 2.5 to 3.8 %. Graphite and carbon black, because of their carbon-based structure, have also been used to fabricate asphalt mixtures [24], [25]. Since graphite is a multilayer structure of carbons with weak bonds between layers, the tensile strength of asphalt mixture is reduced [26]. It has been shown that, to make asphalt concrete reflecting an acceptable resistivity range, a high content of graphite must be used [26], so the mechanical performance of such asphalt can be significantly affected [26], [27]. On the other hand, carbon black is an amorphous material with an electrical resistivity as low as 0.34 Ω.cm that both enhances the electrical conductivity of asphalt mixture and improves the asphalt binder’s aging resistance [28]. It has been shown that modifying an asphalt binder with carbon black increases the binder stiffness, implying that the rutting resistance of the asphalt mixture increases [29].

Steel slag is another conductive material produced from the stainless-steel manufacturing process that can be used in asphalt mixture to improve electrical conductivity [30]. Moreover, steel slag, because of its high Young’s modulus, has been used as coarse aggregate in asphalt mixtures to improve their mechanical performance [30]. It has also been shown that steel slag has high heat capacity because it stores more heat than mineral aggregate [30], and that it exhibits good capability for enhancing the self-healing ability of asphalt binder by an inducing magnetic field [31].
ECAC temperature can be increased either through induction heating or conduction heating. While conduction heating can be used for melting ice and snow on the surface of areas paved with asphalt concrete, induction heating would be used for accelerating a self-healing process in asphalt concrete.

**Induction Heating**

Dielectric heating, or heat induction, is a method for heating an electrically-conductive object through electromagnetic induction, generating eddy currents that result in heat generation. Eddy currents are loops of electric currents (see Figure 2-2) induced within conductors subjected to a time-varying magnetic field [32]. Induction heating can be explained by two principles: electromagnetic induction and Joule heating. Based on Faraday’s electromagnetic induction law, an electromotive force can be produced around a closed path in an alternating magnetic field, and this electromotive force is proportional to the rate of change of magnetic flux through any surface enclosed by the aforementioned closed path.

![Figure 2-2. The Mechanism of eddy-current generation](image)

According to Faraday’s law of electromagnetic induction:
\[ \varepsilon = -\frac{d\Phi}{dt} \]  

(2)

where:

\( \varepsilon \) = electromotive force (volt),

\( B \) = magnetic flux (weber/m²), and

\( t \) = time (second)

In the context of electrically-conductive asphalt mixtures, electric current is induced in conductive materials (i.e., conductive fibers and fillers) when the magnetic flux passes through them [34-36]. This electric current induced generates heat, when electrons travel through the conductive materials, as explained by Joule’s first law:

\[ P = I^2 R \]  

(3)

where:

\( P \) = generated heat per unit time (joule/s),

\( I \) = electric current (ampere), and

\( R \) = electrical resistance (Ω).

For a given time \( t \), the generated heat will be \( Q = I^2 R t \).

According to Ohm’s law, for a voltage \( \varepsilon \) across a circuit with resistance \( R \), the current will be:

\[ I = \frac{\varepsilon}{R} \]  

(4)

Substituting the current from Equation (6), the power dissipated can be written as:

\[ P = \frac{\varepsilon^2}{R} \]  

(5)
The induced electromotive force depends on the time rate change of magnetic field flux. If the change rate (i.e., frequency) of the magnetic field flux is kept constant, the heating rate will have a reciprocal relationship with the resistance, i.e., the higher the resistance, the lower the heating rate, so the resistance of the asphalt concrete should be decreased in to establish more efficient self-healing performance [34].

According to Garcia, et al., [35], if an electrically-conductive asphalt concrete is exposed to a magnetic field, an electric current (eddy currents) will be induced in it (see Figure 2-3) at the frequency as that of the magnetic field [37].

![Figure 2-3. Heat induction mechanism in asphalt concrete [35]](image)

Electrically-conductive asphalt concrete can be heated using a heat induction system. Quantao, et al., [34] and Garcia, et al., [37] used an induction heating system with a capacity of 50 kW and a frequency of 70 kHz, and evaluated the heating performance of their specimens using thermal-imaging systems. To produce accurate results, Quantao, et al., [34] cut gyratory specimens and discarded the top and bottom portions, and such thin samples helped enhance the
heating efficiency by reducing the temperature difference between the top and bottom portions. In addition to increasing heating efficiency, cutting the specimens resolved the binder concentration issue at the specimen surfaces [34].

**Conduction Heating**

Conduction heating is a mechanism transforming electrical power into thermal energy by means of resistive heating. The voltage difference between the two potentials creates an electrical field that forces charges to pass along conductive paths, and this process can be used to increase ECAC temperature in HPS through ohmic heating. Unlike for induction heating, electrodes in this case are in direct contact with the object, so electrodes should be embedded into the ECAC. It is worth noting that all the concepts underlying conductivity enhancement in asphalt concrete for conduction heating are similar to those of induction heating.

**Application of ECAC Through HPS**

The main aim of this study is to fabricate ECAC with a promising mix design procedure to provide a conductive material with high efficiency in terms of heating performance. Wu, et al., [5] tested feasibility of ice and snow melting by fabricating ECAC with multiple conductive additives, i.e., steel fiber, carbon fiber, and graphite at 7% of total mixture weight. While that study revealed that the ECAC slab could be heated from -15°C up to 16.6°C with a high voltage, additional scrutiny reveals that the overall system performance was not efficient with respect to using various conductive materials because it required a high voltage, possibly related to a poor three-dimensional network of conductive paths.
Research Gaps and Purposes

In light of the literature review and current ECAC practice, there are several unclear state-of-the-art gaps in topics this study is seeking to fill by focusing on the following items:

1- Examining the effect of carbon fiber properties on the functional performance and mixture volumetric properties of ECAC.

2- Providing a promising mix-design procedure to ensure that conductive materials (CFs) are well-dispersed within the asphalt matrix.

3- Improve the asphalt mixture’s electrical conductivity

4- More clearly understanding the Joule heating mechanism and the electric field’s role in overall functional ECAC performance from theory to practice

5- Evaluating heating patterns on the surface of ECAC slabs

6- Examining the effects of electrode geometry and spacing on system efficiency.

7- Investigating the mechanical performance of ECAC in terms of thermal crack resistance and moisture susceptibility

References


CHAPTER 3. EFFECT OF CARBON FIBER PROPERTIES ON VOLUMETRICS AND OHMIC HEATING OF ELECTRICAALY CONDUCTIVE ASPHALT CONCRETE

A journal paper published in Journal of Materials in Civil Engineering, ASCE

Mohammad Ali Notani1, Ali Arabzadeh2, Halil Ceylan3, Sunghwan Kim4, Kasthurirangan Gopalakrishnans

Abstract

This experimental study examines the influence of different sources and lengths of carbon fiber (CF) on the volumetric properties, volume resistivity and heat-generation efficiency of electrically conductive asphalt concrete (ECAC). This type of concrete has applications to pavement anti-icing and de-icing in critical areas such as airfields where having surfaces free of ice and snow is of paramount importance. This study revealed that increasing CF length decreased the ECAC air void, voids in the mineral aggregate (VMA) and increased voids filled with asphalt (VFA). The source of CF influenced the electrical conductivity and heat-generation capability of ECAC and decreasing the CF length resulted in volume resistivity reduction and enhancement of heat generation efficiency. The analyses results obtained from volume resistivity and heat generation characterizations performed on ECAC cylindrical specimens were used for fabricating ECAC slabs. It was demonstrated that ECAC slab can melt a dense layer of ice under harsh winter conditions simulated in the laboratory environment.

1 Graduate Research Assistant, Civil, Construction, and Environmental Engineering (CCEE), Iowa State University (ISU), Ames, IA, E-mail: notani@iastate.edu
2 Postdoctoral Research Associate, Civil, Construction, and Environmental Engineering (CCEE), Iowa State University (ISU), Ames, IA, E-mail: arab@iastate.edu
3 Professor, Director, Program for Sustainable Pavement Engineering and Research (PROSPER), CCEE, ISU, Ames, IA, E-mail: hceylan@iastate.edu
4 Research Scientist, Institute for Transportation, ISU, Ames, IA, E-mail: sunghwan@iastate.edu
5 Research Associate Professor, CCEE, ISU, Ames, IA, E-mail: rangan@iastate.edu
Introduction

Presence of ice and snow on paved areas of airfields makes airplanes prone to skidding, resulting in take-off, landing, and taxiing problems, eventually causing flight cancelations - especially if the snow thickness on the paved surfaces exceeds 13 mm (i.e., ½ inch) (FAA, 1965). While spraying de-icing chemicals is a common approach for providing acceptable surface conditions for airport runways, aprons, and taxiways, de-icing chemicals such as sodium chloride cannot efficiently eliminate such ice if the temperature drops under -3.9 °C (Chen et al. 2011). A series of recent studies has also indicated that using de-icing chemicals causes biodegradation-related environmental problems (EPA, 2012, 2000), and according to the Federal Aviation Administration (FAA), the use of deicing chemicals should be limited (FAA, 2008).

Moreover, mechanical approaches conventionally practiced for snow/ice removal, are sometimes not able to remove all snow/ice on pavement surfaces, i.e., there is always a thin layer of snow/ice remaining on the surface no matter how many passes are made by snow-plowing equipment. Some mechanical approaches, typically costly, can also damage pavement surfaces (Nixon, 1993). Apart from these issues, the mechanical snow removal approach is often not able to efficiently remove snow/ice from taxiways and aprons because such areas are typically congested (especially aprons) or have special geometrical designs limiting the maneuver of snow plowing equipment, making the mechanical approach time-consuming and ineffective.

Several recent studies have suggested alternative approaches for mitigating winter-related problems at airfields, including covering pavement surfaces with super-hydrophobic coatings, electrically conductive cement concrete, or imbedding hydronic pipes in hot-mix asphalt (HMA) pavements (Arabzadeh et al. 2017a, 2016; Pan et al. 2015; Loomans et al. 2003; Sassani et al. 2017, 2018; Arabzadeh et al. 2018a, 2017b; Anand et al. 2017). Electrically conductive asphalt
concrete (ECAC) could be another alternative for engineering specific airfield surfaces with anti-icing and de-icing capabilities. Generally, HMA is not electrically conductive, i.e., while conventional HMA has high resistance to electric current due to the high volume resistivity of aggregate, asphalt binder, and filler (Shao-peng et al. 2002), it can be stated that moving charged particles through conductive paths/networks within ECAC releases some energy as heat, a process referred to as resistive heating. In such a case, the flow of electric current through ECAC produces heat through interaction between charged particles and conductive materials in atomic and molecular levels. Besides, one of the critical factors in the self-healing mechanism in asphalt mixture is temperature (Garcia et al. 2014; Notani and Mokhtarnejad. 2018). ECAC can enhance the self-healing property of mixture by increasing temperature to a certain temperature.

Previous studies have shown that the volume resistivity of asphalt concrete can be reduced by incorporation of electrically conductive additives such as carbon black, graphite powder, carbon fiber (CF), steel wool, and other solid particles, such as steel slag, from its original resistivity value of approximately $10^{10}$ to $10^{3} \, \Omega$ cm (Pan et al. 2015; Garcia et al. 2011). It has been reported that use of such additives can enhance the conductivity of asphalt concrete (Wu et al. 2012; Huang et al. 2009). Among conductive additives, CF, because of its high resistance to the high temperatures - with a melting point of about 1,000 °C - and its compatibility with asphalt binder, is a suitable candidate for incorporation into HMA (Abtahi et al. 2010). Wang and coworkers (2016) studied the microwave healing capability of carbon fiber modified asphalt mixture and in their study, they used 6 mm – CF to enhance the conductivity of asphalt mixture. Moreover, Vo and coworkers (2016) used 5-mm CF to enhance the conductivity of asphalt mixture, and they proved that the inclusion of 1 % CF significantly improved the thermal conductivity of asphalt mixture. CF improves the mechanical properties of HMA, and
also greatly enhances electrical conductivity when used in HMA (Abtahi et al. 2010; Moghadas Nejad et al. 2014). According to the available literature, although CF can significantly improve the electrical conductivity of HMA, its dispersion in asphalt concrete can be a complex task primarily due to CF flocculation during the mixing process (Wu et al. 2005).

The primary objective of this study was to evaluate the influence of different CFs on mix design volumetric properties, volume resistivity and heating performance of ECAC, and then to identify a promising mix design procedure with an acceptable CF distribution inside HMA resulting in an ECAC that can efficiently melt ice/snow. To this end, a set of CFs with different lengths and sources were examined to determine their influence on mix-design volumetric properties, volume resistivity, and heat generation efficiency of ECAC specimens fabricated in the form of 152 mm (i.e., 6-in) diameter gyratory specimens at a constant height of 114 mm. After performing analyses on the data obtained from gyratory specimens to identify the best CF source and length, ECAC slabs were compacted using a linear kneading compactor (LKC). The ECAC specimens were then tested with respect to their performance in terms of generating sufficient heat for melting a dense layer of ice at below freezing temperature and simulating what might happen in the field during harsh winters.

**Material and Methodology**

**Material**

A performance Grade (PG) 58-28 asphalt binder was used. Six types of CFs with different lengths (3, 6, and 12 mm) were obtained from two different commercial manufacturing companies/sources (A and B). Those CF types were manufactured using polyacrylonitrile (PAN). Table 3-1 presents the physical properties of the CFs obtained from each source.
Table 3-1. Properties of Carbon Fibers

<table>
<thead>
<tr>
<th>Property</th>
<th>Source A</th>
<th>Source B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon (%)</td>
<td>+94</td>
<td>95</td>
</tr>
<tr>
<td>Melting Temperature (°C)</td>
<td>+1,000</td>
<td>+1,000</td>
</tr>
<tr>
<td>Volume Resistivity(µΩ.m)</td>
<td>17.2</td>
<td>15.5</td>
</tr>
<tr>
<td>Diameter (µm)</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Moisture Content (%)</td>
<td>0</td>
<td>12.5%</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Young Modulus (GPa)</td>
<td>228</td>
<td>242</td>
</tr>
<tr>
<td>Tensile Strength (GPa)</td>
<td>3.8</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Fig. 3-1. Appearance of CFs from two different sources

Fig. 3-1 shows 3-mm CFs obtained from both sources. As it can be seen, the CFs obtained from source B are more bundled than those obtained from source A; this can be attributed to the presence of moisture in the CFs of source B and its production process. To provide more information regarding the higher conductivity and the superior heat generation of CFs obtained from source A, scanning electron microscope (SEM) analyses were performed on specimens fabricated with 3-mm CFs and element maps were acquired. Table 3-2 presents the element map test results, according to which, silicon and oxygen are present on the surface of CFs. These two
elements prove that the surface of CFs is covered with silica. Silica-based tribofilms are crucial for providing wear protection and low friction, and the quantity of silica-based materials has a key role on wear reduction among CFs (Zhang et al. 2015). It has been proved that only 0.05 Wt% of silica, in the context of CF production, is enough to enhance CFs’ surface tribological behavior (Österle et al. 2016). For this reason, the application rate of Si in CF production process is very low (e.g., around 0.05% by weight). Also, the silica-based compounds are electrically-insulating, so to maintain the electrical conductivity of CFs, the surface of CFs should be covered with the lowest possible amount of silica.

Table 3-2. Element map test results for 3-mm CFs

<table>
<thead>
<tr>
<th>Spectrum Label</th>
<th>Source A, Wt%</th>
<th>Source B, Wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>94.8</td>
<td>96.7</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>2.26</td>
<td>1.03</td>
</tr>
<tr>
<td>Oxidation</td>
<td>2.63</td>
<td>2.12</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.31</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Cylindrical and Slab ECAC Specimen Preparation

To prepare ECAC specimens, several trial mixes were prepared to find an optimum aggregate gradation having the least influence on ECAC volumetric properties fabricated at different CF lengths. As a result, an optimum aggregate gradation (see Fig. 3-2) was selected such that different lengths of CF would have minimal influence on ECAC volumetric properties. Limestone aggregate used in this study was obtained from Martin Marietta - Ames Mine, Iowa.
It should be noted that incorporation of CF into HMA increases the mixing time and required compaction effort, compared with the compaction and mixing time required for conventional HMA. In previous studies (Arabzadeh et al. 2018a, 2018b), the authors studied the influence of different CF dosages on changing the electrical behavior of asphalt mastic, and the findings indicated that the incorporation of 1% CF by total asphalt mastic volume results in significant improvement in electrical conductivity. As a result, in this study – looking into the effect of carbon fiber size and source on the electrically conductivity and heat generation performance – we decided to use the CF content of 1% by total volume of HMA.

Furthermore, in another study we conducted on investigating the influence of presence of aggregates on the percolative behavior of electrically conductive cement-based materials, it was revealed that the CFs start to percolate at the same volume content with/without the presence of aggregates (Sassani et al. 2018). In this study, after investigating the influence of binder content
on several trial mixes (each containing 1% of 12-mm CF) to reach 4% air void, it was identified that 6.3% asphalt content resulted in obtaining workable asphalt mixtures. The reason for the selection of 6.3% asphalt content is due to the fact that at lower asphalt binder contents ECAC becomes spongy and at higher asphalt contents it starts to bleed. It should be noticed that to achieve a uniform distribution of CF in HMA and to overcome CF segregation issues throughout the HMA, the CF was mixed in a Hobart mixer with aggregate in room temperature and wet condition - at 4% water content (based on weight of CF-aggregate blend) - for three minutes. The rationale behind mixing CF with aggregate under room temperature and wet conditions was to avoid flying (or missing) and flocculation of CFs during the mixing process to eventually obtain good CF distribution throughout the aggregate blend. The CF-aggregate blend was then placed in an oven set at 110 °C for 24 hours. The dried CF-aggregate blend and asphalt binder were placed in the oven and heated before mixing at a temperature of 150 °C for 3 and 2 hours, respectively; they were then mixed for 3 minutes at 150 °C. The asphalt mixture was workable at the selected temperature of 150 °C and due to oxidation and hence aging in asphalt, higher mixing temperatures were not attempted (Fini et al. 2015). Finally, the obtained mixtures were placed in an oven set at 135 °C for two hours to simulate short-term aging. It was decided to fabricate the entire cylindrical ECAC specimens at constant volume (2,078 cm³) and weight (4,700 gram) to ensure the volume and the weight of all specimens were identical to accurately evaluate the effects of different carbon fiber lengths on volumetric properties. Therefore, for each CF type, five cylindrical specimens were prepared at a constant height of 114 mm by using a gyratory compactor. Fabricating this number of gyratory specimens provided three specimens/replicates for characterizing volume resistivity and heat generation efficiency while also having two specimens/replicates for measuring ECAC volumetric properties. To perform the volume
resistivity measurements followed by heating tests, copper foils (i.e., electrodes) were placed at the bottom and top of specimens before the beginning of the compaction process so that they would completely adhere to the specimens after compaction, ensuring good contact. Fig. 3-3(a) shows an ECAC specimen with copper foils at the top and bottom of the cylindrical specimen.

To simulate field performance and study the heat generation efficiency of ECAC with respect to melting ice/snow, a set of ECAC slab specimens (Fig. 3-3(b)) - with three replicates - was fabricated, using the LKC, at the optimum CF type identified based on analyses performed on the data obtained from cylindrical gyratory specimens. Each slab was compacted using two lifts; first, a 25-mm (approximately 1-inch) lift of ECAC was compacted, and then steel pipes (i.e., electrodes) were embedded. After that, the second lift of ECAC was compacted.

![ECAC specimens](image)

Fig. 3-3. ECAC specimens: (a) ECAC cylindrical specimen from gyratory compactor and (b) ECAC slab specimen from Linear Kneading Compactor

**ECAC Temperature Conditioning**

To perform volume resistivity measurements and then characterize heat generation efficiencies and ice melting capability, all the ECAC specimens (both cylindrical and slab types) were placed in an environmental chamber (equipped with two fans and a dehumidifier) set at -20°C. The fans
continually recirculated the air of the chamber to ensure a uniform temperature distribution. The dehumidifier unit kept the relative humidity (RH) at the lowest possible limit (e.g., 6%) to ensure measurement accuracy.

**Volume Resistivity Measurement**

Volume resistivity is an intrinsic material property that quantifies a material’s ability to allow passage of electric current flow (Lowrie, 2007). The lower the volume resistivity of a material, the higher the capability of the material to conduct electricity. The volume resistivity of a material depends on its cross-section (i.e., electrode-material contact area) and distance between electrodes used for applying an electric potential field. Volume resistivity can be calculated using Ohm’s law (Eq. 1).

\[ \rho = \frac{RS}{L} \]  

where, \( \rho \) is the volume resistivity in \( \Omega \cdot \text{cm} \), \( R \) is the measured electrical resistance of the ECAC specimens in \( \Omega \), \( S \) is the electrode-material contact area in cm\(^2\), and \( L \) is the distance between electrodes in cm. The electrical resistivity of the ECAC specimens was measured using two types of probes (i.e., copper foils on cylindrical specimens or pipes embedded within slab specimens). A FLIR DM 62 digital multimeter was employed to measure resistance values at -20 °C (Fig. 3-4). All volume resistivity measurements were performed in an environmental chamber so that variations in temperature could not influence the obtained resistivity values.
Fig. 3-5. Test set-up for measuring ECAC’s electrical resistance

**Heating Performance Evaluation**

To evaluate the heating performance of the ECAC specimens, a FLIR T650sc IR camera with a resolution of 640 × 480 pixels was used to measure the lateral surface temperature of the ECAC specimens at an environmental temperature of -20 °C, and the resulting data were recorded in the form of radiometric videos. After conditioning the ECAC specimens at -20 °C for at least 3 hours - to achieve thermal equilibrium (Arabzadeh and Guler 2019)-, an AC voltage of 40 V at a frequency of 64 Hz was applied for a duration of 20 minutes. The acquired data were then analyzed using the ResearchIR Max® software package, and the heat generation efficiency was evaluated. Fig. 3-5 illustrates the heating test setup.
Results and Discussion

ECAC Volumetric Properties Results

An asphalt mixture typically consists of aggregates, asphalt binder, and voids. Incorporation of CFs into asphalt mixture changes the HMA volumetric properties (Cleven, 2000). As described earlier, all the ECAC cylindrical specimens were prepared at a constant volume (2,078 cm$^3$) and weight (4,700 gram). Due to this specimen preparation, the compaction level of ECAC specimens – each specimen set having three replicates – was recorded (see Figure 3-6), so that the effect of CF length on the number of gyrations (for obtaining a height of 114 mm) could be identified. Fig. 3-6 presents the compaction effort for all the ECAC specimens modified with different lengths and sources of CF. As it can be seen, increasing the CF length decreases the required number of gyrations. Indeed, specimens modified with 3-mm CFs (from both sources) required a higher compaction effort that can be attributed to better distribution of
3-mm CFs compared with longer ones. Using shorter CFs increases the number of voids in the ECAC, resulting in more compaction effort required to achieve the target specimen volume.

![Graph showing the influence of carbon fiber source and length on compaction level](image)

Fig. 3-6. Influence of carbon fiber source and length on compaction level

Fig. 3-7(a) shows the influence of CF length on maximum theoretical specific gravity ($G_{\text{mm}}$) and bulk specific gravity ($G_{\text{mb}}$). According to Fig. 3-7(a), when CF length increases, $G_{\text{mm}}$ decreases while $G_{\text{mb}}$ increases. As a result of such specific gravity changes, the air void volume within the asphalt mixture is decreased (Fig. 3-7(b)). It is worth noting that, based on observations of this study, since the source of CF has a relatively insignificant effect on volumetric properties, the volumetric property results presented in Fig. 3-7 are the arithmetic means of the values calculated for each CF length from both sources A and B. As mentioned earlier, increasing CF length decreases the amount of ECAC air voids. Considering that the
amount of CF used for modifying ECAC specimens in this study was kept at a constant volume content of 1%, this behavior can be attributed to the fact that, at such a constant content of CF (i.e., 1%), shorter fibers are more omnipresent than longer fibers in the mixture.

To produce a good and workable ECAC mixture, asphalt binder should sufficiently coat the aggregate system, so sufficient space between aggregate particles should be ensured; this space is referred to as voids in mineral aggregate (VMA) (Chadbourn et al. 1999). When CFs are incorporated into an aggregate system, they can vary the VMA, and this variation must be closely examined (Cleven, 2000). Fig. 3-7(c) presents the influence of CF length on changing the VMA and, as can be seen, there is a drastic reduction in VMA when CF length increases from 3 to 6 mm while increasing CF length from 6 to 12 mm has a negligible influence on VMA reduction. The reason for obtaining the highest VMA value for ECAC containing 3-mm CF can be attributed to the superiority of 3-mm CF in terms of achieving uniform distribution; the longer the CF, the higher the possibility of fiber flocculation. In addition to VMA, achieving required voids filled with asphalt (VFA) is one of the critical design factors of HMA, because low VFA causes an unstable asphalt mixture. Increasing CF length increases the VFA (Fig. 3-7(d)) in specimens containing the same asphalt content and prepared at the same volume. It can be concluded that increasing the CF length decreases the VMA and hence increases the resultant VFA. It is worth noting that the optimum VFA must lie within a range that is defined based on both traffic level and the type of location, e.g., airfield or highway where the ECAC is implemented.
Fig. 3-7. Influence of CF length on ECAC volumetric properties: (a) specific gravities, (b) air void, (c) voids in mineral aggregate, and (d) voids filled with asphalt

**Cylindrical ECAC Volume Resistivity Results**

According to Table 3-3, the volume resistivity of ECAC modified with CF increases with increase in fiber length, and such volume resistivity increase was the greatest in ECAC specimens fabricated with CFs obtained from source A. For CFs obtained from source A, while increasing the fiber length results in increase of volume resistivity, there is no such consistent trend observed in the volume resistivity of CFs obtained from source B.
Table 3-3. Resistivity Measurement Results of ECAC Specimens at -20 °C

<table>
<thead>
<tr>
<th>Source</th>
<th>Length (mm)</th>
<th>Resistivity (Ω.cm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ave.</td>
<td>SEa</td>
</tr>
<tr>
<td>A</td>
<td>3</td>
<td>96</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>250</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>801</td>
<td>33</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
<td>168</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>166</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>258</td>
<td>20</td>
</tr>
</tbody>
</table>

*Standard Error

Cylindrical ECAC Heating Performance Results

As mentioned earlier, a heating test was performed on each cylindrical ECAC specimen in an environmental chamber set at -20 °C. The heating test results presented in Fig. 3-8 were obtained from the three replicates of ECAC modified with 12-mm CF obtained from source A. As can be seen, the specimen surface temperature increases linearly, and this trend was observed in all the ECAC specimens modified with CFs from different sources and of different lengths. The slope of surface temperature versus time was also calculated to determine the heat generation rate for each cylindrical specimen, and this rate was used to evaluate the effect of CF length and source on heat generation efficiency (see Fig. 3-8).

![Fig. 3-8. Result of heating test for 12-mm CF produced by Source A](image-url)
According to Fig. 3-9, 3-mm CF obtained from source A resulted in the highest heat generation rate among other specimens. Increasing CF length caused a substantial decrease in the heat generation rate of the specimens fabricated with CFs obtained from source A; the shorter the CFs (e.g., the ones obtained from source A), the better the distribution. While there was no considerable difference between heat generation rates of ECAC specimens made of CFs obtained from source B, consistent with volume resistivity measurements performed on ECAC specimens made of CFs obtained from source B, no consistent trend was observed in the volume resistivities of ECAC specimens made of CFs (of different lengths) obtained from source B. As it is shown in Fig. 3-1, the CF obtained from source B is bundled and also, it has a considerable moisture content compared to the CF obtained from source A (See Table 3-1). As a result, during mixing CF with aggregate, the probability of CF obtained from source B to form clusters in CF-aggregate system is higher than CF obtained from source A. It is worth noting that, based on observations of this study, during the asphalt mixture mixing process, the longer CFs (6 and 12-mm) were more prone to breakage into shorter pieces, and because of such brittle behavior, there was no significant difference observed between the heat generation rate of ECAC specimens fabricated with 3, 6, or 12-mm CFs obtained from source B.

According to Table 3-2, Si content on CFs obtained from source A is higher than the ones obtained from source B, justifying better distribution of CFs obtained from source A during the mixing process, and hence higher electrical conductivity and greater heat generation rate of ECAC made of CFs obtained from source A. As it is indicated in Fig. 3-1 captured from 3-mm CFs obtained from both sources, the CFs obtained from source B, are more bundled than the CFs obtained from source A. As it was mentioned earlier, higher friction among CFs obtained from
source B, increases the probability of CFs obtained from this source to form clusters in CF-aggregate system. On the other hand, CFs obtained from source A, not only have a better sliding capability - compared with the CFs obtained from source B -, but also are not bundled as much as CFs obtained from source B. As a result, CFs obtained from source A are more uniformly distributed in the CF-aggregate system resulting in higher electrical conductivity and higher heat generating rate in ECAC specimens fabricated with CFs obtained from source A.

![Graph showing heat generation rate vs. carbon fiber length and source](image)

Fig. 3-9. The influence of CF length and source on heat generation rate

**ECAC Slab Volume Resistivity and Heating Performance Results**

As mentioned earlier, ECAC slabs were fabricated based on the analyses performed on the data obtained from cylindrical ECAC specimens. As a result, the 3-mm CF obtained from source A was incorporated into HMA to fabricate an ECAC slab with three replicates. The volume resistivity measurements and heat generation evaluation were all conducted in an environmental chamber set at -20 °C. The average volume resistivity of ECAC’s three replicates
became 35 $\Omega$.cm, with a standard error of 1.1 $\Omega$.cm. The heating-test results revealed that the average heat generation rate for the ECAC slab was 1 °C per minute when subjected to an electric potential of 40V. Fig. 3-10(a) presents the slab surface temperature at the beginning of the test. Note that in Fig. 3-10(b) and (c) the temperature on the slab surface increases with respect to time. Fig. 3-10(d) shows the heating test results after 20 minutes, where it can be seen that most surface temperatures (i.e., pixels) rose to 5 °C. With such performance, it would be expected that the ECAC slab, after application of a low voltage of 40V for 20 minutes, can produce a surface free of snow/ice.

Fig. 3-10. Heat generation of ECAC slab: (a) thermographs obtained at the beginning of the test, (b) after 5 minutes, (c) after 10 minutes and (d) after 20 minutes
ECAC Slab Ice-Melting Capability

The central goal of heated pavements is to provide ice-and snow-free pavement surfaces in airports during cold winters. For proving such capability of ECAC, one of the ECAC slabs was tested under a worst-case scenario, i.e., it was tested for its ability to melt a dense layer of ice at an environmental temperature of -20°C. As a general fact, because of the high density of ice compared with snow, since an ice layer requires more energy (in the form of heat) from the pavement surface to melt and vanish (Paterson, 1994), one of the slab surfaces was covered by a dense 20-mm ice layer. The presence of water and ice within the air voids of ECAC slab caused a significant reduction in the ECAC electrical resistivity by changing the volume resistivity from 35 to 16 Ω.cm.

Due to such volume resistivity reduction and to avoid a short-circuit condition, it was decided to expose the ECAC slab to an electric potential field of 30V rather than 40V. In the ice-melting process, total melting time and time duration of applied electrical power are the most significant factors influencing the ice-melting process of the ECAC slab, and the specimen should also not be allowed to overheat. Due to the low resistivity of the slab, since the asphalt binder can easily reach to its melting point, it was decided to turn off the power for some time during the ice-melting process to avoid overheating. The electrical power was applied for two-time intervals during the ice-melting process. After 30 minutes of applying power (i.e., minute 0 to minute 30), the power was turned off for 20 minutes to avoid overheating of the slab (i.e., from minute 30 to minute 50), followed by power applied for 10 more minutes (i.e., from minute 50 to minute 60). Fig. 3-11 (a) shows the slab covered with a 20 mm dense layer of ice at the beginning of the test. Fig. 3-11(b) and (c) reflect the ice-melting process of ECAC slab over time. Finally, after 15 minutes of applying no electrical power (i.e., minute 60 to minute 75), the ice layer had been eliminated by the heat trapped in the ECAC when the power had been off.
following minute 60 (Fig. 3-11(d)). In summary, the ice-melting process took about 75 minutes, and during this time the voltage was applied for only 40 minutes over the two aforementioned time intervals. It can be concluded that ECAC’s high heating capacity makes it a potentially applicable alternative for mitigating winter-related maintenance problems of paved areas of airfields.

This research was dedicated to investigating the influence of carbon fiber type and length on heat generation efficiency of ECAC with applications to pavement anti-icing and de-icing. In the next step, the mechanical performance of ECAC fabricated at 1% CF will be evaluated to make sure that this type of HMA will not result in decreasing the service life of flexible pavements. In fact, the ECAC should be fabricated at a CF content that results in the highest possible heat generation efficiency and durability (e.g., moisture damage resistance and acceptable mechanical performance) comparable to or greater than that of conventional HMA.

Fig. 3-11. Ice-melting capability (a) at time 0, (b) after 45 minutes, (c) after 65 minutes and (d) after 75 minutes
The percolation threshold at different carbon fiber dosages in ECAC mixture will be investigated based on the result of this study as well as mechanical performance. Next, the effect of electrode shape, size, and distance will be evaluated to establish a construction technique for this type of technology.

**Conclusions**

The objective of this study was to investigate the influence of carbon fiber (CF) length and source on mix design volumetric properties, volume resistivity, and heat generation efficiency of electrically conductive asphalt concrete (ECAC). To this end, six types of CF were used to prepare cylindrical ECAC specimens. After characterizing the properties of these specimens and analyzing the acquired data, an ECAC slab was fabricated using a CF with optimum length obtained from source A to prove the heat generation efficiency and the ice melting capability of ECAC in a laboratory environment simulating the harsh winters of North America. It should be noted that all the tests were conducted at below-freezing temperature (-20 °C), one of the novel features of this study. The findings of this study led to the following conclusions:

- Decreasing the CF length from 12 to 3 mm increases the air void and voids in mineral aggregate (VMA) of ECAC specimens and simultaneously decreases the voids filled with asphalt (VFA) at a constant specimen volume. In addition, in this study, the selected CF sources did not result in a substantially significant influence on the volumetric properties of asphalt mixture. To develop a more solid conclusion, in future studies, there is a need to dose asphalt mixtures with CFs obtained from many more different sources.
• Compared with longer CFs, incorporation of shorter CFs into ECAC increases the required compaction effort due to better distribution of shorter CFs throughout an asphalt mixture.

• Decreasing CF length enhances the ECAC volume resistivity due to enhanced distribution of shorter CFs, and it was found that during mixing CF with aggregate, CF type with higher Si content and less bundled can provide better distribution during mixing due to high wear protection and better sliding potentiality, and hence higher electrical conductivity and greater heat generation rate of ECAC can be obtained.

• Because of more uniform distribution of 3-mm CFs, ECAC heating performance modified by this length of CF was enhanced in terms of heat generation rate.

• ECAC slab fabricated in this study demonstrated the capability of ECAC in melting a 20-mm dense layer of ice through a heating test performed in an environmental chamber set at -20 °C.

ACKNOWLEDGMENTS

This paper was prepared from a study conducted at Iowa State University under the Federal Aviation Administration (FAA) Air Transportation Center of Excellence Cooperative Agreement 12-C-GA-ISU for the Partnership to Enhance General Aviation Safety, Accessibility and Sustainability (PEGASAS). The authors would like to thank the current project Technical Monitor, Mr. Benjamin J. Mahaffay, and the former project Technical Monitors, Mr. Jeffrey S. Gagnon (interim), Mr. Donald Barbagallo, and Dr. Charles A. Ishee for their invaluable guidance on this study. The authors also would like to thank the PEGASAS Industry Advisory Board members for their valuable support and feedback. The assistance and efforts of Mr. Robert F. Steffes and Mr. Theodore Huisman, ISU CCEE lab managers, with the lab investigations are
greatly appreciated. The authors would like to express their sincere gratitude to Mr. Paul Kremer, ISU CCEE Program Manager for his significant assistance with lab accessibility. The help received from Ayoub Kazemiyan Zadeh, an ISU undergraduate student, for helping in specimen preparation process is greatly appreciated. The authors would like to thank Jebro Inc. for kindly donating the asphalt binder used in this study. Although the FAA sponsored this project, it neither endorses nor rejects the findings of this research. The presentation of this information is in the interest of invoking comments by the technical community on the results and conclusions of the research.

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CHAPTER 4. FUNCTIONAL AND MECHANICAL PERFORMANCE OF ELECTRICALLY CONDUCTIVE ASPHALT CONCRETE: A TRANSDISCIPLINARY INVESTIGATION APPROACH

To be submitted to the Proceeding of National Academy of Science (PNAS)

Mohammad Ali Notani6, Ali Arabzadeh7, Ayoub Kazemian Zadeh8, Halil Ceylan9, Sunghwan Kim10, and Mani Mina11

Abstract

In this study, the functional and mechanical performance of an innovative electrically conductive asphalt concrete (ECAC) was investigated using transdisciplinary approaches. ECAC was developed using carbon fiber (CF) to be used into autonomous heated pavement system. The functional performance was evaluated at two stages: analytical theories and experimental investigation. Analytical theories have been carried out with the theory of electricity and Ohmic heating mechanism and pattern. In laboratory scale, slabs fabricated with different electrode’s geometries were tested operating volume resistivity measurement and active-infrared thermography at freezing temperatures. The mechanical performance of ECAC was evaluated in terms of thermal-cracking resistance and moisture susceptibility using the semi-circular bending (SCB) and tensile strength ratio (TSR) tests, respectively. The mechanical interaction between ECAC and electrodes was also studied through numerical modeling to assess the potential of

6 Graduate Research Assistant, Civil, Construction, and Environmental Engineering (CCEE), Iowa State University (ISU), Ames, IA, E-mail: notani@iastate.edu
7 Postdoctoral Research Associate, Civil, Construction, and Environmental Engineering (CCEE), Iowa State University (ISU), Ames, IA, E-mail: arab@iastate.edu
8 Undergraduate Student, Civil, Construction, and Environmental Engineering (CCEE), Iowa State University (ISU), Ames, IA, E-mail: kazemiya@iastate.edu
9 Professor, Director, Program for Sustainable Pavement Engineering and Research (PROSPER), CCEE, ISU, Ames, IA, E-mail: hceylan@iastate.edu
10 Research Scientist, Institute for Transportation, ISU, Ames, IA, E-mail: sunghwan@iastate.edu
11 Associate Professor, Department of Electrical and Computer Engineering, Iowa State University, Ames, IA, E-mail: mminta@iastate.edu
interface cracking. The finding of functional evaluations showed that incorporation of ECAC with flat electrode geometry not only could provide a sufficient heat at low voltage to melt ice and snow but also could significantly reduce the interface cracking potential. Moreover, the results of the thermography test and numerical simulation on electric field formation indicated that the electrode’s geometry has not any meaningful effects on ohmic heating performance. Finally, the result of mechanical tests indicated that while ECAC exhibited high low-temperature cracking resistance, some moisture susceptibility adverse effects were observed.

**Significance**

Heated Pavement System (HPS) is an innovative and smart approach to render airport paved surfaces free of ice/snow without causing adverse environmental impacts. Electrically Conductive Asphalt Concrete (ECAC), a specific case of HPS, uses electrodes to convert electrical energy to thermal energy by means of ohmic heating to melt ice/snow. This study shows that ECAC heating performance, mechanism, and pattern are influenced by ECAC electrical resistivity, and current density present in the 3-D network of conductive paths created by carbon fiber, distribution of carbon fiber, and HPS design. The functional performance is also affected by mechanical performance whereas the environmental and traffic loading cause thermal and interface cracking inside ECAC that will interrupt the electrical field.
Graphical Abstract

Introduction

A huge number of air and ground passengers annually experience delays and accidents due to the presence of ice and snow on transportation infrastructure. To alleviate such winter-related problems, conventional approaches such as the deployment of mechanical snowplowing equipment and use of chemical deicers have been widely used [1]. However, such conventional approaches do not always result in efficient snow and ice removal [2-4]. Consistent with increasing movement toward achieving smart transportation infrastructure, winter-related maintenance problems can be mitigated using heated pavement systems (HPS) [2] that could not only alleviate the harsh winter conditions but also minimize time and cost associated with snow/ice removal operations [5].
One promising and innovative approach for providing a surface free of ice/snow is to incorporate an electro-thermal composite material into the top layer of the pavement structure that transforms electrical power into heat through Joule heating [6]. Electrically-conductive asphalt concrete (ECAC), for example, could be a promising electro-thermal composite to be incorporated into an HPS for anti-icing and de-icing purposes [4, 7]. Since a conventional asphalt mixture is an electrically insulating material, it should be dosed with a conductive component to achieve satisfactory electrical conductivity [8], and carbon fiber [9, 10], steel fiber [11], steel wool [12], graphite [13] and carbon black [14] are conductive materials that can be incorporated into asphalt mixture to enhance electrical conductivity. Among them, carbon fiber, produced from either polyacrylonitrile (PAN) or pitch precursors [15], is the most compatible material with asphalt concrete [16] that also has a high conductivity feature [17] that gives it potential to be directly heated by passing charges through its microstructure [17]. Carbon fiber has this superior electrical conductivity because of the presence of graphite filaments in its nanostructure [18]. It has been conclusively shown that carbon fiber (CF) is the best conductivity improvement material choice for asphalt mastic and asphalt mixture [19, 20]. Another reason for such a superior contribution of CF to asphalt mixture conductivity is its high aspect ratio [21] that makes the electron current path longer than other types of conductive material [20]. The contact mechanism between conductive fibers facilitates electron transition paths and forms a conductive network for electrons flowing under the influence of an electric field [20]. According to Notani, et al., [7], although the incorporation of CF into an asphalt mixture enhances its electrical conductivity, the dispersion uniformity of CFs throughout the mixture has an influential role in such enhancement [7]. Arabzadeh, et al., [4] presented an innovative mix design procedure for producing ECAC mixture achieving the highest possible electrical
conductivity as well as the most uniform CF dispersion. According to Notani, et al., [7], using 3-mm carbon fiber results in a highly workable and compactible asphalt mixture and uniform CF dispersion throughout this composite material [7].

The movement of charged particles through electrically-conductive paths dissipates energy in the form of resistive heating (Ohmic heating) that increases the material temperature [7]. In other words, the flow of electrical current through conductive paths produces resistive heating due to atomic collisions created by electrical charges flowing along conductive paths. This mechanism not only increases the ECAC temperature to melt ice/snow but also can accelerate the self-healing property of asphalt-based materials [22-25] containing conductive materials.

As mentioned earlier, ECAC has been introduced for the application heated pavement systems to provide an ice and snow-free surfaces for critical transportation infrastructure systems during the harsh winter season. Notani, et al., [7] studied the influence of carbon fiber properties (source and length) on ECAC mixture workability and heat generation efficiency found that inclusion of 3-mm CF covered with a lower dosage of silicon provided high heat generation efficacy. Since mixing CF throughout ECAC composite to find a sufficient CF distribution is a challenging task, Arabzadeh, et al., [4] reported an innovative mix design that distributed CF strings within asphalt compounds.

The nature of the main micro-level mechanism of such technology for use in transportation infrastructure still remains unclear from a conceptual perspective. Moreover, given that electrode spacing in the conductive layer is associated with ECAC mixture performance in an HPS in which electrodes are responsible for transfusing the electrical current through the ECAC mixture, this is the first study to undertake a longitudinal analysis of functional and
mechanical performance of ECAC using simulated slab specimens and analytical approaches. The best type of electrode for use in an HPS system to provide optimum engineering performance with respect to material cost and heat generation efficiency has not yet been consistently established.

Generally, mechanical performance tests for asphalt pavement systems are mainly used to relate laboratory mix design to actual field performance. A principal criterion for establishing a specific mix design certification that its mechanical performance can deal with both mechanical and environmental loading. HPS will be used in a cold region where pavement experiences high thermal stress in the presence of moisture, so it is necessary to evaluate ECAC performance under the same cold-weather conditions. It is also worth noting that cracking within ECAC pavement reduces heated pavement system efficiency because the presence of cracks on asphalt pavement disrupts current flow and electric fields between HPS electrodes, and this type of disconnection reduces the heat generation performance of ECAC HPS.

This study first intends to address the uncharted role of the electrode and its configuration within an HPS. The influence of electrode geometry and spacing on ECAC heat generation and volume resistivity performance were investigated by a functional evaluation of ECAC mixture in which the resistive heating mechanism producing a heat generation pattern in the ECAC slab was analyzed and analyzed based on the physics of electricity. Second, the mechanical performance was assessed in terms of low-temperature crack resistance, indirect tensile strength, and moisture susceptibility.

**Materials and Methodology**

**Material and Specimens Preparation**

The asphalt binder used in this study, obtained from Jebro, Inc., had a base performance grade (PG) of 58-28. The CF, obtained from Asbury, Inc., was used for imparting electrical
conductivity to asphalt mixture. Based on findings from another study [7], using 3-mm CF at a concentration of 1% by volume of total mixture results in an ECAC with excellent workability, compatibility, and CF dispersion in the presence of 6.3% asphalt binder. Therefore, in this study, 1% CF by volume of total mixture and 6.3% of asphalt binder content by weight of total mixture were used to fabricate the ECAC mixture. Table 4-1 contains information about the CF used in this study.

Table 4-1. Properties of CF used in this study

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>3</td>
</tr>
<tr>
<td>Diameter (μm)</td>
<td>7.2</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.81</td>
</tr>
<tr>
<td>Melting Temperature (°C)</td>
<td>+ 1,000</td>
</tr>
<tr>
<td>Moisture Content (%)</td>
<td>0</td>
</tr>
<tr>
<td>Volume Resistivity (μΩ.m)</td>
<td>17.2</td>
</tr>
<tr>
<td>Carbon (%)</td>
<td>+94</td>
</tr>
</tbody>
</table>

Limestone aggregate with the gradations shown in Table 4-2 were used to fabricate ECAC mixture. This aggregate is obtained from the Martin Marietta limestone mine located in Ames, Iowa, U.S. Arabzadeh, et al., [4] the first to reject a dry-mixing method as a feasible option for incorporating CFs, advised modifying this method by addition of water at a content of 4%, based on the total weight of the CF-aggregate. More information regarding this modification can be found in that study. Adding water to the CF-aggregate blend not only alleviated the CF agglomeration during mixing but also significantly improved CF distribution throughout the aggregate. In this study, based on Arabzadeh, et al.’s recommendation [4], CFs were incorporated into aggregates using a modified dry-mixing method. Both the CF-aggregate blend and the asphalt binder were pre-heated for 3 hours at 150°C then mixed in a Hobart mixer at an agitation rate of 198 rpm. The mixture was then placed in the oven set to 135°C for 2 hours to
simulate short-term aging. The control asphalt mixture was produced at 5.8% asphalt content by total weight of mixture.

Table 4-2. Aggregation gradation

<table>
<thead>
<tr>
<th>Sieve #</th>
<th>1/2&quot;</th>
<th>3/8&quot;</th>
<th>#4</th>
<th>#8</th>
<th>#16</th>
<th>#30</th>
<th>#50</th>
<th>#100</th>
<th>#200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (mm)</td>
<td>12.50</td>
<td>9.5</td>
<td>4.75</td>
<td>2.36</td>
<td>1.18</td>
<td>0.6</td>
<td>0.3</td>
<td>0.15</td>
<td>0.075</td>
</tr>
<tr>
<td>Passing (%)</td>
<td>100</td>
<td>95</td>
<td>64</td>
<td>37</td>
<td>22</td>
<td>15</td>
<td>9.8</td>
<td>7.2</td>
<td>6</td>
</tr>
</tbody>
</table>

ECAC slab specimens were fabricated using various electrode geometries to perform a feasibility investigation of an HPS implementation of ECAC in the field. When the electrodes embedded in the ECAC are electrified, current begins to flow between the electrodes, and this flow can depend significantly on electrode geometry. To simulate this condition and investigate the influence of electrode geometry on heat generation efficiency, ECAC slabs were fabricated with various electrode geometries and different spacings. A linear kneading slab compactor was used to fabricate the ECAC slabs under a maximum pressure of 4,130 kPa (600 psi). To maintain constant conditions for all slabs, all were fabricated with identical dimensions of 76×200×380 mm (3×8×15 in) and weights of 13,780 grams. To maintain consistency of all the material-related conditions, the electrodes were embedded at middle slab depths (See Figure 4-1). In fabricating the slabs with different electrode geometries, pipe and L-shaped electrodes were placed at top of the bottom layer compacted to a 2.54 mm (i.e., 1 inch)-thick layer, while the flat electrodes were placed at the top of the bottom layer and compacted into a 38.1 mm (i.e., 1.5 in)-thick layer. Such electrode embedment approach was chosen to ensure that all electrodes were located at the middle slab depths. The use of two different spacings was only to demonstrate the significant influence of electrode spacing.
During the slab specimen fabrication process, three electrodes are placed at the top of the bottom of the compacted ECAC layer. The middle electrode, as noted above, was used only to demonstrate the influence of electrode spacing on electrical resistivity. Such a demonstration was performed for each electrode geometry to identify the influence of electrode spacing on volume resistivity and heating performance.

![Slab Specimen with Electrodes](image)

Figure 4-1. Appearance of slab fabricated with different electrode geometries

152 mm (6-inch) gyratory specimens were fabricated to first produce 25.4 mm (1-inch) thick semi-circular specimens and then to assess the ECAC mechanical performance. To perform low-temperature cracking resistance tests, the semi-circular specimens were notched at the middle of their flat sides, with notch of depths 15, 25, and 32 mm carved using a diamond table saw. Since AASHTO TP101 requires running the semi-circular bending (SCB) test at 10 degrees above the lower end of the PG temperature of the asphalt binder, and asphalt binder of 58-28 PG was used to prepare ECAC mixture, a SCB test was conducted at -18°C. It should be
noted that, before performing the SCB test, all specimens were temperature-conditioned in a freezer set to -18°C to reach thermal equilibrium. To initiate the test, a contact load of 0.1 KN was applied, after which a constant displacement rate (0.0083 mm/s) was applied to obtain the stress-strain curves of the SCB specimens. 0.5 kN was chosen as the terminating stress level.

To evaluate moisture susceptibility of ECAC, the AASHTO T283 standard was followed in preparing 100-mm diameter (4-inch) specimens, with an indirect tensile strength test performed on both unconditioned (dry) and conditioned specimens (wet). For conditioning the specimens in accordance with AASHTO T283, the specimens should be subjected to one freeze-thaw cycle, and 50-80% of the air void should be saturated by water. For this purpose, the specimens at first were vacuum-saturated and then placed in a waterproof plastic bag in 10 ml of water before conditioning in a freezer set to -18°C for at least 24 hours. After one freezing/thawing cycle, specimens were immediately placed in a water bath set to 60°C for 16 hours. Eventually, before performing the indirect tensile test (ITS), both unconditioned and conditioned specimens were placed in a water bath at room temperature for two hours. In total, 12 specimens (each replicated three times) were prepared, half tested under dry conditions and the other half tested under wet condition. To obtain ITS values for asphalt mixtures, this test was performed in accordance with AASHTO T283 at a loading rate of 5 mm/min to prevent unrealistic brittle behavior.

Methodology

Functional Evaluation

Functional evaluation took the form of real field simulation in which the volume resistivity and heat generation efficiency of ECAC slabs were investigated. Because of the
influential role of electrodes on the functional performance of the ECAC mixture, it was important to understand the influence of their geometries and spacings.

To evaluate the functional performance, all ECAC slabs were first placed in an environmental chamber set at \(-20^\circ\text{C}\) for at least 24 hours to reach thermal equilibrium. Functional performance was assessed using two approaches: volume resistivity measurement and heat generation efficiency evaluation. Volume resistivity is indicative of a material’s ability to support passage of electric current, with low volume resistivity implying a high capability for conducting current \([26]\). Volume resistivity was calculated using Equation 1 \([27]\):

\[
\rho = \frac{RS}{L}
\]

where

\(\rho\) = volume resistivity in \(\Omega\text{.cm}\)

\(R\) = electrical resistance in \(\Omega\)

\(S\) = contact area between electrode and material in \(\text{cm}^2\)

\(L\) = electrode spacing in cm

An active thermography approach was followed in measuring surface temperature of slabs in the environmental chamber with an applied voltage of 40V. More information detailing the volume resistivity measurement and heating characterization is provided in another study conducted by Arabzadeh, et al. \([4]\) and dedicated to thermal and electrical behavior of electrically-conductive asphalt-based materials.

To analyze heating-test results, the average surface temperature of the ECAC slabs was plotted versus time. Figure 4-2 shows a thermal image obtained from an ECAC slab during the heating test.
Mechanical Evaluation

In this study, the mechanical performance associated with functional performance was considered because a deficiency of such mechanical performance can affect the overall functional efficiency of an HPS made of ECAC composite. Low-temperature cracking is a common form of distress that can be observed in flexible pavements [28] (made of asphalt concrete pavement surface) constructed in geographical locations that experience cold temperatures during wintertime. Such cracking occurs when thermally-induced stresses, under the restraint of a surface asphalt concrete course layer to the underlying layer, exceed the tensile strength of the asphalt concrete. Fracture mechanics has been successfully employed as a powerful tool for investigating crack initiation and propagation. A SCB test, for example, is one of the common fracture tests successfully used to assess low-temperature cracking resistance of asphalt concrete [29]. Arabani, et al., [30] performed a study for evaluating SCB test results under both static and dynamic loading conditions to describe the tensile and fracture strengths. According to, Arabani et al. [30], a SCB test could be used for evaluating the tensile strength of the mixture at low temperatures and assessing low-temperature cracking. Moreover, Huang et al.,
evaluated the efficiency of a SCB test by measuring low temperature cracking resistance of asphalt concrete, found that SCB tests can adequately characterize this type of distress. To be able to characterize the fracture resistance of mixture, the critical strain energy release rate, commonly called a J-integral \( J_c \), is considered to be an index for comparing a mixture’s thermal cracking resistance. \( J_c \) can be obtained using Equation 2 [32]:

\[
J_c = - \left( \frac{1}{b} \right) \frac{dU}{da}
\]  

where,

\( J_c \) = critical strain energy release rate in kJ/mm²

\( b \) = sample thickness in mm

\( U \) = strain energy to failure in N.mm

\( a \) = is notch depth in mm

\( \frac{dU}{da} \) = change of strain energy with notch depth

Moisture susceptibility is a common distress factor with a substantial impact on long-term performance of asphalt mixture. The primary mechanism of moisture susceptibility is the rupture of the adhesive bond between the aggregate and asphalt binder due to lack of adhesion and cohesiveness of the asphalt binder film [33, 34]. An ideal mixture should not be affected by water and moisture infiltration through these components. There are several laboratory tests for evaluating moisture sensitivity of asphalt mixture [35-37], and among them, AASHTO T283 has received growing attention [38]. In this test, the moisture resistance of an asphalt mixture can be defined in terms of a tensile strength ratio (TSR) that can be interpreted from indirect tensile ratio (TSR), the ratio of the ITS of dry specimen to that of a wet (conditioned) specimen. An ITS test is commonly performed by applying compressive loads to both wet and dry specimens,
determining the maximum load carried by the specimen from which the ITS value can be calculated based on Equation 3 (AASHTO T283):

$$ITS = \frac{2000f}{\pi LD}$$

where

- $f$ = maximum compressive load carried by the specimen in kN
- $L$ = average specimen thickness in m
- $D$ = average specimen diameter in m

To obtain the moisture resistance of a mixture, the TSR value can be calculated using Equation 4 (AASHTO T283):

$$TSR = \frac{P_{\text{Conditioned}}}{P_{\text{Unconditioned}}} \times 100$$

**Results and Discussion**

**Functional Evaluation**

**Volume Resistivity Evaluation**

Figure 4-3 shows volume resistivity values for slabs fabricated with various electrode geometries, each embedded at two different spacings: 0.5 and 1 ft (15 and 30.5 cm). As can be seen in Figure 4-3a, for a 30.5 cm spacing, all resistivity values were within the range 32 to 36 $\Omega$.cm, and for a 15 cm spacing (Figure 4-3b), all resistivity values were within the range 19 to 23 $\Omega$.cm. In light of such results, it could conceivably be concluded that electrode geometry has no significant influence on electrical resistivity, because pipe one and two other types exhibit little difference.
Figure 4-3. Volume resistivity of ECAC slabs fabricated with various electrode types at two different spacings: a) 1 ft. electrode spacing, b) 0.5 ft. electrode spacing

As mentioned earlier, a clear difference between the two electrode spacings can be observed in Figure 4-3. Because all the resistivity calculations are based on Ohm’s law, the relationship between the resistivity and distance should be linear, but the relationship between resistivity and distance in Figure 4-3 is not linear. This can be explained by noting linearity in this context holds only for an ideal material (i.e., homogenous material), while the ECAC mixture is a heterogeneous composite material.

**Heating Efficiency Evaluation**

Active thermography [19] was performed to seek understanding of the mechanism of heat generated through resistive heating then conducted to the surfaces of the ECAC slab. Figure 4-4 displays three replicate results of heating tests obtained from active thermography testing on ECAC slabs. Each replicate is fabricated with flat electrodes and energized with a 40V power source. As can be seen, there is no remarkable difference between the results, reflecting the appropriateness of the mix design and fabrication procedures used in this study. Because of the linearly-increasing trend of surface temperature of slabs, the heat generation rate defined as the
The slope of the surface temperature plot versus time, can provide meaningful support for examining ECAC heat generation efficiency.

![Surface temperature versus time for slabs fabricated with flat electrode](image)

Figure 4-4. Surface temperature versus time for slabs fabricated with flat electrode

Heat generation rate is a parameter for assessing the influence of electrode geometry on ECAC heat generation performance, and Figure 4-5 displays the results for the three electrode geometries. As can be seen, there was no noteworthy difference in average values for all electrode geometries. In addition, it is apparent from the standard error (SE) values shown in the figure that the L-shaped electrode exhibited a higher SE value compared with the other types, and the lowest SE value is associated with the slab fabricated with flat electrodes.
Figure 4-5. Heat Generation rate for different electrode shapes

To demonstrate heat generation in time window frames, Figure 4-6, obtained from the active thermography measurements, shows initiation and propagation of heat on the surfaces of the ECAC slab made with flat electrodes. As can be seen, after 25 minutes the surface temperature gradient on the surface is the lowest because of progressive heat distribution uniformity. It should be noted that the sides of the specimen, i.e., the outer portion of the ECAC covering the electrodes, always remained colder than other locations independent of testing time because of a lack of current flow there. Such a colder pattern would not be found under real-world conditions because the electrodes diffuse electrical current on both sides. In laboratory testing, current diffuses only towards another electrode.
Figure 4-6. Thermal images obtained during a heating test performed on the slab ECAC fabricated with flat electrodes

**Heat Generation Mechanism**

As mentioned earlier, the surface temperature of an ECAC slab can be increased by converting electrical energy into heat through ohmic/resistive heating. Figure 4-7a shows the heating pattern in slab ECAC exposed to an AC electric potential field at a frequency of 64 Hz. As can be seen, four areas, A, B, C, and D, exhibited different heating patterns during the heating tests. Area A is related to the electrode-ECAC mixture interface. According to Figure 4-7a, the hottest spot was observed in this area before the surface heating pattern had reached its highest degree of uniformity at the 25th minute (see Figure 4-6), at which point the temperatures of areas B and C begin to increase. Area D surrounding area C was the last area to become warm in this heating test. To provide a clearer explanation, the electric field between the electrodes is shown.
in Figure 4-7b. Applying a potential electric field to the slab ECAC forms an electrical field between the two electric potentials, and it can be noted that the electric field shown in Figure 4-7b is based on assuming the ECAC to be a homogenous material, with full contact between electrodes and ECAC mixture. Figure 4-7b shows the electric fields in areas A and B. The electric field emanates from the positive electrode to the negative one [39], and the density of the field lines reflects the relative field magnitude [40].

The electric field is strongest where field lines are the closest to one another, and Figure 4-7b shows that the density of electric field lines near the electrodes is higher than at the middle of the specimen. The electric field causes electrons to flow in a direction opposite to that of the field lines. The highest electrodynamic force in cross-section occurs near electrodes where the electric field magnitude is the highest because this magnitude is directly proportional to the field-line density.

Resistive heating is caused by interaction between electrons in the electric field and material structure within a conductor [41] like an ECAC mixture. The voltage difference between the electrodes embedded in ECAC accelerates charged particle velocity and increases their kinetic energy. When charged particles collide with the ECAC structure, their moving pattern scatters and randomizes electric current flow. This behavior accounts for the creation of thermal energy through resistive heating. In conclusion, interaction between charges and ECAC structure at the middle of slab and in the vicinity of electrode are higher due to stronger electrical fields there. It should be noted that the contact area between electrode and ECAC mixture is also a factor contributing to heat generation in which low contact area magnifies the current density and causes more heat to be generated near the electrode.
Figure 4-7. The heating mechanism in ECAC: a) heating pattern on top and lateral surface, b) electric field on lateral surface, c) Electric field lines between two potential electrodes

Figure 4-7c shows the electrical field on the top and lateral surfaces of an ECAC slab, and the electric field at the middle of slab surface is greater than that in the surrounding region. Since the current density is proportional to the electric field \[ j \propto \mathcal{E} \], this implies that the current density in an area of high electric field line density is high. Since heat dissipation is a function of both current density and the medium’s electrical resistivity, i.e., \( j \mathcal{E} \rho \), where \( j \) is current density and \( \rho \) is electrical resistivity \[42\]. In light of such electrohydrodynamic, some heat pattern will be created in a media with constant electrical resistivity that accelerates ECAC slab heat formation in an area with higher electric field strength. Also, similar to the discussion provided for Figure 4-7b, on the surface of the slab, the density of electric field lines is higher than that at the corners and borders of the slab. Another theory which change the heating pattern in a conductive media is the mobilization pattern of charge into a conductive material \[43\]. Electron
viscous flow theory recently has been introduced to provide understanding of the non-uniform electron flow pattern. Levitov and Falkovich [43] highlighted the presence of electrical current vortices that create negative nonlocal resistance into the electric field of carbon-based conductors in areas where the electric field is weak. According to viscous electron flow theory, some current vortices will be created in areas where electric field lines are not jammed (Area D in figure 4-7a). This is another reason supporting existence of a temperature gradient at a resistor’s surface. The core of the conductive path’s network presented in Figure 4-7c is positioned in good agreement with the above discussion on thermal energy released by interaction between charges and ECAC mixture structure.

To seek better understanding of the heat pattern mechanisms, an ECAC slab was modeled using COMSOL Multiphysics software. In this model, the ECAC material was assumed to be a uniform homogeneous material with conductivity of 4E-2 siemens per centimeter, and the electrode material was defined as steel AISI 4340 well-connected to the ECAC material. In the model, an ambient temperature of -20°C was chosen, and a heat flux of 0.75 W/(m².k) was considered as the ECAC heat transfer coefficient. The simulation results could also provide an explanation for the heating pattern on the ECAC surface. Figure 4-8 shows the result of model after 15 minutes of applying a 15 Ampere current.
Figure 4-8. COMSOL modeling on the heating pattern in the stationary analysis mode

Figure 4-8a shows the heating pattern in the stationary analysis mode. As can be seen, the hottest location is located at the center of the specimens, either at the top or lateral surfaces, in good agreement with the thermography test results described above. The most surprising aspect of the data is in the heating pattern shown in Figure 4-8b that indicates all area with the same temperature placed on a uniform elliptical plate, creating a 3-dimensional elliptical geometry. It can also be seen that the corners are the coldest area of slab due to both the lack of current and also the greater heat flux. While the temperature of such areas would appear to be increased due to heat flux from adjacent locations, in reality such phenomena would not occur because there should be an electrical field at each side of the electrode.

As observed from the thermal test results described as the heating rate shown in Figure 4-5, there was no meaningful difference between electrode geometries. Several factors might affect the Joule heating efficiency in a media: the medium’s conductivity, the design of the resistor system, the medium’s thermophysical characteristics, the strength of the electric field, and the impedance of the material that might vary with temperature [44]. In the ECAC case, all these features were kept constant except for electrode geometry that might affect the field line distribution from the potential surface. To determine the effect of electrode geometry on the
electric field pattern, three simulations were using PHET interaction online software for the three geometries shown in Figure 4-9. As can be seen, at this scale there are no differences between electric field lines to indicate that one provides a stronger field than others. Such simulation led to the conclusion that the geometry of equally-sized electrode does not affect the electric field, so the same heat generation rate for all three electrode geometries in Figure 4-5 would be expected.

Figure 4-9. Result of field line simulation for different protentional geometries

To demonstrate the functional efficiency of ECAC slab under realistic conditions, such a slab was tested for feasibility of its ice-melting potential in harshly-cold simulated weather. For this purpose, a dense layer of ice was formed on the surface of an ECAC slab at -20°C ambient temperature in an environmental chamber. For 40 minutes a 30V potential was applied to the slab, and the ice layer vanished after 75 minutes. Figure 4-10 exhibits the thermal and real images during ECAC ice-melting process. Consistent with the heating mechanism described above, in this simulation test, the core of the slab was the hottest point of the slab. To conclude,
heating patterns either in model or real tests represent a balance between the heat flux to ambient temperature regions and electric field strength in the ECAC mixture.

![Image of ECAC slab during ice-melting process at -20°C ambient temperature](image)

Figure 4-10. ECAC slab during the ice-melting process at -20°C ambient temperature

Since ECAC composite materials are to be used in cold region for purposes of providing ice/snow-free surfaces, thermal stress and presence of moisture that influence ECAC mechanical properties can be prioritized as the most common concerns in that area. As mentioned in the introduction, functional performance of an HPS system depends greatly on the presence of a sufficiently-large electric field inside the material, so presence pavement cracks can disrupt this field and subsequently decrease the overall functional performance of system. This requires investigation of the mechanical performance of such composite materials in the presence of high thermal stress and moisture. To this end, the next section describes activates intended to evaluate
the interface crack potential of an ECAC slab, and then evaluate the low-temperature crack resistance and moisture susceptibility of ECAC composite.

**Mechanical Evaluation**

In this section, ECAC mechanical performance is compared to that of conventional asphalt mixture. First, the potential of reflective cracking of electrode geometry on ECAC slabs was analyzed using COMSOL multiphasic software that focused on solid mechanical concepts. Second, thermal crack resistance and moisture susceptibility of ECAC mixture were tested and analyzed using semi-circular bending and indirect tensile strength tests.

**Interface Crack Resistance**

Drawing upon the nearly identical functional performance of different electrode geometries, the next consideration would be to minimize the influence of electrode geometry on a pavement’s mechanical performance with respect to maintaining a satisfactory electrical field in the material. Since the mechanical behavior of the composite system, including ECAC material and electrodes within HPS, is different from that of ECAC material alone, there is some degree of the potential for interface cracking rooted from the interface between the electrode and ECAC material toward to the surface of pavement. Since to evaluate such crack potential, it would be reasonable to analysis the stress concentration throughout the ECAC slab, the ECAC slab was modeled using COMSOL Multiphysics software under a load applied at the top of electrode to simulate the worst-case stress condition for HPS system. Figure 4-11 shows the principal stress patterns for slabs, including included all electrode geometries. Under identical loading conditions, it can be seen that the highest stress concentration happens exactly on the element placed on top of the L-shape electrode (A), and it can be seen that the electrodes absorb more energy than the surrounding material due to the high Young’s modulus of steel compared to that of the asphalt composite. The stress concentration on the slab containing the pipe-shaped
electrode is considerably higher than that of the other geometries. The highest stress concentration, at the interface between material and electrode (C), is almost the same as that at the top of the surface (B). Considering that these two locations, B and C, are close to one another, implies that at a stress point exceeding the maximum tensile stress of ECAC mixture, crack is initiated from the interface between the electrode and ECAC materials (C), then propagates toward area B where the high-stress concentration makes it prone for initiation of top-down cracking. However, use of a flat bar electrode within the slab considerably alleviates the interface concentration stress, and the highest concentration stress occurs under applied load area (D) where the presence of an electrode does not interfere with the stress concentration pattern under the given load. In light of such analysis, selection of flat bar electrode into HPS would be advisable for extending system longevity. From this point of view, incorporating flat bars electrodes into an HPS system could result not only in highly efficient performance but could also decrease cracking potential and HPS cost. The conclusion is that using a flat-shaped electrode is would be best because the results show that it is associated with excellent repeatability, a good heat generation rate (See SE value in Figure 4-5), and less potential for interface cracking potential. It is also worth noting that increasing temperature through Joule heating excites the self-healing capability of asphalt mixture because heat accelerates the wetting and inter-molecular diffusion processes at crack interfaces. It can therefore be concluded that if micro cracks occur into the ECAC materials, they might be healed by taking advantage of ohmic heating [25].
Low-Temperature Crack Resistance

Figure 4-12a and b shows the load-displacement curves at -18°C test temperature for CF reinforced and control mixtures, respectively. As it can be observed, increasing notch depth from 15 to 32 mm reduces the peak load carried by specimens, and the final displacement before failure of the ECAC mixture is approximately twice that of the control mixture. Also, for a 32 mm notch depth, the displacement before final failure of the ECAC mixture is about three times greater than that of the control mixture. This strongly suggests that incorporating CF into asphalt mixture enhances mixture flexibility at low temperatures. In other words, ECAC presents a less brittle behavior than the control mixture at low temperatures. Simply put, a CF-reinforced mixture exhibits plastic deformation rather than cracking under huge thermally-induced stresses [16].

Moreover, reinforcing an asphalt mixture with CF provides additional tensile strength that increases the final failure strain supported by the higher displacement value of ECAC.
compared to the control mixture. Interestingly, for a CF reinforced mixture subjected to different notch depths, the reduction in failure strain is lower than those fabricated without CF. Increasing notch depth from 15 to 25 mm decreases the mixture’s peak load capacity by about 35%, and the failure strain is reduced by about 5%, implying that the presence of fiber strings within an asphalt mixture mostly provides a crack barrier rather than serving as an element to carry tensile loads. This is supported by the idea that post-crack toughness of ECAC composite, related to the load-displacement area after peak load, is considerably increased by the presence of the bridging effect of CFs in the asphalt mixture [45].

Figure 4-12. SCB test result at three notch depths: a) ECAC and b) control mixture, c) Toughness value at different notch depths for both mixtures
To provide a more in-depth insight into the fracture mechanism of ECAC mixture, the toughness of this composite material was compared with that of the control mixture for various notch depths, and Figure 4-12c shows the toughness values for both mixture types. As can be seen, increasing notch depth reduces the mixture toughness of either ECAC or control, and it is also indicated that the ECAC mixture absorbs more energy before failure than the control mixture. This proves the improved resistance of an ECAC mixture to cracking when subjected to thermally induced stresses, implying plastic deformation that can prevent brittle failure of ECAC when exposed to freezing temperatures and hence reduce the probability of thermal cracking.

As mentioned earlier, SCB specimens notched at three different depths were tested, first to develop load-displacement curves and then to identify final displacements and peak loads. The area under the load-displacement curve before peak load was calculated to determine strain energy (or U) at each notch depth (or a). To illustrate the variation in strain energy with notch depth, strain energies to failure versus different notch depths are plotted. The rate of this variation reported in Figure 4-13a was calculated using linear regression.

![Figure 4-13. Fracture mechanics results: a) Strain energy versus notch depth b) J-integral value for ECAC and control mixtures](image)

Using Equation (4), \( J_c \), i.e., the critical strain energy release rate, was calculated for both mixture types to describe the mixture’s elastoplastic behavior. A \( J_c \) value reflects more energy...
required to initiate and advance the crack, therefore implying that the mixture has higher thermal cracking resistance. According to Figure 4-13b, the $J_c$ value of an ECAC mixture is higher than that of a control mixture, i.e., the ECAC mixture, when compared to the control mixture, requires greater critical energy to support crack propagation; in this case, it is four times greater, as shown in Figure 4-13b. Reinforcement of an asphalt mixture with CFs multiplies the terminal strain failure value, because such fibers increase the energy required to initiate micro-cracks within the asphalt mixture. This implies that reinforcing an asphalt mixture with carbon fiber can extend the pavement longevity in terms of providing a smoother surface for a longer time, especially for airport runways where the asphalt material should transfer and reduce high vertical and horizontal stresses.

**Indirect Tensile Strength and Moisture Susceptibility**

The ECAC mixture presented a higher indirect tensile strength than the control mixture (Figure 4-14a), confirming that the presence of fibers in an asphalt mixture improves mixture stiffness. A study conducted by Lui and Wu [46] also mentioned that adding carbon fiber up to 2% by volume of total mixture improve their marshal stability and rutting resistance, and such enhancement could be attributed to the bridging effect of fiber strings within the mixture [45], because CFs within an asphalt mixture composite create a 3-dimensional network that reinforces the mixture’s skeleton against shear forces [45]. Following the method proposed in this study, incorporating CFs increases the ITS value and hence the stiffness of an asphalt mixture.
Figure 4-14. a) Indirect tensile strength result b) Tensile strength ratio of ECAC and control mixtures

Figure 4-14b shows the TSR value calculated for both ECAC and control mixtures using Equation 3, and the ECAC mixture can be seen to have a lower TSR value compared to the control mixture because CFs creates more space for retaining water inside the composite material [45]. The study conducted by Xu, et al. [45] mentioned that such lower moisture resistance could also be attributed to different thermal contraction rates of asphalt mixture and CFs that increase the number of voids inside the asphalt mixture. However, the TSR value presents only the reduction ratio of tensile strength, and the wet specimens have a higher ITS value than the control specimens.

**Conclusions**

This study investigates the functional and mechanical performance of electrically-conductive asphalt concrete (ECAC) as an innovative and alternative solution for pavement winter maintenance operations. To meet the study’s objectives, since the ECAC mixture should be utilized in heated pavement systems in which the mixture is connected to an electrical power supply by electrodes, it was decided to first investigate mechanisms of heat generation pattern from electricity physics, and follow this by studying the influence on heat generation efficiency
of electrode geometries and spacings similar to those of field construction. For this purpose, three different 1" electrode shapes were selected: Flat, Pipe and L-shape placed at two different electrode spacings: 0.5 and 1 ft. Functional performance of ECAC mixture from theory to practice was assessed using three approaches: volume resistivity, heat generation rate, and microphysics of electricity, focusing on mechanisms of heat-generation in an ECAC slab. COMSOL Multiphysics software was used to theoretically verify such mechanisms. The functional performance of the technology depends on maintenance of a good continuous conductive medium through which electrical current should easily flow throughout the whole area of ECAC composite, and material cracks can interrupt the flow of electrical current, reducing heated pavement system (HPS) efficiency. Harsh winter seasons can also cause huge thermal stress on asphalt pavement materials, and such stress is commonly dissipated by creation and propagation of the low-temperature cracks. The mixture is also often exposed to high moisture percentages that can reduce adhesion between ECAC compounds, so mechanical performance of ECAC slabs and mixtures were examined using solid mechanic simulation and fracture mechanics experiments. The findings of this study led to the following conclusions:

- Conductive asphalt concrete, a posistor material, responds to temperature drop by a decrease in volume resistivity, so inducing relatively low electrical power into an ECAC mixture can sufficiently increase the surface temperature of ECAC slabs result in ice and snow-free surfaces.

- It was shown that greatest heat is generated from the center and near the electrode area where the electric field magnitude is high compared to that at the border.
• At the specimen center, the magnitude of the electric field is high, providing the electrons with high kinetic energy that results in higher heat generation due to transforming kinetic into thermal energy.

• Since a flat shaped electrode decreases interface cracking potential, that shape is recommended for fabricating a ECAC mixture for use in a heated pavement system.

• No meaningful difference was found with respect to electrode shape in terms of heat generation rate and volume resistivity values.

• It was also found that reducing electrode spacing drops volume resistivity, while a comprehensive view of spacing effects cannot be formed due to limitation of numbers of spacings studied, so additional evaluation of spacing effects at large scale would be required to determine optimum electrode spacing based on cost and heat generation efficiency.

• The ECAC mixture exhibited higher thermal-crack resistance than the control mixture due to the presence of carbon fiber.

• The ECAC mixture had exhibited plastic deformation a very cold temperature, preventing inhibiting thermal cracking.

• The ECAC mixture exhibits greater indirect tensile strength than a conventional mixture, but after conditioning it exhibits a lower tensile strength ratio (TSR) than the conventional mixture.

**Acknowledgments**

This paper was prepared from a study conducted at Iowa State University (ISU) under the Federal Aviation Administration (FAA) Air Transportation Center of Excellence Cooperative Agreement 12-C-GA-ISU for the Partnership to Enhance General Aviation Safety, Accessibility,
and Sustainability (PEGASAS). The authors would like to thank the current project Technical Monitor, Mr. Jeffrey S. Gagnon (interim), and the former project Technical Monitors, Mr. Benjamin J. Mahaffay, Dr. Charles A. Ishee, and Mr. Donald Barbagallo for their invaluable guidance on this study. The authors also would like to thank the PEGASAS Industry Advisory Board members for their valuable support and feedback. The assistance of Theodore (Ted) Huisman as laboratory supervisor and Paul Ledtje as advanced asphalt laboratory supervisor is greatly appreciated. The authors would like to thank Asbury Carbons Inc. and Jebro Inc. for kindly donating the materials used in this study. The help of Dr. Pouria Hajikarimi through with analytical modeling is greatly appreciated. Although the FAA sponsored this project, it neither endorses nor rejects the findings of this research. This information is presented in the interest of invoking comments by the technical community on the results and conclusions of the research.

References


CHAPTER 5. CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

Summary

This study was directed toward fabrication of electrically-conductive asphalt concrete (ECAC) capable of melting ice/snow by transformation of electrical power through Ohmic heating within a heated pavement system (HPS). In this study, carbon fiber was used as the main conductive additive to create a three-dimensional network of conductive paths within the asphalt mixture. CF was selected because of its high aspect ratio that provides relatively longer conductive paths inside the asphalt mixture. This theory suggests that CF properties undoubtedly affect system functional efficiency, and since ECAC used in an HPS must be connected to an electrical source, the role of electrodes with respect to HPS heating performance is undeniable.

To investigate ECAC material properties, cylindrical specimens were produced by fabricating ECAC between two disk-shaped copper foils. To simulate real-life conditions, steel electrodes was chosen for use in the HPS. To this end, the feasibility of such a mixture was first investigated by focusing on mix-design procedure, and the influence of carbon fiber properties (main conductive components within ECAC) on the heating performance of ECAC was evaluated. Second, the mechanisms of heat and pattern creation in asphalt mixtures in terms of electrical theories were discussed to seek understanding of the contribution of design variables in the overall functional performance of HPS using ECAC. Third, the mechanical and functional performance of a slab fabricated with ECAC was examined to determine the effects of electrode geometry on functional and mechanical performance. Finally, the mechanical performance of the ECAC mixture was investigated in terms of low-temperature crack resistance and moisture susceptibility.
The research presented in this thesis has led to several innovative findings that contribute to the state of the art with respect to the future of smart construction material. Each chapter of this thesis presented a new procedure, idea, or scientific discussion. Some of the main contributions of this thesis are:

- Demonstrated feasibility of ECAC for providing free ice and snow surface.
- Distinguished the influential characteristics of CF involving electrical resistivity.
- Provided a deep insight into heat pattern mechanisms in HPS.
- Discovered the effects of electrode on interface cracking potential.
- Investigated thermal crack and moisture resistance of ECAC material.

It is hoped that the findings of this research will contribute to the body of construction techniques of HPS related to minimizing initial cost and extending lifetime of HPS. Moreover, discussions related to the theory of such technology at the micro-level will be used as a foundation for future research on self-sensing and self-healing materials.

**Conclusions**

The following findings present the major conclusions of this research related to achieving the stated objectives of the study.

**Effect of Carbon Fiber Properties on Volumetrics and Ohmic Heating of Electrically-Conductive Asphalt Concrete.**

The objective of this chapter was to investigate the influence of carbon fiber (CF) length and source on mix-design volumetric properties, volume resistivity, and heat generation efficiency of electrically-conductive asphalt concrete (ECAC). To this end, six types of CF were used to prepare cylindrical ECAC specimens. After characterizing the properties of these specimens and analyzing the acquired data, an ECAC slab was fabricated using a CF with
optimum fiber length obtained from source A to confirm the heat generation efficiency and ice melting capability of ECAC in a laboratory environment that simulated the harsh winters of North America. It should be noted that all tests were conducted at below-freezing temperature (-20 °C), a novel feature of this study. The findings of this study led to the following conclusions:

- Decreasing the CF length from 12 to 3 mm increases the air void and voids in mineral aggregate (VMA) of ECAC specimens and simultaneously decreases the number of voids filled with asphalt (VFA) at a constant specimen volume. In addition, variation in the selected CF sources did not substantially influence the volumetric properties of the asphalt mixture. To develop a firmer conclusion, future studies are needed using mixtures with CFs obtained from more different sources.
- Incorporation of shorter CFs into ECAC increases the required compaction effort due to better distribution of shorter CFs throughout an asphalt mixture.
- Decreasing CF length enhances ECAC volume resistivity through enhanced distribution of shorter CFs, and it was found that during mixing CF with aggregate, CF type with higher Si content and less bundled achieved better distribution during mixing, providing higher wear resistance and better sliding potential, and hence greater electrical conductivity and greater heat generation rate of ECAC.
- Because of the more uniform distribution of 3-mm CFs, ECAC heating performance modified by this length of CF was enhanced in terms of heat generation rate.
- ECAC slabs fabricated in this study demonstrated through a heating test performed in an environmental chamber set at -20°C the capability of ECAC for melting a 20-mm dense layer of ice.
This study investigated the functional and mechanical performance of electrically-conductive asphalt concrete (ECAC) as an innovative alternative solution for pavement winter maintenance operations. To meet such objectives, since the ECAC mixture to be utilized in the heated pavement system should be connected to an electrical power supply through electrodes, it was decided to first investigate the mechanism of heat generation pattern from physics of electricity and then the influence on heat generation efficiency of electrode geometry and spacings similar to those in field construction. Accordingly, three different 1”-electrode shapes were selected: Flat, Pipe and L-shaped, to be placed at two different electrode spacings: 0.5 and 1 ft. Functional performance of ECAC mixture from theory to practice was assessed using three approaches: volume resistivity, heat-generation rate, and mechanisms of ECAC heat-generation based on electricity microphysics. COMSOL Multiphysics software was used to verify such mechanisms in theory. Since functional performance of this technology depends on maintenance of a satisfactory continuous conductive medium in which electrical current should easily flow throughout the whole ECAC composite area, presence of cracks in the material can interrupt the flow of electrical current and thereby reduce heated pavement system (HPS) efficiency; In addition, harsh winter seasons result in huge thermal stresses on asphalt pavement materials that are commonly dissipated by development and propagation of low-temperature cracking. In addition, such a mixture is usually exposed to a high percentage of moisture that reduces adhesion between the ECAC compounds. The mechanical performance of ECAC slabs and mixtures were examined using solid mechanic simulation and fracture mechanics experiments. The findings of this study led to the following conclusions:
• Conductive asphalt concrete, being a posistor material, responds to a temperature drop by a decrease in its volume resistivity, inducing low electrical power to an ECAC mixture, and increasing the surface temperature of ECAC slabs enough to make them capable of providing an ice and snow-free surface.

• It was shown that heat is generated more at the center and near the electrode area where the electric field magnitude is higher than in the border area.

• At the specimen center, the electric field strength is high, giving electrons high kinetic energy that results in higher heat generation from transforming kinetic into thermal energy.

• Since a flat-shaped electrode decreases the interface cracking potential, it is recommended for use in fabricating an ECAC mixture for use in a heated pavement system.

• No meaningful difference was found among all electrode shapes with respect to heat generation rate and volume resistivity.

• It was also found that reducing electrode spacing drops volume resistivity, although a comprehensive view spacing effects cannot be formed because of the few spacing values considered. Spacing effects at larger scales should be performed to determine the optimum electrode spacing based on cost and heat generation efficiency.

• Because of the presence of carbon fiber, the ECAC mixture had higher thermal-cracking resistance than the control mixture.

• The ECAC mixture has the capability of exhibiting plastic deformation at very cold temperatures, inhibiting thermal cracking.
While the ECAC mixture exhibits higher indirect tensile strength than the conventional mixture, after conditioning it exhibits a lower tensile strength ratio (TSR) than the conventional mixture.

**Recommendations for Future Studies**

This study established several foundations for future research in the smart materials area. It is hoped that the findings of this study will advance the future of pavement technology.

**Effect of Carbon Fiber Properties on Volumetrics and Ohmic Heating of Electrically Conductive Asphalt Concrete.**

In this section, the effects of CF properties, length and source, were studied to seek improvement of ECAC electrical conductivity. Since this study was limited to only two CF sources, investigation of a wider array of CF sources is recommended. Also, while in this study carbon fiber is the primary source of conductivity, it is not beyond possibility that the intrinsic properties of asphalt binder itself could be changed to become more electrically-conductive, i.e., modifying asphalt binder by using graphene and conductive polymers might improve its electrical conductivity.
Functional and Mechanical Performance of Electrically Conductive Asphalt Concrete: A Transdisciplinary Investigation Approach from Theory to Practice

Even though this paper covers a wide array of challenging aspects of HPS and ECAC, there are still several unclear aspects of topics to be considered as future recommendations. Investigation of the self-healing capability of ECAC around the electrode to determine the interaction of self-healing capability and interface crack potentiality is recommended. Investigation of the effects of different voltage frequencies on functional performance of the ECAC slab is also recommended.