Electrified infrastructure for sustainable and resilient winter maintenance operation

by

Amir Malakooti

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Civil, Construction and Environmental Engineering
(Intelligent Infrastructure Engineering; Civil Engineering Materials)

Program of Study Committee:
Halil Ceylan, Major Professor
Kristen Cetin
In-Ho Cho
Sunghwan Kim
Mani Mina
Peter C. Taylor

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 dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred

Iowa State University
Ames, Iowa

2023

Copyright © Amir Malakooti, 2023. All rights reserved.
DEDICATION

I am writing this dedication section while my homeland, Iran, is experiencing unrest, injustice, and pain. It is with genuine gratitude and warm regard that I dedicate this work,

First and foremost, to all the freedom fighters in every corner of Iran and specifically to Mahsa Amini and her family and many others in the history of my motherland who fought for my country.

Second, to my parents and siblings, you were my cheerleaders from day one. I feel so lucky and honored to be part of this family.

Third, to my friends throughout the course of my life. Every one of you impacted my life in a way and shaped me into the person who stands today.

Fourth, to my hometown, Birjand, and my homeland Iran. If it was possible to have the choice today to pick where I would like to be born again, I would still choose Birjand in Iran.

Fifth, to all my teachers and advisors, from my kindergarten to my university professors. I am standing today on the shoulder of all of you and will always be indebted to all your love, care, and teaching.

Last but not least, to my future wife, whomever she may be. I have learned research skills at a great institution, Iowa State University, and now is the time to find you.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>ACKNOWLEDGMENTS</th>
<th>vi</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>vi</td>
</tr>
<tr>
<td>CHAPTER 1. GENERAL INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>References</td>
<td>4</td>
</tr>
<tr>
<td>CHAPTER 2. EXPERIMENTAL AND THEORETICAL CHARACTERIZATION OF ELECTRODES ON ELECTRICAL AND THERMAL PERFORMANCE OF ELECTRICALLY CONDUCTIVE CONCRETE</td>
<td>7</td>
</tr>
<tr>
<td>Abstract</td>
<td>7</td>
</tr>
<tr>
<td>Introduction</td>
<td>8</td>
</tr>
<tr>
<td>Theoretical Background</td>
<td>11</td>
</tr>
<tr>
<td>Methodology</td>
<td>13</td>
</tr>
<tr>
<td>Electrode Types for Thermal Performance Evaluation</td>
<td>13</td>
</tr>
<tr>
<td>Thermal Performance Test Procedure and Finite-Element Model of Electrodes in Water</td>
<td>14</td>
</tr>
<tr>
<td>Thermal Performance Test Procedure of Electrodes in ECON</td>
<td>18</td>
</tr>
<tr>
<td>Results</td>
<td>21</td>
</tr>
<tr>
<td>Water Test Thermal Performance and Finite Element Model Results</td>
<td>21</td>
</tr>
<tr>
<td>ECON Prototype Slab Thermal Performance Results</td>
<td>24</td>
</tr>
<tr>
<td>Discussion of Practical Implications</td>
<td>28</td>
</tr>
<tr>
<td>Energy Conversion Efficiency</td>
<td>28</td>
</tr>
<tr>
<td>Cost Analysis</td>
<td>29</td>
</tr>
<tr>
<td>Conclusions and Recommendations</td>
<td>30</td>
</tr>
<tr>
<td>References</td>
<td>32</td>
</tr>
<tr>
<td>CHAPTER 3. SYSTEM DESIGN IMPROVEMENTS OF HEATED PAVEMENTS: RECOMMENDATIONS FOR FUTURE PROJECTS</td>
<td>37</td>
</tr>
<tr>
<td>Abstract</td>
<td>37</td>
</tr>
<tr>
<td>Introduction</td>
<td>38</td>
</tr>
<tr>
<td>Research Significance</td>
<td>40</td>
</tr>
<tr>
<td>ECON HPS Improvements</td>
<td>40</td>
</tr>
<tr>
<td>ECON Mix Design</td>
<td>41</td>
</tr>
<tr>
<td>Voltage Selection</td>
<td>42</td>
</tr>
<tr>
<td>Control System Design</td>
<td>42</td>
</tr>
<tr>
<td>Electrode Design</td>
<td>44</td>
</tr>
<tr>
<td>Sensor Selection</td>
<td>45</td>
</tr>
<tr>
<td>Cross slope Design</td>
<td>45</td>
</tr>
<tr>
<td>Performance Comparison</td>
<td>46</td>
</tr>
<tr>
<td>Conclusions and Recommendations</td>
<td>47</td>
</tr>
<tr>
<td>References</td>
<td>49</td>
</tr>
</tbody>
</table>
CHAPTER 4. DESIGN AND FULL-SCALE IMPLEMENTATION OF THE LARGEST OPERATIONAL ELECTRICALLY CONDUCTIVE CONCRETE HEATED PAVEMENT SYSTEM ........................................................................................................... 51
Abstract ......................................................................................................................... 51
Introduction .................................................................................................................... 52
Full-Scale ECON HPS Implementation Overview ............................................................. 54
  Key Components of ECON HPS Technology ............................................................... 54
  ECON HPS System Design ......................................................................................... 55
Description of Materials ................................................................................................. 58
ECON and PCC layer Mix Design .................................................................................. 58
Electrodes ....................................................................................................................... 59
Sensors and Data Acquisition System ........................................................................... 60
Control System ............................................................................................................. 60
Instrumentation and Installation Methods ..................................................................... 61
  Installation of Electrodes ............................................................................................. 61
  Sensors Instrumentation Plan ....................................................................................... 63
  Integration of Power Supply and Control System ......................................................... 63
Construction Procedure ............................................................................................... 66
Iowa DOT ECON HPS Performance Evaluation ............................................................. 68
Summary, Conclusions, and Recommendations ............................................................. 72
References ...................................................................................................................... 74

CHAPTER 5. ELECTRICALLY CONDUCTIVE CONCRETE HEATED PAVEMENT SAFETY CONCERNS AND MITIGATION APPROACHES .................................................. 77
Abstract ......................................................................................................................... 77
Introduction .................................................................................................................... 78
Hazard Assessment ........................................................................................................ 80
  Human Body Equivalent Circuit Model ..................................................................... 81
  Effects of Current on the Human Body ...................................................................... 81
  Hazard Assessment Field Experimental Study ............................................................. 82
  Hazard Assessment Results and Discussion ............................................................... 84
Hazard Mitigation Strategies ......................................................................................... 85
  Reducing the Voltage usage in ECON HPS ................................................................. 86
  Grounding ..................................................................................................................... 86
  Insulation Layer ........................................................................................................... 89
Conclusions .................................................................................................................. 91
References ...................................................................................................................... 92

CHAPTER 6. GENERAL CONCLUSION ............................................................................. 94
Conclusions .................................................................................................................. 94
Recommendations for Implementation and Future Research Directions ......................... 96
ACKNOWLEDGMENTS

I would like to thank all my committee members for their guidance and support throughout the course of this research, especially my advisor, Dr. Halil Ceylan for his trust and mentorship. In addition, I would also like to thank my friends, colleagues, the department faculty and staff for making my time at Iowa State University a wonderful experience. I would like to thank the Iowa Department of Transportation (DOT) and the Iowa Highway Research Board (IHRB) for providing the matching funds for this research which is sponsored by the Federal Aviation Administration (FAA). I would also like to thank the FAA Air Transportation Center of Excellence for the Partnership to Enhance General Aviation Safety, Accessibility and Sustainability (PEGASAS). The IHRB technical advisory committee (TAC) members from Iowa DOT and Iowa Counties, particularly Mr. Mike Harvey, Director of Iowa DOT’s Support Services Office Administrative Services Division, and Iowa DOT electricians, the FAA PEGASAS Technical Monitor for Heated Airport Pavements project, and Mr. Gary L. Mitchell of the American Concrete Pavement Association (ACPA) are gratefully acknowledged for their guidance, support, and direction throughout the research. I would like to express their sincere gratitude to other research team members from ISU’s Program for Sustainable Pavement Engineering and Research (PROSPER) at Institute for Transportation for their assistance with the lab and field investigations. Although the Iowa DOT and FAA have sponsored this study, they neither endorse nor reject the findings of this research. The presentation of this information is in the interest of invoking comments by the technical community with respect to the results and conclusions of the research. This dissertation does not constitute a standard, specification, or regulation.
ABSTRACT

Many transportation agencies allocate significant time and resources each year to remove ice and snow from their paved surfaces to achieve a safe, accessible, and operational transportation network. An electrically conductive concrete (ECON) heated pavement system (HPS) has been shown to be a promising alternative to conventional snow removal operations using snowplows and deicing chemicals, which are time-consuming, labor-intensive, and environmentally unfriendly. An ECON HPS utilizes the inherent electrical resistance of concrete to maintain the pavement surface above freezing and thus prevent snow and ice accumulation on the surface. Such a sustainable concrete pavement system improves infrastructure resiliency by allowing it to be safe, open, and accessible even during harsh winter storms. The primary objective of this research was to demonstrate the full-scale implementation of 10 ECON HPS slabs at the Iowa Department of Transportation (DOT) headquarters’ south parking lot in Ames, Iowa. To identify the most electrically and thermally efficient type of electrode through experimental testing and theoretical analysis, several laboratory and preconstruction investigations were conducted regarding the influence of electrode size and geometry on the resistive heating performance of an ECON HPS. In addition, a theoretical formulation showing the relationship between thermal and electrical performance as well as the material properties in an ECON HPS was developed for the first time. Testing electrodes in water as a conductive medium was also found to be a quick, nondestructive, and cost-effective alternative method for monitoring the thermal performance of electrodes. The field demonstration study consisted of developing the system design and identifying electrode and sensor instrumentation procedures for the construction of the ECON HPS, which took place during October 2018. The system design included the ECON mix design, electrode configuration design, sensor selection, and
control system design using a programmable logic controller (PLC) to remotely control, operate, and monitor the system. Electrode and sensor instrumentation procedures included identifying suitability in terms of performance and finding appropriate sensors for monitoring system behavior to compare and contrast different electrode design configurations. The heating performance of the remotely operated ECON slabs was evaluated during the 2018 through 2021 winter seasons using instrumented sensors located under the snow and ice. The performance evaluation showed promising results in producing snow- and ice-free pavement surfaces through several winter weather events.
CHAPTER 1. GENERAL INTRODUCTION

Transportation networks often experience a significant reduction in mobilization capacity due to delays, sometimes resulting in a complete shutdown of some parts of a network, due to snow and ice accumulation during winter seasons (1). Departments of transportation (DOTs) and airports annually spend millions of dollars to remove snow and ice from pavements and maintain the safety of the transportation infrastructure (2). For example, US freeways, including interstates, experience 5% to 40% average speed reduction and 12% to 27% mobilization capacity reduction during snow and ice precipitation (3). Implementing heated pavement technology, especially in supporting critical infrastructure (e.g., airports, highways), can reduce these costs by increasing transportation network resiliency during the winter season, particularly as climate change continues to make winter seasons harsher, resulting in more extreme conditions in some regions (4).

Conventional methods for removing ice and snow include the use of snow-removal equipment and anti-icing or deicing chemicals (5). In 2019, the US consumed 27 million tons (24.5 million metric tons) of rock salt for roadway deicing purposes (6). Such methods are time-consuming, labor-intensive, and negatively impact the environment (7, 8), because deicing chemicals contaminate soil, surface runoff, and groundwater, thereby impacting the ecological system as a whole. It has been estimated that 50% of the world’s arable land could be salinized by 2050, directly affecting the global food supply (9). Deicing with chemicals not only affects the ecosystem but also increases the rate of corrosion of already aging infrastructure (10).

In Iowa, snow and ice removal are expensive components in winter road maintenance for the state DOT as well as for counties and cities. The Iowa DOT, alone, is responsible for snow and ice removal on more than 9,000 miles (14,000 km) of Iowa highways, uses approximately
900 snowplow trucks, and uses approximately 200,000 tons (181,000 metric tons) of rock salt each year in snow and ice removal on Iowa roadways.

Several innovative techniques have been proposed for facilitating the removal of ice and snow from surfaces by other than these conventional methods. These include hydronic-heated pavement systems (HHPSs) (11, 12), phase-change materials (PCMs) used in integrated pavement systems (13), and electrically conductive concrete (ECON) heated pavement systems (HPSs) (14). An HHPS circulates heated glycol, potentially toxic and harmful to the environment, especially if leakage occurs, within embedded pipes to heat the pavement (8). PCM-integrated pavement systems utilize the heat of fusion generated by phase transformation to increase the pavement temperature. This technology has been found to have an adverse effect on both the dynamic elastic modulus and the compressive strength of concrete, and it is not applicable in harsh climates (13). The ECON HPS has gained increasing attention in recent years based on promising results from full-scale field implementations at the Des Moines International Airport (DSM) in 2016 and the Iowa DOT headquarters in 2018.

ECON, using regular portland cement concrete (PCC) combined with a conductive additive material (e.g., carbon fiber, steel shaving), relies on resistive heating of the ECON when embedded electrodes are subjected to an applied electric potential difference (voltage) (14). To properly facilitate the flow of electricity, a minimum dosage of conductive additive based on the mix’s percolation threshold must be present in the mix (8, 15-18); 1% by volume has been found to be an adequate amount of carbon fiber for ECON HPS purposes (19, 20).

The advantages of ECON HPS technology include electrification and automation of winter maintenance operations, environmental-friendliness, extended pavement life through elimination of deicing chemicals, and providing a safer platform for use by aircraft, vehicles, and
pedestrians (14). Another application of ECON HPS is self-sensing and dynamic infrastructure monitoring using the operating conductivity range of ECON (21-24).

Given that weather conditions impact the performance of an ECON HPS, each specific region needs a particular design for ensuring the best system performance (25). The design parameters for an ECON HPS include the thicknesses of the regular and conductive concrete layers, joint spacing, electrode spacing, and electrode size and shape. Among these parameters, electrode spacing and electrode size and shape are those unique to the ECON HPS design and not required for conventional rigid pavement systems. Electrodes, which are essential parts of the ECON HPS design, should exhibit an acceptable level of electrical conductivity to convey electrical current from a power supply into the ECON to increase the surface temperature to a value above the freezing point (41°F [5°C]) and melt accumulated ice and snow on the ECON surface. Adequate bonding between the electrodes and the ECON is critical for achieving satisfactory resistive heating for this system (23, 26, 27).

The objective of this study was to construct, demonstrate, and monitor a full-scale implementation of the largest-to-date operational ECON HPS using different electrode configurations. Ten full-scale slabs were constructed at the south parking lot entrance of the Iowa DOT headquarters in Ames, Iowa, as part of a reconstruction project. These slabs contained various electrode configurations with different spacings, sizes, and shapes to evaluate their effect on the energy and thermal performance of the ECON HPS. Along with the 10 ECON HPS slabs, the test setup included standard concrete slabs as control sections to compare the structural performance of the ECON HPS to standard rigid pavements. The remainder of this dissertation is structured as follows:
- Chapter 2. experimental and theoretical characterization of electrodes on electrical and thermal performance of electrically conductive concrete
- Chapter 3. system design improvements of heated pavements: recommendations for future projects
- Chapter 4. design and full-scale implementation of the largest operational electrically conductive concrete heated pavement system
- Chapter 5. electrically conductive concrete heated pavement safety concerns and mitigation approaches
- Chapter 6. general conclusion

References


5. Baskas, H. 2011. Winter Survival Strategies from the USA’s Snowiest Airports. USA Today


CHAPTER 2. EXPERIMENTAL AND THEORETICAL CHARACTERIZATION OF ELECTRODES ON ELECTRICAL AND THERMAL PERFORMANCE OF ELECTRICALLY CONDUCTIVE CONCRETE

Amir Malakooti¹, Hesham Abdualla², Sajed Sadati³, Halil Ceylan⁴, Sunghwan Kim⁵, and Kristen Cetin⁶

¹: Ph.D. Student, Iowa State University, Ames, IA
²: Pavement Research Engineer, Applied Research Associates Inc., Champaign, IL
³: Postdoctoral Research Associate, Iowa State University, Ames, IA
⁴: Professor of CCEE, Iowa State University, Ames, IA
⁵: Research Scientist, Institute for Transportation, Iowa State University, Ames, IA
⁶: Assistant Professor of Civil & Environmental Engineering, Michigan State University, East Lansing, MI

Modified from a manuscript published in Composites Part B: Engineering

Abstract

Transportation agencies regularly seek innovative, cost-effective, and environmentally-friendly approaches to help manage winter maintenance operations during snow and ice events. The use of an electrically-conductive concrete (ECON) heated pavement system (HPS) is a smart and promising alternative to conventional snow and ice removal methods using de-icing chemicals and snow-removal equipment. ECON is made electrically conductive by introducing conductive agents into the concrete mix and applying electrical current through electrodes embedded in the ECON layer. This study investigates the influence of electrode size and geometry on the resistive heating performance of ECON HPS and identifies the most electrically and thermally-efficient type of electrode through experimental testing and theoretical analysis. Electrode performance was investigated in water, prototype ECON slabs, and through
development of a finite-element model, and good agreement was found between the results obtained from these three evaluation methods. A theoretical formulation between thermal performance and electrical and material properties in ECON HPS was first developed. Testing electrodes in water was then found to be a quick, non-destructive, and cost-effective alternative method for monitoring thermal performance of electrodes. Finally, electrode surface contact area was identified as the dominant electrode characteristic with respect to influencing temperature increase. Cost and energy analysis for each electrode type showed that smaller-diameter electrodes exhibited higher cost-effectiveness, and conversely, larger diameter electrodes were found to have higher energy-conversion efficiency. The results of this work will provide guidance for choosing the most cost-effective and optimized type of electrode for design and construction of a large-scale ECON HPS.

Introduction

Transportation networks often experience significant reduction in mobilization capacity due to delays, sometimes resulting in complete shutdown of some parts of a network due to snow and ice accumulation during winter seasons [1]. Airports and departments of transportation (DOTs) annually spend millions of dollars to remove snow and ice from pavements and maintain safety of the transportation infrastructure [2]. For example, flight delays in airports, one-third of which are weather-related, have a significant impact on the U.S. economy. It has been estimated that the U.S. air transportation sector in 2007 incurred 32.9 billion dollars of revenue loss due to flight delays only; the estimated cost per minute of such delays in 2018 is $74.20 [3,4]. Implementing heated pavement technology, especially for use in supporting critical infrastructure (e.g., airports, heavy traffic areas, etc.), can reduce these costs by increasing transportation network resiliency during the winter season, particularly as climate change is making winter season harsher, with more extreme conditions, in some regions [5].
Conventional methods for removing ice and snow include the use of snow-removal equipment and anti-icing or de-icing chemicals [6]. In 2019, the U.S. consumed 24.5 million metric tons of rock salt for roadway de-icing purposes [7]. Such methods are time-consuming, labor-intensive, and negatively impact the environment [8,9] as de-icing chemicals contaminate soil, surface runoff, and groundwater, thereby impacting the ecological system as a whole. It has been estimated that 50 percent of world arable land would be salinized by 2050, which directly affect the global food supply [10]. De-icing not only affects the ecosystem but also increases the rate of corrosion of already aging infrastructure [11].

Several innovative techniques have been proposed for facilitating the removal of ice and snow from surfaces without using such conventional methods. These include hydronic-heated pavement systems (HHPS) [12,13], phase-change materials (PCM) integrated pavement systems [14], and electrically-conductive concrete (ECON) heated pavement systems (HPS) [15–19]. HHPS circulates heated Glycol, which can be toxic and harmful to the environment especially if leakage occur, within embedded pipes to heat the pavement [8]. PCM-integrated pavement systems utilize the heat of fusion generated by phase transformation to increase pavement temperature. This technology has been found to have an adverse effect on the dynamic elastic modulus and compressive strength of concrete, and is not applicable in harsh climates [14]. ECON HPS has gained increasing attention in recent years through its promising results and full-scale field implementation at Des Moines International Airport in 2016 and Iowa Department of Transportation headquarter in 2018 [8,20–22].

ECON, using regular Portland cement concrete (PCC) combined with a conductive additive material (e.g., carbon fiber, steel shaving, etc.), relies on resistive heating of the ECON when embedded electrodes are subjected to an applied electric potential difference (voltage)
To properly facilitate the flow of electricity, based on the mix’s percolation threshold [23–26], a minimum dosage of conductive additive must be present in the mix [8]; one percent by volume has been found to be an adequate amount of carbon fiber for ECON HPS purposes [27,28]. The advantages of ECON HPS technology include electrification and automation of winter maintenance operations, environment-friendliness, extended pavement life through elimination of de-icing chemicals, and providing a safer platform for use by aircraft, vehicles, and pedestrians [15]. ECON HPS can also be used for self-sensing and dynamic infrastructure monitoring using the operating conductivity range of ECON [29–32].

Electrodes, essential parts of the ECON HPS design, should exhibit an acceptable level of electrical conductivity to convey electrical current from a power supply into the ECON to increase the surface temperature to above the freezing point (5°C) and melt accumulated ice and snow on the ECON surface. Adequate bonding between the electrodes and the ECON is critical for achieving satisfactory resistive heating for this system [33–35]. Different types of electrodes for resistive heating, including copper mesh, steel mesh, and perforated galvanized steel bars, have been studied by other researchers [36,37]. In perforated galvanized steel angles, perforations larger than the nominal maximum aggregate size have been suggested because such perforations would help provide satisfactory interlock between the electrode and ECON [38]. Use of angle-shaped electrodes, however, increases crack-formation potential in the concrete pavement due to stress concentration at the angled edge, potentially resulting in durability issues during pavement lifetime [39]. Corrosion of steel bars has been found to negatively impact temperature increase in a heated pavement system because of weakened electrode-ECON contact [40]. While conductive adhesive on electrodes has also been used to ensure sufficient bonding...
between the ECON and electrodes, this method was found to have limited cost-effectiveness [41].

Such findings from previous studies reflect a need for a more in-depth investigation of a cost-effective alternative electrode shape and geometry that will minimize cracking potential while providing sufficient heating performance. Testing each ECON electrode type is also time-consuming, expensive, and less ideal because of the nonhomogeneous nature of concrete that significantly increases when large amounts of carbon fibers are present in the mix [39]. There is therefore a need for a non-destructive, quick, and simplistic test to predict the thermal performance of each electrode. There is also no physics-based theoretical formulation in the literature related to studying the thermal performance of ECON HPS.

This study investigates the electrical and thermal performance of various stainless-steel electrodes to identify the most thermally energy-efficient and cost-effective electrode design for use in large-scale ECON HPS. A theoretical formulation is developed for ECON HPS thermal behavior, and a non-destructive test suggested for predicting electrode thermal performance is validated using theory, experimental, and finite-element (FE) modeling. The findings of this study can provide theoretical, practical, and in-depth guidance and recommendations for future large-scale design and construction of ECON HPS.

**Theoretical Background**

ECON HPS relies on resistive heating, also known as Joule heating, by heat generation due to resistivity of a material when exposed to electric current. In the resistive heating mechanism, electrical energy \( E \) is converted into thermal energy \( Q \) [42]. Steady-state conditions and negligible losses in electrical and thermal performance is assumed here. Since this paper is a comparative study under identical environmental conditions, the assumption of
negligible losses is a fair assumption. Electrical energy can be calculated by multiplying power 
\( P \) by operational time \( \Delta t \), as shown in Equation 1 [43].

\[
E = P \cdot \Delta t = \frac{V^2}{R} \cdot \Delta t
\]  

(1)

Where \( V \) is the applied voltage, and \( R \) is the electrical resistance of the material. \( R \) can be calculated using resistivity \( \rho \), a material property normalized by specimen dimensions [44], as shown in Equation 2.

\[
R = \frac{\rho \cdot L}{A}
\]

(2)

Where \( L \) and \( A \) are the length and the conductive cross-sectional area in the direction of current flow, respectively. Combining Equations 1 and 2, electrical energy can be written, as shown in Equation 3.

\[
E = \frac{V^2 \cdot A}{\rho \cdot L} \cdot \Delta t
\]

(3)

The thermal energy generated in a material can be calculated from the mass \( m \), the specific heat capacity \( C \), and the temperature increase in the material \( \Delta T \) using Equation 4 [45].

\[
Q = m \cdot C \cdot \Delta T
\]

(4)

Equation 5 results from equating the electrical energy with the thermal energy \( (E = Q) \) in Equations 3 and 4 and rearranging.

\[
\frac{\Delta T}{\Delta t} = \frac{V^2 \cdot A}{\rho \cdot L \cdot m \cdot C}
\]

(5)

This equation determines the relationship between the temperature increase rate \( \Delta T/\Delta t \) and specimen dimensions, and the electrical and thermal properties of a material undergoing
resistive heating. It shows that the applied voltage has an exponential correlation with the temperature increase rate while the other properties have a linear correlation.

In addition, since voltage and conductive cross-sectional area have positive correlations while resistivity, length, mass, and specific heat capacity have negative correlations. Therefore, in order to maximize the temperature increase rate in ECON HPS, higher applied voltage ($V$), larger ECON layer thickness with considering constant slab dimensions ($A$), lower ECON resistivity ($\rho$), and shorter electrode spacing ($L$) will result in better thermal performance. The conductive cross-sectional area ($A$) in Equation 5 can also be represented as the electrode surface area since the first stage in which electricity is applied to the material is through the surface area of the electrode where the current flows to the material. Throughout this paper, the temperature increase rate is measured for different electrode sizes and geometries (different surface areas), and thermal and electrical performance is discussed.

**Methodology**

**Electrode Types for Thermal Performance Evaluation**

Stainless steel A316L, a chromium-nickel stainless steel containing molybdenum, was chosen as the electrode material [46]. This material is extremely corrosion-resistant, especially to acid sulfates and alkaline chlorides [46], so it would be expected to prolong the performance and durability of the concrete pavement system. The stainless steel electrodes used in this study have an electrical resistivity of 74.6 $\mu$Ω-cm at 20°C and are capable of conducting electrical current into the ECON layer [47]. Three different electrode geometries (circular, hollow circular, and flat bar) in different sizes were tested. The details of the electrode geometries and their respective unit prices per meter are shown in Table 2-1. The unit price is based on an average of ten different market quotes for the same quantities. The unit price of electrodes increases significantly with an increase in electrode diameter, and hollow bars are also ten percent cheaper
than solid bars of the same diameter. Photos of the individual electrodes selected are shown in Figure 2-1. The following sections describe the test setup for thermal performance evaluation of electrodes in water, ECON prototype slab, and the developed finite-element model.

Table 2-1 Selected electrodes with the associated cost.

<table>
<thead>
<tr>
<th>Electrodes</th>
<th>Geometry</th>
<th>Average unit price (USD/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.7 mm OD</td>
<td>Smooth circular</td>
<td>10.77</td>
</tr>
<tr>
<td>19.0 mm OD</td>
<td>Smooth circular</td>
<td>19.66</td>
</tr>
<tr>
<td>25.4 mm OD</td>
<td>Smooth circular</td>
<td>35.26</td>
</tr>
<tr>
<td>38.1 mm OD</td>
<td>Smooth circular</td>
<td>91.80</td>
</tr>
<tr>
<td>25.4 mm OD, 19.0 mm ID</td>
<td>Hollow circular</td>
<td>31.80</td>
</tr>
<tr>
<td>25.4 mm × 4.7 mm</td>
<td>Flat bar</td>
<td>9.92</td>
</tr>
</tbody>
</table>

Note: OD-outside diameter; ID-inside diameter

Figure 2-1 Electrodes used in the study.

**Thermal Performance Test Procedure and Finite-Element Model of Electrodes in Water**

The advantage of testing electrodes in water is that very good electrical contact can be achieved between water and the electrodes; this is more difficult when testing electrodes embedded in ECON because of air pockets that can occur at the electrode-ECON interface. Testing electrodes in water represents an idealized situation in terms of electrical contact between an electrode and its surrounding matrix. Since water is also homogenous and hence provides virtually uniform heat distribution while ECON is a heterogeneous material, testing in
water, due to its non-destructive nature, represents a rapid, inexpensive, ideal, and cost-effective assessment method for validating hypotheses based on theory.

The plastic water tank used in all tests was 229 mm long, 203 mm deep, 101 mm wide, and 2 mm thick as shown in Figure 2-2a. The water used in this test was tap water with a measured average electrical resistivity of 1450 Ω-cm, and for each test an identical amount of water (3 kg) was poured into the water tank. The electrodes were placed in the water at least 8 hours prior to test initiation to allow both water and electrodes to reach thermal equilibrium at ambient temperature (20℃). A 120-volt alternating current (VAC) was then applied to the electrodes to pass electric current into the water tank. The temperature and heat generation behavior were monitored using the FLIR T650sc infrared thermal camera shown in Figure 2-2b, and electrical current was measured using a Southwire true RMS clamp meter. The emissivity setting for the thermal camera was set to 0.95 based on calibration using thermocouple and thermal camera measurements.

The electrodes were initially tested in water with a 2% (wt.) aqueous solution of sodium chloride because the electrical conductivity of a sodium chloride solution is higher than that of pure and tap water due to its concentration of charge-carrying ions. However, since using sodium chloride led to sedimentation that resulted in heat concentration visible in the thermographic images at the tank bottom where the sodium chloride had settled (see Figure 2-3a), it was decided to eliminate the use of sodium chloride to achieve more uniform temperature increase within the water tank such that the performance of different electrodes in an ECON matrix could be more accurately simulated (see Figure 2-3b).
Figure 2-2 Electrode test in water: (a) water tank dimensions; (b) electrode in water test setup.

Figure 2-3 Electrode thermal performance behavior in water: (a) water with 2 percent sodium chloride; (b) water without sodium chloride.

To compare the temperature increase measured in the tests performed in water with theoretical temperature increase values, a finite-element model of the electrodes in water was developed using ANSYS 2019 [48,49]. The model was developed using eight-node SOLID5 elements capable of modeling resistive heating. The maximum mesh size of 1 cm was found by incrementally refining the mesh size until there were no significant changes in the model results. The final meshed model for a pair of 25 mm OD circular electrodes is shown in Figure 2-4.

Since the water container was a thin-walled plastic container, its impact on the temperature increase of the water and the heat transfer between the container wall and the
surrounding air were assumed to be negligible. In addition, since this paper is a comparative study under identical and controlled environmental conditions, the assumption of negligible losses is a fair assumption. The material properties included in the model were density, heat capacity, electrical conductivity, and thermal conductivity, all except thermal conductivity measured and used in the model. The thermal conductivity of water was used to calibrate the model. A trial value based on the literature was selected for the thermal conductivity of water, and the value was modified to make the model results match the measurements. This calibration was performed only for the model with 25 mm OD circular pair of electrodes, and the value obtained for thermal conductivity of water was used for all other models, i.e., all material properties were the same in all the models.

The material properties for the stainless steel electrodes were obtained from existing data [50]. Temperature increase profile in water for the 25 mm OD electrodes in the FE model and experimental data are shown in Figure 2-5a and Figure 2-5b, respectively. The profile shows a similar temperature increase for both the calibrated FE model and the experimental results (Figure 2-5c). The FE model for the ECON slabs is not included in the scope of this manuscript; since it was covered in the literature which its findings also back this study [51].

![Finite element model mesh for a pair of 25 mm OD electrodes in water.](image.png)
Figure 2-5 Average surface heat generation profile for 25 mm OD electrodes in water from: (a) finite element (FE) model; (b) experimental results; (c) model validation.

**Thermal Performance Test Procedure of Electrodes in ECON**

Five prototype slabs with different electrode geometries and sizes were designed and constructed, all with dimensions of 610 mm by 610 mm with a fixed center-to-center electrode spacing of 460 mm. Figure 2-6 shows the plan and cross-sectional views of the constructed ECON prototype slabs. Identical features and parameters in all slabs included electrode spacing (460 mm), electrode cover (50 mm), applied testing voltage (60 VAC), and ECON mix design. The ambient temperature for all the tests was kept at 20°C. The electrical resistivity of air-dried normal portland cement concrete (PCC) is typically between $6.54 \times 10^5$ and $11.4 \times 10^5$ Ω-cm [52–54], while the average electrical resistivity of the ECON slabs in this study was 60 Ω-cm due to
the presence of carbon fiber in the mix at one percent by volume. The carbon fiber used in this experiment has a length of 6 mm, diameter of 7.2 microns, tensile strength of 4,137 MPa, electrical resistivity of $1.55 \times 10^{-3} \, \Omega \cdot \text{cm}$, specific heat of 600 J/Kg.K, and thermal conductivity of 6.4 W/m.K.

The two-lift approach used in constructing the ECON prototype slabs (similar to full-scale field implementation design) consisted of casting an 89 mm ECON layer on top of a 25 mm PCC layer. The first underlying reason for this design was to minimize costs, since using only one layer of ECON required less carbon fiber than using two layers of ECON combined with normal PCC of the same thickness. The second reason was to mainly generate heat closer to the surface where snow and ice accumulate. Two-lift paving is similar to retrofitting existing full-scale pavement systems, where the heated pavement would include overlaying a layer of ECON on an existing pavement.

Figure 2-7a shows the framework of the ECON prototype slab constructed in two main steps. First, a 25 mm PCC was cast with an iButton temperature sensor with an accuracy of $\pm 1^\circ \text{C}$ placed at its center (100 mm below the slab surface). The PCC surface was then finished and tined, as shown in Figure 2-7b, to achieve a better bond between the regular concrete and the ECON layer. In the second step, an 89 mm thick ECON layer was placed on top of the hardened PCC layer, with iButton sensors placed in the middle of the ECON layer 44 mm below the slab surface (Figure 2-7c). Consolidation was performed using a probe vibrator. The finished surface is depicted in Figure 2-7d. While the 25 mm normal PCC layer for all tested slabs were constructed and cast at one time, the ECON layers were cast on separate days using the same process. The reason for this approach was to improve the uniformity of carbon fiber dispersion in the ECON mix by mixing in small batches. For larger batches, the mixing power of the drum
mixer would have been insufficient to achieve better fiber dispersal within the concrete mixture.

All slabs were wet-cured after casting for eight days using wet rags were tested at the same age (eight days). ECON mixing proportions used for casting the slabs are given in Table 2-2. This mix design is based on that used in previous studies [55,56], the one difference being the inclusion of a viscosity-modifying admixture (VMA) to increase the mix viscosity for improvement of ECON finishing while decreasing the possibility of segregation. Air-entraining agent was used in the ECON concrete mix to provide freeze and thaw resistant in the winter season.

![Figure 2-6](image1.png)

Figure 2-6 ECON prototype slab dimensions for all slabs: (a) plan view; (b) cross-sectional view.

![Figure 2-7](image2.png)

Figure 2-7 Construction steps of ECON prototype slabs: (a) mold fabrication; (b) casting 25 mm of normal PCC and surface roughing with a screed; (c) placing temperature probe; (d) casting and finishing of 89 mm ECON layer.
Table 2-2 ECON mix proportions.

<table>
<thead>
<tr>
<th>Components</th>
<th>Type</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basic</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse aggregate (19 mm)</td>
<td>Limestone</td>
<td>606 kg/m³</td>
</tr>
<tr>
<td>Intermediate aggregate (9.5 mm)</td>
<td>Limestone</td>
<td>303 kg/m³</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>River sand</td>
<td>690 kg/m³</td>
</tr>
<tr>
<td>Fly ash</td>
<td>Class F</td>
<td>98 kg/m³</td>
</tr>
<tr>
<td>Cement</td>
<td>Holcim Type I/II</td>
<td>388 kg/m³</td>
</tr>
<tr>
<td>Water</td>
<td>Tap water</td>
<td>176 kg/m³</td>
</tr>
<tr>
<td><strong>Admixtures</strong></td>
<td>MasterAir AE 90</td>
<td>29.6 ml/CWT</td>
</tr>
<tr>
<td>Air-entraining agent (designed for 6% air)</td>
<td>WR Grace &amp; Co. DCI</td>
<td>26 Kg/m³</td>
</tr>
<tr>
<td>Derex Corrosion Inhibitor (DCI)</td>
<td>MasterGlenium 7500</td>
<td>0.5% wt. cem.</td>
</tr>
<tr>
<td>High range water reducer (HRWR)</td>
<td>VMA</td>
<td>3100 ml/m³</td>
</tr>
<tr>
<td>Viscosity-modifying admixture</td>
<td>Synthetic carbon fiber</td>
<td>0.97 (% Vol.)</td>
</tr>
<tr>
<td>Carbon fiber 6-mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: CWT- hundredweight of cementitious materials

**Results**

The following section presents the results from the water, ECON prototype slab, and FE modeling.

**Water Test Thermal Performance and Finite Element Model Results**

Examples of thermal images taken during the electrode test in water are shown in Figure 2-8a. These images, captured at 5-minute intervals, represent the performance of a 38.1 mm OD electrode (left) and a 12.7 mm OD electrode (right). The average surface temperatures of both water tanks were measured and are plotted in Figure 2-8b. The current readings during this test, taken every 5 minutes, is also shown in Figure 2-8c. Based on these figures, the temperature increase rate of the 38.1 mm OD electrode was higher than the 12.7 mm OD because of the larger surface contact area of this electrode with the water.
Figure 2-8 Electrode test in water tank: (a) thermography imaging during test; (b) average surface temperature versus time plot; and (c) current versus time plot.

The temperature increase rate shows how quickly each electrode can generate heat, and eventually when used in ECON HPS, melt ice, and snow. It is essential to know how quickly the surface temperature of ECON HPS rises above the freezing point (5°C) to start the melting process. The temperature increase curve was found to be linear even when tested for long hourly durations, but it eventually reached a plateau because of the limitation of water ion availability. The current was also found to increase linearly, with larger electrodes exhibiting higher current
values than smaller electrodes. Current is an important parameter in designing an ECON HPS system since it directly impacts the power demand requirements for slab heating that also impacts operational costs.

Temperature increase for all electrodes, similar to the one shown in Figure 2-5b, was found to be linear with respect to the amount of time in the water. Thus, the rates of temperature increase, i.e., the slopes of the plots of temperature versus time, were calculated and compared to determine both the most and least favorable electrodes in terms of rate of temperature increase. Figure 2-9 shows the temperature increase rate for each electrode type obtained from the experimental tests and the FE models. The 38.1 mm OD smooth stainless steel bar achieved the highest temperature increase, about a 0.26°C per minute, while the 12.7 mm OD electrode had the lowest rate among the electrodes tested. It should be noted that the greater heat generated by larger electrode sizes can be attributed to the larger contact area with the water that allows a greater amount of electric current to pass through. Note that in the case of the hollow bars, since the ends were blocked to ensure that contact between electrode and water occurs only on the outer surface of the electrodes, similar heat performance between a 25.4 mm OD hollow electrode with the blocked-end and a 25.4 mm OD solid electrode (same surface area) was observed.

These findings can help in the future design of more efficient heated pavement systems using ECON since hollow bars are less expensive and easier to transport. The results of thermal performance tests also showed that changing the orientation of the same flat bar in the water tank (vertically and horizontally) produced no significant change in the rate of temperature increase. As shown in Figure 2-9, the temperature increase obtained by the FE model follows a similar trend to that of the experimental tests and the theory considered.
ECON Prototype Slab Thermal Performance Results

An ECON prototype slab test with an embedded 25 mm × 5 mm flat bar and an embedded 25.4 mm OD smooth circular bar is shown in Figure 2-10. The left ECON slab represents the flat bar prototype slab, and the right slab represents a prototype slab with a 25.4 mm OD smooth electrode. Figure 2-10a shows the initial condition of the two slabs. Over time, the slab with the 25.4 mm OD smooth electrode exhibited a more rapid temperature increase than the slab with the flat bar (Figure 2-10b, c, and d). Figure 2-11a depicts the average surface temperature over time for the ECON prototype slabs containing the flat bar, 25.4 mm OD smooth electrodes, and other electrodes. The slope of the temperature versus time curve is plotted in Figure 2-11b. The greater the slope, the greater the temperature increase rate associated with a specific electrode. The results show that a 38.1 mm OD smooth electrode provided the highest temperature increase rate among all the electrodes tested, in agreement with the electrode tests in the water, the FE model, and the theory.

The current remained nearly constant during all test periods. Table 2-3 shows the average measured current and the resistivity for each individual ECON prototype slab. Despite
similarities between the water tank and ECON experiments with respect to identifying the best-performing electrode, there were some discrepancies in terms of ranking of the electrodes’ thermal performance. The performance ranking results from slab tests for the flat bar and the 25.4 mm OD solid bar differed from those from the water test. This can be ascribed to the higher resistivity of the ECON in these slabs (see Table 2-3) compared to the other slabs (~40 Ω-cm) due to the nonhomogeneous nature of the ECON. Based on Equation 5 and the literature [45,57], the temperature increase rate (ΔT/Δt) has a linear inverse correlation with resistivity (ρ), meaning, ECON with higher resistivity results in lower temperature increase rate. In other words, higher ECON resistivity will resist input current and result in a lower thermal performance. Consequently, an adjustment to the temperature increase rate was necessary to eliminate the effect of resistivity in electrode thermal performance for these two slabs. The temperature increase rate for the only two slabs with higher resistivities was adjusted by their respective resistivity values to find the equivalent temperature increase rate if the resistivity of the slabs were 40 Ω-cm. For instance, the temperature increase rate for ECON slab with flat bar was multiplied by 118.5/40 ratio where, 118.5 Ω-cm is the current resistivity, and 40 Ω-cm is the desired resistivity.

The temperature increase rate for both water and the ECON prototype slab is plotted against the perimeter of each electrode (Figure 2-12), clearly showing the correlation between the perimeter (electrode surface contact area) with the temperature increase rate. The slope of the perimeter versus temperature increase rate curve was found to be identical for the water and the ECON prototype slab tests. This is an important finding that can help future researchers, supporting the notion that water can be used for testing of thermal performance as an easier, less expensive, and non-destructive test method. The theory also showed that the electrode surface
contact area has a positive linear correlation, a similar result to the experimental and FE model findings in both water and ECON prototype slabs.

Table 2-3 Current and resistivity of ECON prototype slabs.

<table>
<thead>
<tr>
<th>Identification</th>
<th>Embedded electrode</th>
<th>Current (A)</th>
<th>Resistivity (Ω-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECON prototype 1</td>
<td>Flat bar (25.4 mm × 4.7 mm)</td>
<td>4.50</td>
<td>118.5</td>
</tr>
<tr>
<td>ECON prototype 2</td>
<td>19.0 mm OD smooth circular bar</td>
<td>13.36</td>
<td>39.9</td>
</tr>
<tr>
<td>ECON prototype 3</td>
<td>25.4 mm OD smooth circular bar</td>
<td>8.29</td>
<td>64.3</td>
</tr>
<tr>
<td>ECON prototype 4</td>
<td>25.4 mm OD hollow circular bar</td>
<td>13.10</td>
<td>40.7</td>
</tr>
<tr>
<td>ECON prototype 5</td>
<td>38.1 mm OD smooth circular bar</td>
<td>13.76</td>
<td>38.8</td>
</tr>
</tbody>
</table>

Figure 2-10 Thermographic imaging for ECON prototype slabs with embedded flat bar and 25.4 mm OD electrode at (a) initial condition; (b) after 30 minutes; (c) after 90 minutes; (d) after 120 minutes.
Figure 2-11 ECON prototype slab results, including (a) average surface temperature versus time; (b) corrected temperature increase per each minute for different electrodes.

Figure 2-12 Temperature increase rate versus perimeter of each electrode for both water and ECON tests.
Discussion of Practical Implications

Energy Conversion Efficiency

In resistive heating, not all the electrical energy is converted to thermal energy, and the energy conversion efficiency (EF) is the efficiency of converting electrical energy ($E$) into thermal energy ($Q$) and thereby energy conversion efficiency can be calculated using Equation 6.

$$EF \, (\%) = \frac{Q}{E} \times 100 \quad (6)$$

Since both the thermal and electrical performance of the ECON prototype slabs were monitored during this study, both can be calculated. The electrical energy is calculated using Equation 1, and thermal energy is calculated based on the thermal performance curves (Figure 2-11a) and Equation 4. Energy consumption and energy conversion efficiency calculations for all the ECON prototype slabs are given in Table 2-4. Based on these calculations, among the electrodes tested, the 38.1 mm OD bar exhibited the highest energy conversion efficiency, and the 19.0 mm OD bar the lowest. These results show that conversion efficiency is increased by increasing electrode size (electrode surface contact area) in the ECON prototype slab. The average energy conversion efficiency calculated based on this study was found to be 55.4 percent.

Table 2-4 Energy conversion efficiency calculation for ECON prototype slabs.
Cost Analysis

The cost analysis in this section focuses only on the cost of electrodes, one component of ECON HPS, while also considering thermal performance of different electrodes. The bar plots shown in Figure 2-13 of the temperature increase rate were taken from the water (Figure 2-9) and ECON prototype tests (Figure 2-11b) and normalized by the average initial cost of each electrode (Table 2-1). This figure depicts the initial cost-effectiveness of each electrode, considering the temperature increase rate capacity, with a higher value corresponding to greater cost-effectiveness of that electrode. From this cost analysis, the flat bar was found to be the most cost-effective, and the 38.1 mm OD the least cost-effective electrode, with electrode cost-effectiveness decreasing with an increase in electrode size due to the higher cost of the larger-size electrodes relative to the temperature increase rate each can provide. This pattern was found to be similar for both water and ECON prototype slab tests. The average electrode cost of each electrode is also plotted in the secondary vertical axis.

It is essential to note that the speed of ice and snow melting is important, and that while larger diameter electrodes can provide more heat more quickly than smaller electrodes, they may not be as cost-effective, and larger electrodes have also slightly greater energy conversion efficiency. This issue would be more critical in locations such as airports or critical infrastructure requiring faster snow/ice clearing. This means that in choosing an electrode for ECON HPS design, the speed of temperature increase and cost-effectiveness of the electrode type should both be taken into consideration, so it is best when designing ECON HPS for these types of infrastructure systems to continue using the most cost-effective electrode but at a higher voltage to achieve faster snow and ice melting.
Figure 2-13 Temperature increase rate per average initial cost of different electrodes

**Conclusions and Recommendations**

The purpose of this study was to theoretically and experimentally assess the operational performance of different electrode shapes and sizes on the performance of electrically conductive concrete (ECON) heated pavement system (HPS) and to evaluate the feasibility of a non-destructive test method for this assessment. Several varieties of electrodes were tested in water and ECON prototype slabs, and a finite element (FE) model was developed. The electrical and thermal performance due to resistive heating was evaluated by measuring the average surface temperature increase rate under fixed experimental conditions, i.e., identical slab geometry, applied voltage, electrode spacing, and fixed test ambient temperature. Both energy conversion efficiency and cost analysis were developed to help determine the most energy and cost-effective electrode. The key findings drawn from this effort can be summarized as follows:
Based on the theory, the experimental study, and the FE model, the temperature increase rate of an electrode is influenced by its surface contact area (perimeter).

Testing electrodes in water for monitoring temperature increase rate is a faster, repeatable, non-destructive, and cost-effective method for identifying favorable electrode sizes and comparing electrode performance for use to describe an ECON-heated pavement system.

A theoretical formulation was developed to describe ECON HPS thermal behavior.

Considering initial costs of the electrodes, flat-bar and smaller-diameter electrodes were found to be more cost-effective than the larger electrodes due to the lower cost of smaller-sized electrodes relative to the temperature increase rate associated with them.

An increase in electrode size resulted in an increase in energy conversion efficiency.

The slope of the temperature increase rate versus perimeter curve for different electrodes was found to be identical in both water and ECON prototype slab tests.

Both surface temperature and current linearly increased with respect to time both in water and ECON HPS.

Flat bar orientation (vertical vs. horizontal) did not significantly change the thermal performance of the electrodes in water tests.

The findings of this study should facilitate design and implementation of ECON HPS in future full-scale demonstration projects. The cost analysis in this study focuses only on the cost of electrodes, one component of ECON HPS, taking into account the thermal performance of different electrodes. A future study, based on measurements of full-scale test sections at Iowa
DOT headquarters will conduct a thorough economic analysis for different electrode design configurations.

References


[52] Malakooti A. Investigation of Concrete Electrical Resistivity As a Performance Based Test. Utah State University, 2017.


CHAPTER 3. SYSTEM DESIGN IMPROVEMENTS OF HEATED PAVEMENTS: RECOMMENDATIONS FOR FUTURE PROJECTS

Amir Malakooti\textsuperscript{1}, Sajed Sadati\textsuperscript{2}, Halil Ceylan\textsuperscript{3}, and Sunghwan Kim\textsuperscript{4}

\textsuperscript{1}: Ph.D. Student, Iowa State University, Ames, IA
\textsuperscript{2}: Postdoctoral Research Associate, Iowa State University, Ames, IA
\textsuperscript{3}: Professor of CCEE, Iowa State University, Ames, IA
\textsuperscript{4}: Research Scientist, Institute for Transportation, Iowa State University, Ames, IA

Modified from a manuscript published in \textit{Proceedings of the 12th International Conference on Concrete Pavements (ICCP)}

Abstract

Many agencies allocate a great deal of resources to clearing infrastructure systems (e.g., roads, bridges, and airports) from ice and snow during winter seasons using traditional snow-removal equipment and application of salt or de-icing chemicals. Using an electrically-conductive concrete (ECON) heated pavement system (HPS) is a cost-effective and environmentally friendly approach to melting ice and snow. ECON is a carbon-fiber-reinforced form of concrete that uses carbon fiber (conductive agent) with low median electrical resistivity to conduct electrical current through the concrete ECON layer through embedded stainless-steel electrodes. The inherent electrical resistance in the concrete generates heat used in the ECON HPS to melt ice and snow on the surface. ECON HPS construction is different from regular concrete construction in using two-lift paving, two different concrete mixes, and embedded stainless-steel electrodes with electrical connections to a power supply. An ECON HPS demonstration project has recently been constructed at the south parking lot of the Iowa Department of Transportation in Ames, Iowa. This project consists of 10 instrumented slabs, and this paper is focused on the ideas for improvement and lessons learned emerged from the full-
scale demonstration project with respect to the construction methods the ECON mix design, control system design, electrode, cross slope design, and instrumentation of the concrete pavement system. These improvements in the construction of this unique concrete pavement system are expected to increase future paving quality, ECON HPS performance, and significantly decrease construction time and cost of such systems.

**Introduction**

A considerable part of the annual budget of each transportation agency is devoted to winter maintenance (1). The current state of practice in tackling winter maintenance is to use snow removal equipment combined with salt and deicing chemicals (conventional method). Since this method is labor-intensive, time-consuming, and creates environmental hazards from carbon dioxide emission from the machinery and water and soil contamination from the use of deicing chemicals (2), heated pavement technologies for wholly or partially replacing conventional winter maintenance operation have gained attention (3). There are several alternatives and innovative heated-pavement approaches, including hydronic heated-pavement systems (4, 5), phase-change materials (6), electrically-conductive asphalt concrete (ECAC) (7, 8), and electrically-conductive concrete-heated pavement systems (ECON HPS)(9).

A hydronic heated pavement uses heated ethylene glycol, a toxic and environmentally harmful material, circulating within pipes buried beneath the pavement (2). The other primary disadvantage of hydronic heated pavements is that they require space for a boiler and a pumping system, and it is also challenging to diagnose and rehabilitate such a system when leakage from the embedded pipes occurs (2). Phase-change material technology uses the heat of fusion produced during phase transformation to melt ice and snow, but this technology has been found to produce an adverse effect on the concrete’s dynamic elastic modulus and compressive strength when introduced into the mix, and is not applicable in harsh environments (6). While ECAC has
produced promising results during the laboratory phase, further investigations are needed before entering into future field implementation (8).

ECON HPS uses electrical current and the inherent resistance of the concrete to generate heat and melt surface ice and snow. The concrete used in ECON is carbon-fiber reinforced concrete, with the carbon fiber significantly decreasing the electrical resistivity in the concrete, allowing it to conduct sufficient current to produce the desired heating effect. The typical electrical resistivity of ECON is between 50 to 3000 Ω-cm compared to the normal concrete value of between $6.54 \times 10^5$ and $11.4 \times 10^5$ Ω-cm ($10^{-14}$). Current is supplied to the ECON through embedded stainless-steel electrodes with chosen spacing connected to a power source ($15, 16$). ECON HPS can be implemented using either a two-lift new construction or as an overlay on top of an existing pavement in good condition. In the two-lift approach, the bottom lift is regular PCC designed based on a specified traffic load pavement with the top lift (ECON layer) design based on the environmental conditions ($17–19$).

ECON HPS is an environmentally-friendly, cost-effective, and remotely-operated heated pavement technology ($20$) with the potential to eliminate the use of salt and deicing chemicals, potentially increasing pavement service life and decreasing preservation and rehabilitation costs. Use of this technology is also consistent with on-going efforts related to the electrification of processes in agencies to convert to low-emission technologies ($21$). While this technology can be operated remotely and requires few human resources for its operation, its most important advantage is that it provides a reliable, accessible, and safe pavement during snow and ice events.
Research Significance

This study focuses on the two full-scale field implementations of ECON HPS at the Des Moines International Airport (9) and the Iowa Department of Transportation headquarters and presents insights related to construction system design improvements and future recommendations for its future field implementation. The project at the DSM Airport is the first construction of ECON HPS in an airport environment in the US, and the Iowa DOT project is the largest operational ECON HPS. The construction steps used for this type of concrete pavement differ from those of regular concrete pavement because it requires two-lift paving with two different mix designs, design of the electrode configuration, electrical wiring, and design of the control system.

ECON HPS Improvements

This paper compares and contrasts two ECON HPS slabs constructed, one at the general aviation area at the Des Moines International Airport (DSM Airport), the other at the south parking lot entrance of the Iowa Department of Transportation (Iowa DOT) in Ames, Iowa. Table 3-1 shows the slabs dimensions, thicknesses, and construction time. The Iowa DOT construction was five times larger than the DSM airport project, and this led to construction difficulties that will be explained in this report.

Table 3-1 DSM Airport and Iowa DOT concrete pavement system information

<table>
<thead>
<tr>
<th>Items</th>
<th>DSM Airport</th>
<th>Iowa DOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab dimensions</td>
<td>3.8 m × 4.6 m</td>
<td>3.6 m × 4.6 m</td>
</tr>
<tr>
<td>Number of slabs</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>ECON thickness</td>
<td>8.9 cm</td>
<td>7.6 cm</td>
</tr>
<tr>
<td>PCC thickness</td>
<td>10.1 cm</td>
<td>17.8 cm</td>
</tr>
<tr>
<td>Electrode type</td>
<td>Angle</td>
<td>Circular and flat bar</td>
</tr>
<tr>
<td>Electrode spacing</td>
<td>91.4 cm</td>
<td>50.8, 64.8, and 91.4 cm</td>
</tr>
<tr>
<td>Construction time</td>
<td>November 2016</td>
<td>October 2018</td>
</tr>
</tbody>
</table>
ECON Mix Design

The ECON mix design was similar to regular PCC mix design with carbon fiber added as a conductive agent. Table 3-2 gives a side-by-side comparison of the DSM Airport and Iowa DOT ECON mix proportions. The water to cementitious materials ratio for both mixes was set to 0.42, and aggregate gradation and proportion were similar for both mixes. The research team encountered loss of workability (flash set) during construction at the DSM airport because of both the long distance from the concrete plant to the construction site and incompatibility between some of the admixtures used. It was therefore decided to use 20 percent fly-ash type C replacement by weight for the Iowa DOT project and to eliminate Methylcellulose and DCI admixtures from the ECON mix to solve the flash set problem, resulting in an ECON slump of 10 cm. The carbon fiber content also increased from 1 percent to 1.25 percent because of the elimination of fiber-dispersive agent (Methylcellulose), reducing the risks of poor carbon fiber dispersion within the mix and insufficient carbon fiber at every location. This elimination also helped simplify the ECON mix design and make it easier to reproduce at any ready-mix concrete plant.

Table 3-2 ECON mix proportions for DSM Airport and Iowa DOT projects

<table>
<thead>
<tr>
<th>Components</th>
<th>Type</th>
<th>DSM Airport (Kg/m³)</th>
<th>Iowa DOT (Kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic</td>
<td>Coarse aggregate</td>
<td>1.9 cm concrete stone</td>
<td>594</td>
</tr>
<tr>
<td></td>
<td>Intermediate aggregate</td>
<td>0.95 cm chips</td>
<td>296</td>
</tr>
<tr>
<td></td>
<td>Fine aggregate</td>
<td>Concrete sand</td>
<td>673</td>
</tr>
<tr>
<td></td>
<td>Cement</td>
<td>Holcim type I/II</td>
<td>475</td>
</tr>
<tr>
<td></td>
<td>Fly ash</td>
<td>Type C</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>Potable water</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Carbon fiber, 0.64 cm</td>
<td>Synthetic carbon fiber</td>
<td>1.00 (% Vol.)</td>
</tr>
<tr>
<td>Admixtures</td>
<td>Air entrainment</td>
<td>EUCON AEA-92</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Water reducer</td>
<td>EUCON WR 91</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Methylcellulose</td>
<td>Fiber dispersive agent</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>DCI admixture</td>
<td>Corrosion inhibitor and conductivity agent</td>
<td>25</td>
</tr>
</tbody>
</table>
Voltage Selection

The applied voltage is directly correlated with snow/ice melting speed and power consumption of ECON HPS, i.e., the higher the voltage, the faster the snow melting and the higher the power consumed. While the DSM Airport project can only operate at 208 VAC, the Iowa DOT project can be operated using either 120 or 208 VAC. This flexibility of using two different voltages provides a capability for the ability to adjust the speed of melting to meet specific needs. For example, snow events started during busy weekdays can use, 208 VAC, while snow precipitating during a weekend can be managed using 120 VAC.

Control System Design

The ECON HPS control system turns the system on and off using electrical switches. Arduino board microcontrollers used in the DSM Airport project, which is cheap and easy-to-program control system. Conversely, the disadvantage of the Arduino controller was that it required connection to a computer to control turning it on and off using its software, and it was also not capable of automatic system turn on/off based on pavement surface temperature to save energy. Therefore, the programmable logic controller (PLC) was chosen as the standard control system for the Iowa DOT project, because it did not require an additional user laptop since it had onboard memory, CPU, and communication modules connected to the internet, allowing remote control. The expandable PLC system gave the user the flexibility in adding more modules and more slab control without additional cost.

A PLC also provides the capability for monitoring and controlling slab surface temperature using relays (switches) and different voltages (120 and 208 VAC) to affect the speed of snow and ice melting on the surface. A recommendation for future ECON HPS control system design for ECON HPS projects would be to embed thermocouples within the ECON slabs and connect them to PLC analog temperature input modules, enabling the control system to
continually monitor the temperature within the slabs ($T_{slab}$). When the ambient temperature drops, $T_{slab}$ will decrease as well, and once this temperature has dropped below a pre-determined temperature ($T_{sys\_on}$) the control system will signal the relays to connect the ECON HPS to a 120 VAC power source, turning the system on and generating heat. If the temperature continues to drop below a specified threshold temperature ($T_{thres}$), the system will automatically switch to 208 VAC instead to generate more heat for efficiently melting the snow and ice on top of the slabs, thereby maintaining a surface temperature that discourages snow or ice buildup. After the ambient temperature has risen back above the freezing point or $T_{sys\_on}$, the system will turn off to save energy and eliminate overheating. Figure 3-1 is the flowchart of the procedures used by the control system. In summary, the system will use higher voltage (208 Volts) if the weather condition is harsh and uses lower voltage (120 Volts) to maintain its temperature.

Figure 3-1 Flow chart control system determines which voltage to use
Electrode Design

As shown in Table 3-1, the DSM Airport project was constructed only with stainless-steel angle electrodes with fixed spacing, while the Iowa DOT project used three different types of stainless-steel electrodes and spacings. Since the sharp edges of the angle electrodes produce Angle electrode due to stress concentration, creating a potential for cracking during the service life of the pavement, the research team decided to reinforce the DSM structure with perpendicular fiberglass bars to eliminate this cracking potential (see Figure 3-2a). However, since only circular and flat bar electrode shapes were chosen for the Iowa DOT project, their shape eliminated premature cracking and eliminated the need for fiberglass reinforcement during construction to save cost and time (see Figure 3-2b).

Figure 3-2 Electrodes: (a) DSM airport electrodes perpendicularly reinforced with fiberglass bar, (b) Iowa DOT electrodes without fiberglass bar reinforcement
**Sensor Selection**

Sensor instrumentation for monitoring or controlling pavement surface temperature to not prevent system overheating is a part of the construction of any ECON HPS. The presence of carbon fiber makes ECON act as a semiconductor that can conduct significant current between its electrodes (cathode and anode), and sensors can measure the current passing through the ECON. For example, since, most sensors for measuring temperature (e.g., thermocouples) use two conductors that produce a temperature-dependent voltage to be measured and correlated with temperature, thermocouples or other sensors that use electrical readings must be protected by an insulation of both the measuring tip and the cable. The cable must also withstand the ECON operational temperature that can range from -30°F to 50°F and be protected for temperature-related measurements. The research team tested the Arduino temperature sensor at the DSM Airport project and found out that some of them ceased to measure temperature while the ECON HPS was operating and resumed measurement when the system stopped operating. Consequently, the research team decided to use Campbell Scientific thermocouple (type E) for the Iowa DOT; they are electrically-insulated and can operate in ECON operational temperatures at both the measuring tip and in the cable, allowing continuous temperature measurement even when the system was turned on. In summary, it is was found best to first test different types of sensors in a small ECON slab prior to use in field construction.

**Cross slope Design**

The cross slope for allowing water to run off the road surface is a geometrically necessary feature of each pavement. If the cross slope is insufficient, the water will stay on top of the heated section and potentially freeze after the system is not operational, so this feature is essential for designing ECON HPS technology. It becomes even more important when some part of the area is heated while other parts are not. In that scenario, the designer should design a
heated pass for the water to a drainage outlet point so that water resulting from snow/ice melting does not refreeze. During the performance evaluation of the two slabs at DSM Airport, the research team encountered ice accumulation between the heated slab and the regular slab, so special attention was given at the Iowa DOT project to allow water to drain faster from the heated sections.

**Performance Comparison**

The performance of the DSM International Airport and Iowa DOT ECON HPS were monitored every winter season after their construction and both of the systems were capable to provide snow and ice-free surface. Figure 3-3 shows the performance of both systems during a snow event. It was found that the best practice to operate ECON HPS is to turn the system in advance so that the slabs would be warm enough to melt the snow and ice precipitation right away. This would lead to shorter operation time and consequently the cost of operation. Furthermore, this approach will lead to maintaining the serviceability of the road from the beginning of a snow event. Abdualla et al. and Malakooti et al. analyzed the performance of DSM Airport and Iowa DOT (9, 15). It was found that the average power density for DSM airport and Iowa DOT slabs were 360 and 270 W/m² respectively. It is worth reminding that DSM airport and Iowa DOT project operate with 240 and 120 VAC respectively.
Electrically-conductive concrete (ECON) heated pavement systems (HPS) represent a promising alternative to conventional snow removal operations. ECON HPS provides a safe, accessible, environmentally-friendly, and cost-effective platform for use by appropriate agencies during winter seasons. This study, comparing an ECON HPS construction at DSM International Airport (October 2016) with another at the south parking lot of the Iowa Department of Transportation in Ames, Iowa (November 2018), shed light with respect to construction.

Figure 3-3 ECON HPS performance: (a) Iowa DOT ECON HPS snow melting on 02/11/2019 with 5 cm snow event, (b) Infrared thermography of slabs performance at Iowa DOT, (c) DSM International Airport ECON HPS snow melting on 01/24/2017 with 4 cm snow event, (d) Infrared thermography of slab performance at DSM International Airport
improvements and potential recommendations for future implementation of this technology. The findings of this study are:

- Twenty-percent fly ash type C replacement and removal of Methylcellulose and DCI admixtures helped improve the slump to 10 cm during the Iowa DOT project ECON placement.

- If sensors are to be incorporated into the ECON HPS system design, their tips and cables of the sensor must be electrically insulated and thermally operational.

- Programmable logic controller (PLC) exhibited better control flexibility than Arduino board microcontrollers in terms of autonomous control, expandability, and control capability.

- Using multiple voltages with the PLC control device gave ECON HPS users control over snow and ice melting speed.

- Premature cracking due to use of an angle-shaped electrode can be eliminated by incorporating circular and flat bar electrode shapes.

- The paths followed by water produced as the resulted of melting ice and snow from the heated slabs to drainage outlet must be heated to eliminate any ice formation near the heated slabs.

- The best operation practice of heated pavements is to turn the system on before the snow event starts. Therefore, the snow accumulation will not occur and the operation time and consequently the operation cost will decrease.
References


CHAPTER 4. DESIGN AND FULL-SCALE IMPLEMENTATION OF THE LARGEST OPERATIONAL ELECTRICALLY CONDUCTIVE CONCRETE HEATED PAVEMENT SYSTEM

Amir Malakooti¹, Wei Shen Theh², Sajed Sadati³, Halil Ceylan⁴, Sunghwan Kim⁵, Mani Mina⁶

Kristen Cetin⁷, Peter C. Taylor⁸

¹: Ph.D. Student, CCEE, Iowa State University, Ames, IA
²: Ph.D. Student, ECpE, Iowa State University, Ames, IA
³: Ph.D. Candidate, CCEE, Iowa State University, Ames, IA
⁴: Professor of CCEE, Iowa State University, Ames, IA
⁵: Research Scientist, Institute for Transportation, Iowa State University, Ames, IA
⁶: Associate Professor of ECpE, Iowa State University, Ames, IA
⁷: Assistant Professor of Civil & Environmental Engineering, Michigan State University, East Lansing, MI
⁸: Director of National Concrete Pavement Technology Center, Iowa State University, Ames, IA

Modified from a manuscript published in Construction and Building Materials

Abstract

Many aviation and transportation agencies allocate significant time and resources each year to remove ice and snow from their paved surfaces to achieve a safe, accessible, and operational transportation network. An electrically conductive concrete (ECON) heated pavement system (HPS) has been shown to be a promising alternative to the conventional snow removal operations using snowplows and deicing chemicals, which is time-consuming, labor-intensive and environmentally unfriendly. ECON HPS utilizes the inherent electrical resistance of concrete to maintain the pavement surface above freezing and thus prevent snow and ice
accumulation on the surface. This sustainable concrete pavement system improves the resiliency of infrastructure by allowing it to be safe, open, and accessible during even harsh winter storms. The purpose of this study was to demonstrate the full-scale implementation of 10 ECON HPS slabs at the Iowa Department of Transportation headquarter south parking lot in Ames, Iowa. This study consists of system design and control, field implementation, and sensor instrumentation procedures for the construction of the ECON system, which took place on October 2018. A programmable logic controller (PLC) was designed, programmed, and utilized to control, operate, and monitor the system remotely. The heating performance of the remotely-operated ECON slabs was evaluated using the instrumented sensors under snow and ice events in 2019. The performance evaluation showed promising results in providing snow, and ice-free pavement surfaces through several winter weather events.

**Introduction**

Removal of snow and ice is an inescapable activity for transportation infrastructure owners in cold climates, to ensure safe and accessible transportation systems. To enhance the capability and resiliency of transportation systems to overcome the challenges that arise during snow events, an electrically conductive concrete (ECON) heated pavement system (HPS) has been developed (1–4). This is a special type of heated pavement system (5–8) that includes a top concrete layer made by adding electrically conductive material, such as carbon fibers (9–11) and steel shavings (3) to the concrete mixture (12). These systems not only enhance the accessibility of transportation infrastructure but also prevent the excessive need for chemicals and fossil fuel-based vehicles for snow and ice removal. Moreover, ECON HPS is an electricity-based system, and its utilization can help with the ongoing efforts for electrification of processes at airports (13), which are more environmentally friendly and can reduce water and air pollution at airports (2, 14).
Weather conditions impact the performance of ECON HPS; therefore, each specific region needs a particular design for ensuring the best performance of the system (2). The design parameters for ECON HPS include the thickness of the regular and conductive concrete layers, joint spacing, electrode spacing, and electrode size and shape. Among these parameters, electrode spacing and electrode size and shape are the ones that are unique to the ECON HPS design and are not required for conventional rigid pavement systems. Therefore, the motivation for this study was to investigate the impact of these two parameters on the thermal and energy performance of ECON HPS through a field experimental study. Previous experimental studies on ECON HPS have only focused on investigating the construction and performance, assuming only one design configuration (3, 15).

Abdualla, et al. (15), designed ECON HPS test slabs for the general aviation section of Des Moines International Airport (DSM) in Iowa. The ECON was made by adding carbon fibers to the concrete mix, and the design included angled stainless-steel electrodes at a spacing of 91 cm (3 ft). Abdualla found that ECON HPS has the potential to reduce temperature gradient within the pavement thicknesses and consequently reduce the curling stresses (16). Tuan (3) designed and tested an ECON HPS with vertically positioned steel plates as electrodes having a spacing of 122 cm (4 ft). The ECON material was made by adding steel shavings to the concrete mix, and this setup was tested on a bridge deck in Lincoln, Nebraska, which is out of service since 2009. Use of steel shavings as the conductive material for ECON is not recommended for transportation infrastructure since the steel shavings can potentially corrode and also cause damage to the vehicle tires and aircraft engines by creating foreign object debris (1). There are a few other studies on the performance of ECON HPS through numerical models developed using the results of experimental studies (2, 17–19). Only one study previously published with ECON
HPS has focused on the performance of this system with various electrode design configurations, which was based on only numerical study and not full-scale experimental study in different real weather condition (18).

The objective of the current study was to construct and demonstrate a full-scale implementation procedure of the largest operational ECON HPS with different electrode configurations. Ten full-scale slabs were constructed at the south parking lot entrance of the Iowa Department of Transportation Headquarter (Iowa DOT) in Ames, Iowa as part of a reconstruction project. These slabs have various configurations of electrodes with different spacing, sizes, and shapes (configuration) in order to evaluate their effect on the energy and thermal performance of the ECON HPS. Other than the 10 ECON HPS slabs, the test setup included two regular concrete slabs as the control sections to compare the structural performance of the ECON HPS to regular rigid pavement systems for future studies. The remainder of this paper provides the implementation overview, description of the materials, instrumentation and installation methods, construction procedures, and slabs performance evaluation during different snow events.

**Full-Scale ECON HPS Implementation Overview**

The test site was located at the south parking lot entrance of Iowa DOT in Ames, Iowa (Figure 4-1(a)). As part of the reconstruction project, 10 slabs, 4.6 m (15 ft.) long and 3.6 m (12 ft.) wide, were dedicated to the ECON HPS implementation. The slabs close to the south entrance were chosen as the heated pavement test site specifically because it was located in a high and heavy volume of traffic section.

**Key Components of ECON HPS Technology**

The key components of ECON HPS technology include an ECON layer (heating element), electrodes, temperature sensors, electrical wiring, polyvinyl chloride (PVC) conduits,
control system, and power supply. This technology can be either constructed as an overlay on top of an existing pavement system if the pavement is in good condition, or as a top layer of a two-lift paving for a new construction. Two-lift paving can be used to reduce construction material costs by reducing the ECON layer thickness since it is necessary to heat only the surface of pavement where the snow and ice accumulation occurs. Temperature sensors are installed to give the control system the ability to monitor the pavement surface temperature and set surface temperature to above-freezing temperature (5°C/41°F). This helps to reduce the possibility of overheating and to reduce energy consumption by not continuously operating the system when the surface temperatures are sufficiently warm. The energy consumption due to the thermal performance of ECON HPS can be monitored with wireless voltage and current sensors remotely.

**ECON HPS System Design**

The ECON system design consists of procedures to determine the required layer thicknesses for structural adequacy, electrode configuration based on the environmental conditions, and power demand estimation. The layer thicknesses for the Iowa DOT ECON HPS project were designed based on heavy traffic volume. Figure 4-1(b) is the plan view of the construction site, which shows the 10 slabs, location of conduits, shed, and power supply. All the electrical wiring from the electrodes to the power supply and the sensor wiring in each test section went through trenches to the shed. The control system and the data acquisition system were placed in the shed. Figure 4-1(c) illustrates the cross-sectional view of different structural layers, which include 22.9 cm (9 in.) special backfill base layer, 17.8 cm (7 in.) C-3WR-C20 regular portland cement concrete (PCC) layer specified in Iowa DOT standard specification, which is explained in detail in section 3.1 (20), and a 7.6 cm (3 in.) ECON layer. The electrodes were placed on top of the PCC layer, ensuring a 5 cm (2 in.) concrete cover on top of the
electrodes. Special backfill materials that were used for the base layer consisted of crushed stone, crushed PCC, and crushed composite pavement aggregates according to Iowa DOT specification (20).

Figure 4-1 ECON HPS construction location and design plans: (a) construction location, (b) plan view, and (c) cross-section view.
The 10 constructed ECON slabs each have different electrode configurations. This was designed to monitor the performance of different electrode configurations in a real pavement and environmental conditions. The electrode configuration for each test section is tabulated in Table 4-1. Circular solid bar [1.9 cm (0.75 in.) or 2.5 cm (1.0 in.)], circular hollow bar [2.5 cm (1 in.) OD with 0.3 cm (1/8 in.) wall thickness], and flat bar [2.5 cm (1 in.) × 0.4 cm (3/16 in.)] were chosen for field implementation based on laboratory investigations conducted before the construction (21). Four slabs were designed with ten electrodes [50.8 cm (20.0 in.) spacing], four slabs with eight electrodes [64.8 cm (25.5 in.) spacing] and two slabs with six electrodes [91.4 cm (36.0 in.) spacing].

Each test section was given a section ID where the first number represents the number of electrodes in the test section (6, 8, or 10), following by a letter representing the type of electrode (S, H, or F), and it ends with a number indicating the size of the electrode in inches that has been used (0.75 or 1.0). As an example, a slab with an ID number of 10S-0.75 has 10 smooth circular bars with 1.9 cm (0.75 in.) outer diameter. The location of each constructed slab can be seen in Figure 4-1 (b).

Table 4-1 Electrode configuration in each slab.

<table>
<thead>
<tr>
<th>Test section</th>
<th>Section ID</th>
<th>No. of electrodes (spacing)</th>
<th>Size of electrodes, cm (in.)</th>
<th>Electrode type &amp; shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test section 1</td>
<td>10S-0.75</td>
<td>10 (50.8 cm/20.0 in.)</td>
<td>1.9 (0.75)</td>
<td>Smooth circular bar</td>
</tr>
<tr>
<td>Test section 2</td>
<td>10S-1.0</td>
<td>10 (50.8 cm/20.0 in.)</td>
<td>2.5 (1.00)</td>
<td>Smooth circular bar</td>
</tr>
<tr>
<td>Test section 3</td>
<td>10F-1.0</td>
<td>10 (50.8 cm/20.0 in.)</td>
<td>2.5 (1.00)</td>
<td>Flat bar</td>
</tr>
<tr>
<td>Test section 4</td>
<td>10H-1.0</td>
<td>10 (50.8 cm/20.0 in.)</td>
<td>2.5 (1.00)</td>
<td>Hollow circular bar</td>
</tr>
<tr>
<td>Test section 5</td>
<td>6S-0.75</td>
<td>8 (64.8 cm/25.5 in.)</td>
<td>1.9 (0.75)</td>
<td>Smooth circular bar</td>
</tr>
<tr>
<td>Test section 6</td>
<td>8S-0.75</td>
<td>8 (64.8 cm/25.5 in.)</td>
<td>1.9 (0.75)</td>
<td>Smooth circular bar</td>
</tr>
<tr>
<td>Test section 7</td>
<td>8S-1.0</td>
<td>8 (64.8 cm/25.5 in.)</td>
<td>2.5 (1.00)</td>
<td>Smooth circular bar</td>
</tr>
<tr>
<td>Test section 8</td>
<td>8F-1.0</td>
<td>8 (64.8 cm/25.5 in.)</td>
<td>2.5 (1.00)</td>
<td>Flat bar</td>
</tr>
<tr>
<td>Test section 9</td>
<td>8H-1.0</td>
<td>6 (91.4 cm/36.0 in.)</td>
<td>2.5 (1.00)</td>
<td>Hollow circular bar</td>
</tr>
<tr>
<td>Test section 10</td>
<td>6S-1.0</td>
<td>6 (91.4 cm/36.0 in.)</td>
<td>2.5 (1.00)</td>
<td>Smooth circular bar</td>
</tr>
</tbody>
</table>
Description of Materials

ECON and PCC layer Mix Design

The ECON mix design was developed based on numerous trial batches in the lab (21) and prior full-scale demonstration experience at DSM International Airport in 2016 (22). First, the research team obtained samples from aggregate, cement, fly ash, and all the admixtures from the concrete plant. Second, numerous trial batches were made in the lab in order to attain a balanced ECON mix design to meet workability and mechanical property requirements in accordance to Iowa DOT specifications as well as ensuring good electrical conductivity. Third, the concrete supplier was asked to batch three cubic yards of the ECON mix design from the laboratory phase for laboratory testing. This step was taken as a precaution step before construction to ensure that the mixture from the batch plant was consistent with the construction specifications. It was found in the trial batch that the ECON was highly workable, but on the other hand, its electrical resistivity was high. Therefore, adjustments were made to the carbon fiber content and the admixture dosages to reduce the workability and resistivity. It was also found during the laboratory phase that (1) adding carbon fibers withholding moisture reduces the fiber loss during ECON production and (2) mixing fibers with aggregate before the presence of cementitious materials helped with achieving a better, more uniform fiber dispersion. Therefore, these suggestions were incorporated into the construction phase.

The finalized ECON mix design is shown in Table 4-2. The mixture contained 1.25% carbon fiber by volume, and 20% fly ash replacement. The significant differences between this mixture and its predecessors (22) were first introducing 20% fly ash to the mix to increase workability and durability. Second, the elimination of methylcellulose fiber dispersion agent and corrosion inhibitor admixtures in order to decrease the possibility of incompatibility between the admixtures. In addition, the carbon fiber content was increased from 1 percent to 1.25 percent by
volume to account for any potential carbon fiber losses that may take place during batching and placing. The regular PCC layer (bottom layer) mix design was C-3WR-C20, and it is composed of 45% fine and 55% coarse aggregate with 20% type C fly ash. It is worth mentioning that the typical electrical resistivity of a regular concrete is about $9 \times 10^5 \, \Omega \cdot \text{cm}$ (23–26), while achieved electrical resistivity for ECON was 1300 $\Omega \cdot \text{cm}$ due to the addition of 1.25% carbon fiber into the mixture.

Table 4-2 ECON mix proportions for field implementation.

<table>
<thead>
<tr>
<th>Components</th>
<th>Type</th>
<th>Content Kg/m$^3$ (lb./yd$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic</td>
<td>Coarse aggregate 1.9 cm (3/4 in.) limestone</td>
<td>585.0 (986.1)</td>
</tr>
<tr>
<td>Intermediate aggregate</td>
<td>0.9 cm (3/8 in.) chips</td>
<td>301.5 (508.2)</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>Concrete river sand</td>
<td>640.3 (1,079.2)</td>
</tr>
<tr>
<td>Cement</td>
<td>Holcim type I/II</td>
<td>375.4 (632.7)</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>Type C</td>
<td>96.4 (162.5)</td>
</tr>
<tr>
<td>Water</td>
<td>Potable water</td>
<td>199.9 (336.9)</td>
</tr>
<tr>
<td>Carbon fiber, 0.63 cm (0.25 in.)</td>
<td>in length</td>
<td>1.25 (% Vol.)</td>
</tr>
<tr>
<td>Admixtures</td>
<td>Air Entrainment EUCON AEA-92</td>
<td>0.9 l/m$^3$ (3.0 oz./cwt)</td>
</tr>
<tr>
<td>Water Reducer</td>
<td>EUCON WR 91</td>
<td>2.3 l/m$^3$ (7.5 oz./cwt)</td>
</tr>
</tbody>
</table>

**Electrodes**

Electrodes in ECON HPS have the role of applying the electricity to ECON layer due to their high electrical conductivity properties. All the electrodes were chosen 316L grade stainless steel, which has promising resistance to corrosion. Therefore, the electrodes would stand degradation and cracking, which will lead to system efficiency reduction and electrode debonding from ECON. Circular and flat bar electrode geometries were chosen rather than angled electrodes, which have been used in the predecessor projects (1) to minimize stress concentrations and thus reduce cracking potential. In addition, the chosen electrode geometries also eliminated using fiberglass bars perpendicular to the electrodes, which have been used in other projects (1) to minimize the possible cracking. All the electrodes were anchored to the PCC
layer to secure them and minimize their movements during the pavement construction. The wires which were used to connect the electrodes to the power supply were specially selected for 208 Volts AC (VAC), 600 A usage. The wires were also designed for use in a rough environment, such as a construction project, and had a special insulation layer.

**Sensors and Data Acquisition System**

Both wired and wireless sensors were utilized in the demonstration project. 130 Campbell Scientific Thermocouple (type E), 40 Geokon strain gauges, 10 wireless Monnit voltage sensors, and 10 wireless Monnit current sensors were installed. Thermocouples and strain gauges were embedded within the slabs in both the ECON and PCC layer. Voltage and current wireless sensors were installed in the power distribution box within the shed to monitor the electrical consumption of each test section.

All the sensors were tested in the lab prior to the field installation. In order to gather all the data, two Campbell Scientific CR6 data loggers and five Campbell Scientific AM16/32B Multiplexers were installed in the shed. The Monnit voltage and current sensors transmit the readings to a gateway before being transferred to a cloud-based real-time monitoring system. All other sensors were connected to a laptop in the shed which can be accessed remotely through a wireless hotspot provided in the shed. Therefore, system operation tasks including turning the slabs on/off, data collection, and real-time monitoring can be easily conducted remotely.

**Control System**

The research team had selected a robust control system for this project. Programmable Logic Controller (PLC) is an industrial standard control system. The PLC is a modular system comprising of a CPU unit, analog temperature input module, digital output module, and relays. In addition, the modular design will allow expansion if the research team deems necessary in the future. One embedded thermocouple sensor in the center of each slab, 1.3 cm (0.5 in.) from the
pavement surface, was linked to the PLC system. This enables the control system to monitor the pavement surface temperature. Once pavement surface temperature drops below a pre-determined temperature (5°C/41°F), the control system activates the 120/208 VAC power source using the relays to generate heat within the ECON layer. The ECON system can melt ice and snow much quicker in 208 VAC compare to 120 VAC and can be used in times when the winter weather conditions are particularly harsh (e.g. snow/ice storms during a polar vortex) and the road serviceability needs to be maintained continuously under such harsh conditions.

**Instrumentation and Installation Methods**

The instrumentation plan for EOCN HPS consists of steps that were taken for installing electrodes, sensors, data acquisition system, and a power supply system. These steps have been developed based on extensive previous experiences during both field and laboratory experiments. Figure 4-2 depicts the installation procedures for different components during the construction phase.

**Installation of Electrodes**

The location of each stainless-steel electrode was marked on each slab, and the electrodes were fixed using steel straps, as shown in Figure 4-2(a). A drill was used to make the holes and secure the straps to the PCC layer. After anchoring the electrodes, all the electrodes were connected to electric wires using gauge-ring wire connectors for flat bars and hose clamps for circular bars (see Figure 4-2(b)).
Figure 4-2 Electrode and sensor wiring and instrumentation: (a) anchorage of electrode to the PCC layer, (b) electrode electrical wiring, (c) thermocouple sensor tree installation, (d) thermocouple sensor placement, (e) strain gauge installation, and (f) electrical and sensor wiring in the shed.
**Sensors Instrumentation Plan**

Sensor instrumentation locations were chosen based on the critical response locations within a slab with regards to the temperature and strain variations. The temperature trees were mounted on a 0.6 cm (¼ in.) fiberglass bar in order to eliminate temperature and electricity gradients in different layers. A hole was first drilled in the PCC layer at the center of each slab (see Figure 4-2(c)), and the temperature trees were installed inside and secured with cement grout (see Figure 4-2(d)). Each temperature tree consisted of six thermocouples in the following locations: top and bottom of ECON layer, middle, and bottom of PCC layer, middle of the base layer, and one sensor in the subgrade layer.

Strain gauges were mounted on the PCC layer using two plastic chairs and steel straps (see Figure 4-2(e)). The steel straps were screwed to the PCC layer to secure them. In the case where two strain gauges needed to be placed at different depths, two 0.6 cm (¼ in.) fiberglass bars were used to place and secure the strain gauges. The chosen locations of strain gauge were center, edge, corner in wheel path direction, and corner in a diagonal direction. The strain gauges were installed both in ECON layer and PCC layer. The strain gauge configuration was chosen to measure the strain in both layers to monitor the effect of heating in the ECON layer. Sensors wires were guided to a separate PVC pipe to the shed (see Figure 4-2(f)). The PVC pipe for electrical wiring was not chosen to host the sensors wire to prevent possible interferences in sensor signals and for safety purposes.

**Integration of Power Supply and Control System**

There was no existing power supply source close to the construction site; therefore, a new 45-1 pole with 3-100kVA XFMRS was placed to the southwest corner of the site. A meter was installed on the pole to measure electrical power usage, and a power line trench was excavated from the pole to the shed. This enables powering ECON HPS test section using either a three-
phase 208 VAC, or a single phase 120 VAC, both with a maximum of 600 A source. Two three-phase double pole power panels were installed in the shed with two circuit breakers. Each circuit breaker can feed five slabs with 120/208 VAC. The three-phase 208 VAC was achieved by using two lines, one for each phase, while the 120 VAC was carried in each single line. The 120 VAC was achieved using one line and the neutral. The different electrode configuration design would cause each slab to draw a different amount of current compared to the other slabs. Thus, the research team conducted a series of tests and simulations and grouped the slabs in a way to distribute the power load evenly within each phase and to eliminate overloading on one phase.

Another added feature of using PLC as a control system is electrode-based control. The electrode-based control feature gave the research team extra degree of control to create different electrode configurations (spacing) within one slab with turning on/off individual electrodes. Therefore, the research team added more relays for test sections with 10 electrodes (4 slabs) to incorporate this feature. The electrode wiring diagram for the 10 electrode slabs is shown in Figure 4-3(a). The other six slabs were designed using slab-based control, which can only turn all the electrodes in each slab on and off at once (Figure 4-3(b)). The PLC system and its wiring are being shown in Figure 4-3(c).
Figure 4-3 PLC control configurations: (a) electrode-based control (test section 1 to 4), (b) slab-based control (test section 5 to 10), (c) PLC and relay wirings.
Construction Procedure

Construction started on October 11, 2018 and lasted for four weeks due to the weather condition. The existing pavement was a 40 years old PCC pavement with numerous cracks at the joints and midspan. The pavement had also been rehabilitated at several spots because of intensive damages. This parking section experiences a high amount of heavily loaded traffic, including 18-wheeler tractors and trailers, being at the entrance of the Iowa DOT receiving station. The project was a reconstruction project, and the first task was to remove the existing 15.2 cm (6 in.) concrete pavement. The existing pavement did not have any base layer, and it lacked any drainage system; therefore, a geofabric system was utilized on top of the subgrade, and a 22.9 cm (9 in.) special backfill layer was compacted for the base layer.

The ECON HPS was designed with two layers, 17.8 cm (7 in.) regular PCC layer (bottom layer) and 7.6 cm (3 in.) ECON layer (top layer). The construction steps in sequence are shown in Figure 4-4. Dowel bars [1.9 cm (¾ inch) in diameter] were used for proper load transfer between the adjacent slabs at sawn joints. A joint spacing of 15 feet was designed, and the joints were matched with the surrounding concrete slabs. A vibrating screed was used to compact the PCC layer (Figure 4-4 (a)). A broom was used perpendicular to traffic flow after finishing the PCC layer to roughen the surface and increase the bond between the bottom PCC layer and the top ECON layer (Figure 4-4 (b)). Curing compound was not suggested for curing the PCC layer due to its potential adverse impact on the bond between the two layers, therefore, wet curing using curing blankets was chosen for the bottom PCC layer.
Figure 4-4 ECON HPS construction steps: (a) C-3WR-C20 PCC placement, (b) PCC layer screeding, (c) electrode installation, (d) PVC conduit placement, (e) surface cleaning, (f) ECON layer before placement, (g) ECON placement and compaction with vibrating screed, and (h) curing compound spraying.
The research team started mounting the electrodes on top of the PCC layer (Figure 4-4c). The electrodes were first washed and then dried in order to remove any debris or possible oil on their surface. This was an essential step to ensure a good bond between each electrode and the ECON layer. The perimeter of the ECON test sections, where it meets the regular concrete sections, got isolated using expansion joints to minimize any interaction and potential strain build-up with other unheated regular concrete slabs. The strain gauge and thermocouple trees were installed, and their wires were guided to its designated PVC conduits (Figure 4-4(d)). The surface of the PCC layer got cleaned using an air blower and damped to ensure a good bond between the two lifts (Figure 4-4(e)). A white flag was installed at each sensor location so that the sensors do not get stepped on during the ECON placing (Figure 4-4(f)).

The ECON layer was placed on October 25, 2018, and a vibrating screed was used to compact this layer (Figure 4-4g). In the end, the curing compound was sprayed on top of the test section (Figure 4-4(h)) to prevent moisture loss. The shed was placed in the southwest corner of the test section, and the wires were installed to connect the electrodes to the power supply source. Meanwhile, the joints were cut full depth through the ECON layer to match those in the bottom PCC layer. The last step in the construction phase was to fill the trenches which hold the electrical and sensor PVC conduits with 15.2 cm (6 in.) hot mix asphalt.

**Iowa DOT ECON HPS Performance Evaluation**

The current winter maintenance operation conducted by Iowa DOT ground crew for their parking lot consists of eight crews with eight snow removal equipment. It takes the ground crew an average of 5 hours to remove the snow from the whole Iowa DOT parking lot in a normal 5 cm (2 in.) snow event. The ground crew has been using 10 tons of deicing chemicals and sand between only January 1, 2019, and February 20, 2019. The ground crew first plow and gather the snow in several designated areas in the parking lot and then apply deicing chemicals for the
remaining snow on the ground. The ground crew then haul the gathered snow from different designated locations and transfer it to the Iowa DOT south parking lot to be melt eventually by the sun. Iowa DOT sends out several emails to its employees before each snow event to move the personal and Iowa DOT owned vehicles from the parking lot to facilitate the winter snow removal operation. The deicing chemicals usually get transferred to the grass areas during the winter season, which kills the vegetation. Therefore, the ground crew needs to plant new grasses, especially near the paved area each summer season and gather all the sand which has been spread during each winter season at the beginning of spring. Nahvi et al. have done a life-cycle benefit cost analysis (LCBCA) of ECON HPS on airfield pavements and found out that the construction of ECON HPS would be 50 percent higher than the regular PCC (27, 28). The current state of practice for removing ice and snow is time-consuming, labor-intensive, and environmentally unfriendly due to the usage of deicing chemicals.

Figure 4-5 shows the ECON HPS system performance during the period of February and March of 2019. The resistive heating performance of ECON HPS was capable of maintaining a snow and ice-free surface while the remaining parking lot was covered with about 5 cm (2 in.) of snow. A snow event started at 8 pm on February 11, 2019, and lasted until 2 am the next day (6 hours). The average air temperature and relative humidity in this period were -8.4°C (17°F) and 86%, respectively. The system started operating at 8 PM and was capable of melting all the snow by 11 pm (3 hours later) and maintaining a snow-free surface until the snow event ended.

The power density (P) is the amount of energy consumed by each slab per unit area and was calculated using the average current usage (I) and the voltage applied to the slabs during a snow event. The applied voltage for the operation was chosen 120 VAC for ECON HPS performance evaluation. The power density range for all the slabs was between 109.8 and 491.5
W/m² with an average of 265.1 W/m². There was a resistivity variation observed between the slabs, which was due to carbon fiber dispersion within each test section. Therefore, in order to compare the power demand for each electrode configuration regardless of the slab’s electrical resistivity, the power density was normalized by the resistivity measurement for each slab. This normalization is necessary since the effect of resistivity is the linear inverse of power density, which means, a slab with higher resistivity has a lower power density and vice versa. This normalization is essential to only see the effect of electrode configuration and eliminate the effect of ECON resistivity on the analysis. The normalized power density for each test section and the slab surface temperature while in operation are shown in Figure 4-6.

![Figure 4-5 ECON HPS heating performance: (a) Southside slabs performance, (b) 5 cm (2 in.) of snow accumulation in the surrounding slabs, (c) Northside slabs performance, and (d) infrared thermography of ECON slabs.](image-url)
Figure 4-6 (a) corrected power density per square meter per resistivity of each slab, (b) slab surface temperature and air temperature vs. time
As shown in Figure 4-6 (a), the electrode configuration directly affects the corrected power density (power density/resistivity). In all slabs with the same number of electrodes, the slabs with flat bar (F), 2.5 cm (1 in.) hollow bar (H), 2.5 cm (1 in.) solid bar (S-1.0), and 1.9 cm (0.75 in.) solid bar (S-0.75) have the same corrected power density ranking with the flat bar having the highest and the 1.9 cm (0.75 in.) solid bar the lowest corrected power density. It has also been found that by increasing the electrode diameter in circular solid bars from 1.9 cm (0.75 in.) to 2.5 cm (1 in.), the corrected power density increased in all different spacing options, which is due to the increase in the contact area between the electrode and the ECON layer. In addition, the corrected power density decreased in flat bar and 2.5 cm (1 in.) circular solid bar by decreasing the spacing (increasing the number of electrodes within a slab).

Figure 4-6 (b) shows the thermal performance of each slab and the air temperature versus time. These data were gathered from the thermocouples placed 1.3 cm (0.5 in.) below the pavement surface. The temperature in each slab increased after the slab got turned on, but after some time, the slab temperature stayed constant, which is due to melting snow on the surface (phase change). 10H-1.0 slab showed the highest temperature increase (7.4°C/13.3°F in 2 hours), and the 8S-0.75 slab showed the lowest. The average temperature rise for all the slabs was 5°C (9°F) in 2 hours. The slabs with eight electrodes showed a lower heating performance compare to the slabs with 10 electrodes.

Summary, Conclusions, and Recommendations

The objective of this study was to demonstrate the design, full-scale demonstration, and performance monitoring of the largest operational electrically conductive concrete (ECON) heated pavement system (HPS). Ten ECON test slabs were designed and constructed at the south parking lot of Iowa DOT headquarter in Ames, Iowa on October of 2018. Programmable logic controller (PLC) system and slab instrumentation using temperature sensors were designed and
implemented for the remote-control operation and system performance monitoring respectively. The deicing and anti-icing performance of ECON HPS was evaluated during February to March of 2019. The summarized findings of this study, along with the recommended future investigations are as follows:

- Ten ECON HPS test slabs with different electrode configurations were constructed in the south parking lot of Iowa DOT headquarter as the largest ECON HPS implementation project. All the test slabs showed promising snow and ice-free capabilities through various winter weather events.

- A PLC system was designed, programmed, and implemented in the construction and it showed a promising and robust remote-control system to be used in ECON HPS technology.

- Each ECON HPS test slab had a different electrode design configuration, including electrode shape, size, and spacing compared to other test slabs. In all different spacing options, the flat bar, 2.5 cm (1 in.) hollow bar, 2.5 cm (1 in.) solid bar, and 1.9 cm (0.75 in.) solid bar have the same power density ranking with the flat bar having the highest and the 1.9 cm (0.75 in.) solid bar the lowest power density.

- The power density range for all the slabs was between 109.8 and 491.5 W/m² with an average of 265.1 W/m². The power density normalized by the resistivity of each ECON HPS slab ranges between 4.6 W/m² (slab 8S-0.75) to 93.1 W/m² (slab 8F-1).

- Increasing the electrode diameter in circular solid bars resulted in an increase in the power density in all electrode spacing.

- The power density decreased in flat bar and 1 in. circular solid bar by decreasing the electrode spacing (increasing the number of the electrodes used in each slab).
The findings of this study facilitate the design of ECON HPS and provide detailed information on the construction steps. The ECON HPS performance will be monitored in the upcoming winter seasons, and the performance of each designed configuration will be evaluated through a thorough economic analysis. The electrical safety and other related issues that might arise during the operation will also be considered.

References


20. *Iowa Department of Transportation Standard Specification with GS-15008 Revisions*. 


23. Malakooti, A. Investigation of Concrete Electrical Resistivity As a Performance Based Test. Utah State University, 2017.


CHAPTER 5. ELECTRICALLY CONDUCTIVE CONCRETE HEATED PAVEMENT SAFETY CONCERNS AND MITIGATION APPROACHES

Amir Malakooti\textsuperscript{1}, Wei Shen Theh\textsuperscript{2}, Halil Ceylan\textsuperscript{3}, Mani Mina\textsuperscript{4}, Sunghwan Kim\textsuperscript{5}, Peter C. Taylor\textsuperscript{6}

\textsuperscript{1}: Ph.D. Student, CCEE, Iowa State University, Ames, IA
\textsuperscript{2}: Ph.D. Student, ECpE, Iowa State University, Ames, IA
\textsuperscript{3}: Professor of CCEE, Iowa State University, Ames, IA
\textsuperscript{4}: Associate Professor of ECpE, Iowa State University, Ames, IA
\textsuperscript{5}: Research Scientist, Institute for Transportation, Iowa State University, Ames, IA
\textsuperscript{6}: Director of National Concrete Pavement Technology Center, Iowa State University, Ames, IA

Modified from a manuscript to be submitted in \textit{Construction and Building Materials}

Abstract

Electrically-conductive concrete (ECON) heated pavement system (HPS) has been developed as a sustainable and environmentally-friendly alternative winter maintenance method to keep infrastructure safe, open, and accessible during the winter season. While ECON HPS has proven to be an effective method in removing ice and snow, safety aspects of such a system have often been brought up. Considering the high voltage used and the wide conductive surface, the safety of those exposed to ECON HPS is a valid concern that must be addressed. The focus of this study was to first investigate the potential electrocution hazard of electrically-conductive concrete ECON HPS, then provide strategies to mitigate or such a risk. Painting ECON HPS surfaces can be an effective electrocution hazard mitigation strategy for reducing surface voltage and increase overall system safety.
Introduction

Accumulation of ice and snow on paved surfaces decreases pavement surface skid resistance, often leading to hazardous conditions for aircraft, vehicles, and pedestrians each winter season (1, 2). Furthermore, snow and ice limit a transportation network's mobilization capacity by causing delays, or in some situations, entire shutdown of a portion of the network (3). For example, according to the US Bureau of Transportation Statistics, inclement weather in US air transportation resulted in about 32 million minutes of delay, equivalent to 61 years during the 2019 calendar year (4). The Federal Aviation Administration (FAA) reported that US air transportation lost 33 billion dollars in 2019 mainly due to flight delays (one-third due to weather), a 62.6 percent increase over 5 years, with the cost per minute of aircraft delay estimated to be about $74.24 (5–8).

Federal Highway Administration (FHWA) reported that seventy percent of US roadways are located in snowy regions, i.e., receiving more than 13 cm (5 in.) on average of snow (9). Snow and ice control operations account annually for about 20 percent of state Departments of Transportation budgets (11). The US highway network incurs a 5 to 40 percent drop in speed and a 12 to 27 percent loss in mobilization capacity during winter weather events, directly impacting US economic competitiveness with respect to transport of goods and services. Winter weather events are responsible for 24 percent of all vehicle accidents each year, with over 1,300 people killed and 116,800 people injured annually (11). Also, based on the US Bureau of labor and statistics, there were 25,370 ice, sleet, and snow-related occupational injuries in 2019 (10).

While the current state of practice in combatting snow and ice events is to utilize snow-removal equipment in conjunction with deicing chemicals, deicing chemicals contaminate soil, surface run-off, and groundwater, thereby harming the environment. In 2020, for this purpose the US consumed 22.8 million metric tons (25.1 US tons) of rock salt (43 percent of total US salt
consumption), a 2,300 percent increase from 1960 (11), and it is anticipated that by 2050, half of the world's arable land would be salinized, posing a threat to global food security (12). Deicing chemicals not only harm the environment but also accelerate infrastructure degradation speed. The annual cost of corrosion damage caused by salting US roadways is estimated to be more than 5 billion dollars (14), and traditional snow removal operation is time-consuming, labor-intensive, and environmentally unfriendly, resulting in a need for alternate winter maintenance practices to increase infrastructural resiliency and sustainability throughout the winter season (15, 16).

The electrically-conductive concrete (ECON) heated pavement system (HPS) was developed as a sustainable and environmentally-friendly alternative winter maintenance method for keeping the infrastructure safe, open, and accessible during the winter season. ECON is a mixture of conventional Portland cement concrete with the addition of conductive agents such as carbon fiber that allows electrical current to flow through ECON, resulting in resistive heating due to the inherent resistance of concrete to current flow. For comparison, the electrical resistivity of air-dried conventional concrete is in the range of about 6.5×10^5 and 11.4×10^5 Ω-cm (25.6×10^4 and 44.9×10^4 Ω-in), while the resistivity of ECON is about 1,000 Ω-cm (394 Ω-in).

While ECON HPS has proven an effective method in removing ice and snow, the safety aspect of this system has often been brought up. Considering the high voltage used and the wide conductive surface, the safety of those exposed to ECON HPS is a valid concern that must be addressed.

First and foremost, there is the issue of the human body equivalent circuit model (HBECM). In general, it is widely accepted that the HBECM of a given person can differ greatly from that of another. Every characteristic of a person, be it gender, age, mass, height, conditions,
etc. is a contributing factor in determining the HBECM. For example, a male subject is generally considered to have higher resistance compared to a female subject due to larger body size. The human body is also made up of cells and organs of varying conductivity. For example, a blood vessel is highly conductive, while human fat is not. There is also the question of how organs are connected to one another. In simple terms, the human body is made up of a complex connection of resistors, capacitors, and inductors, making determination of the HBECM a unique challenge. Once an HBECM has been arrived at, to determine the possibility of an electric shock, it becomes a matter of measuring current values and comparing the result with other readily available data.

The HPS is essentially a closed-loop wire through which current flows to generate a magnetic field, as dictated by the Maxwell-Ampere law:

$$\nabla \times \mathbf{H} = \mathbf{j} + \frac{\delta \mathbf{D}}{\delta t}$$

(1)

The electrical properties of the ECON determine the potential electromagnetic (EM) wave emission and/or absorption, and a highly capacitive material generates more EM waves. Since the ECON HPS is connected to the power grid of the United States of America, a purely resistive material reflects the 60 Hz frequency of that source.

**Hazard Assessment**

A comprehensive literature review was conducted, first to develop a better understanding of the HBECM, and second to investigate the effects of current on the human body. Related studies have reported investigative approaches and associated challenges were reviewed and discussed. From the review results, materials, information, to improve the accuracy of the tests methods were incorporated into an experimental investigation.
**Human Body Equivalent Circuit Model**

Different parts of the human body display different resistance to current flow. The human skin, its largest organ, shows high resistance depending on its condition. A calloused, dry hand may have resistance greater than 100,000 Ω \((17)\), while the mineral and fluid-rich internal body resistance is about 300 Ω \((17)\). This shows that while the human skin plays a fundamental role in electrical protection, skin resistance can be bypassed under certain conditions, e.g., physical skin damage, high voltage (500 V or more), rapid voltage application, and immersion in water.

However, due to the unique characteristic of each person, no literature could be found that gave a specific value to HBECM. The contact resistance of skin is in the range of 1 – 100 kΩ \((17)\), and since there are two contact points plus the internal resistance, the HBECM resistance can lie anywhere between 2.3 to 200.3 kΩ.

**Effects of Current on the Human Body**

There are several forms of electric current related injury. Electric shock is defined as a sudden violent response to electric current flow through any part of a person’s body, and electrocution is death caused by electric shock. Electrical injury can be further divided into two categories: (1) primary electrical injury related to tissue damage produced directly by electrical current, and (2) secondary electrical injury such as a fall indirectly caused by a primary electrical injury.

The literature mentions that the threshold for ventricular fibrillation for 60 Hz AC is 50 mA for shocks longer than 2 seconds \((17)\). A summary of effects due to a various amount of electric current flowing through the body is shown in Table 5-1.
Table 5-1. Estimated Effects of 60 Hz AC Currents (17)

<table>
<thead>
<tr>
<th>Current</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mA</td>
<td>Barely perceptible</td>
</tr>
<tr>
<td>16 mA</td>
<td>Maximum current an average man can grasp and “let go”</td>
</tr>
<tr>
<td>20 mA</td>
<td>Paralysis of respiratory muscles</td>
</tr>
<tr>
<td>100 mA</td>
<td>Ventricular fibrillation threshold</td>
</tr>
<tr>
<td>2 A</td>
<td>Cardiac standstill and internal organ damage</td>
</tr>
<tr>
<td>15/20 A</td>
<td>Common fuse breaker opens the circuit</td>
</tr>
</tbody>
</table>

**Hazard Assessment Field Experimental Study**

HBECM aims to pull the maximum amount of current to the surface while connecting the lowest possible yet realistic resistance value in the HBECM. Steps are also taken to create safety factors that are set in place to create a worst-case scenario to make the conclusion of the test reliable and considers any unforeseen circumstances. For the HBECM study, random individuals were asked to submerge their hands into water buckets while holding the probes of a multimeter set to read resistance, as shown in Figure 5-1. This step was repeated using salt water. The water will slightly negate the effects of skin resistance, the first safety factor used to select the lowest possible resistance value that is then used for the second stage of this test.

![Figure 5-1. Lowest resistance measurements](image)

For the second stage, a circuit was created to represent a human body in contact with the ECON surface. The circuit was comprised of a parallel resistor-capacitor in series with another
resistor. In the schematic diagram shown in Figure 5-2, R1 represents the resistance from stage 1, the total resistance of the human body, C1 represents the human body capacitance, and R12 is any unaccounted-for resistance outside the body.

Figure 5-2. HBECM Schematic Diagram

The circuit inputs were connected to the ECON slab surface (see Figure 5-3), and duct tape was used to create a shallow well on each contact point, after which plain or salt water was poured into these wells. The reasoning behind using such wells was to draw more current to the surface (the second safety factor). A multimeter set to measure voltage was then connected in parallel to R1, and current can then be calculated via Ohm’s law.

\[ I_{HBECM} = \frac{V_{R1}}{R1} \]  

(2)

Figure 5-3. HBECM during the current measuring test.

Although the literature review suggested that 50 mA was an appropriate cut-off value, but 20 mA was selected as the current threshold value for this test. This was the third safety factor.
The current being measured is the total current into the body, and danger arises when a 20 mA current reaches the heart. By setting the threshold to 20 mA, the current to the heart will surely be lower than 20 mA since the total current is transmitted to other parts of the body.

Hazard Assessment Results and Discussion

A series of tests were conducted in the first stage of experimentation. As shown in Table 5-2, the lowest resistance measured from stage 1 was 22.32 kΩ, and this value was rounded up to 22 kΩ. A fourth safety factor is created in the form of a lower resistance value of 10 kΩ. As previously shown in the Ohm’s law equation (Equation 2), since the voltage from the source is constant, such a lower resistance will result in an increase in current.

In December 2017, a set of 8 experiments were conducted on ECON HPS full-scale slabs at Des Moines International Airport, and some of the experimental parameters were:

- Different R1 values - 10 kΩ or 22 kΩ
- Different content of wells – dry, water, salt water (low and high concentrations)
- Presence of salt bridge connecting the two wells
- Constant applied voltage of 240 VAC

A summary of each parameter and the measured result is shown in Table 5-2. The current was measured on the sample at the DSM International Airport (see Figure 5-4), and the final values are included in Table 5-2.

As shown in Table 5-2, all measured readings were lower than the pre-defined 20 mA threshold value, suggesting that ECON HPS is generally safe to the human touch.
Table 5-2. List of Experiments, Parameters, and Respective Current Value

<table>
<thead>
<tr>
<th>Experiment</th>
<th>R1 (kΩ)</th>
<th>Content of wells</th>
<th>Salt bridge</th>
<th>Current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>Dry</td>
<td>Absent</td>
<td>1.38</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>Water</td>
<td>Absent</td>
<td>6.19</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>Saltwater (low conc.)</td>
<td>Absent</td>
<td>10.06</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>Saltwater (low conc.)</td>
<td>Present</td>
<td>8.70</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>Water</td>
<td>Absent</td>
<td>3.90</td>
</tr>
<tr>
<td>6</td>
<td>22</td>
<td>Saltwater (low conc.)</td>
<td>Absent</td>
<td>4.20</td>
</tr>
<tr>
<td>7</td>
<td>22</td>
<td>Saltwater (low conc.)</td>
<td>Present</td>
<td>4.13</td>
</tr>
<tr>
<td>8</td>
<td>22</td>
<td>Saltwater (high conc.)</td>
<td>Present</td>
<td>3.87</td>
</tr>
</tbody>
</table>

Figure 5-4. Measuring the current at on ECON HPS full-scale slabs at Des Moines International Airport

Hazard Mitigation Strategies

In the hazard assessment section, it was shown that ECON HPS is safe for human interaction and does not represent a significant hazard to humans, but there still remain mitigation strategies to further reduce the risk, and their effectiveness was investigated. Since ground personnel in an airport or any other infrastructure will be in contact with the ECON HPS when the system is active, these safety strategies are meant to minimize the risk of injury.
Reducing the Voltage usage in ECON HPS

One of the easiest strategies for reducing the electrocution hazard in ECON HPS is to reduce the ECON HPS applied voltage in the field. The hazard assessment section in this study was conducted for an applied voltage of 240 VAC, a value that is considered to be high. However, by lowering the voltage to 120 VAC, based on Ohm’s law (Equation 2) the current will be reduced to half (50 percent risk reduction).

Grounding

When the ECON HPS is turned on, current flows through the ECON slabs. One property of the current flow is that it will always find the shortest path to ground. In an ideal closed-loop circuit, current will flow from one electrode (into the system) to another electrode (out of the system) because this is the easiest path available. Since the ECON slabs are fabricated in the ground, there are alternate paths for current to flow, as depicted in Figure 5-5. Even the regular concrete layer underneath the ECON HPS in an overlay system, although it has a relatively high resistance, and represents a path to ground if the supplied voltage is high. While the ECON samples in DSM International Airport did not display current leaks to the surrounding area, the situation might differ due to different soil properties for ECON HPS constructed at a different location.

Figure 5-5. Current (green arrows) flowing out of the ECON slab through the sides.

The researcher proposes to introduce a direct path to the ground using metal rods near the ECON HPS surface as shown in Figure 5-6. A metal tab can be constructed within the ECON
slab, and this tab can then be connected by wires to the embedded metal rod. This is a common grounding method for buildings, large electrical appliances, and lightning-rod applications. Since the Earth is a natural ‘perfect ground’ and metals such as copper are good conductors, this path has the least resistance. Leakage current flowing directly into the Earth is harmless to a human on the surface.

Figure 5-6. A metal rod is connected to the ECON slab as an alternate path to the ground for current.

For this test, a 3-feet long steel rod was hammered into the Earth, as shown in Figure 5-7(b). Figure 5-7(c) shows the ring clamps used to connect a copper wire to the rod, and the ECON sample has short metal stubs protruding on the top, as shown in Figures 5-7(a) and (d). A 120 VAC power supply was used for this test, and surface current and current to ground were measured. The results from this test are recorded in Table 5-3 (a) for dry ground and Table 5-3 (b) for wet ground.
Figure 5-7. Setting up to test grounding as a safety plan. (a) test plan, (b) inserting metal rod into the Earth, (c) connecting the ECON sample to metal rod using wire, (d) overall setup of ECON sample.

Table 5-3. Measured Current Value for Grounding Test: (a) Ground is Dry, (b) Ground is Wet.

(a)

<table>
<thead>
<tr>
<th>Test</th>
<th>Position of Ground Wire</th>
<th>Current into Slab (A)</th>
<th>Surface Current (mA)</th>
<th>Current into Ground (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>N/A</td>
<td>19.32</td>
<td>5.47</td>
<td>N/A</td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>19.20</td>
<td>5.39</td>
<td>1.04</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>19.25</td>
<td>5.37</td>
<td>1.17</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>19.65</td>
<td>5.47</td>
<td>0.94</td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>19.20</td>
<td>5.29</td>
<td>1.03</td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th>Test</th>
<th>Position of Ground Wire</th>
<th>Current into Slab (A)</th>
<th>Surface Current (mA)</th>
<th>Current into Ground (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>N/A</td>
<td>19.63</td>
<td>5.53</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>A</td>
<td>19.30</td>
<td>5.48</td>
<td>0.96</td>
</tr>
<tr>
<td>6</td>
<td>B</td>
<td>20.41</td>
<td>5.45</td>
<td>1.31</td>
</tr>
<tr>
<td>7</td>
<td>C</td>
<td>19.65</td>
<td>5.50</td>
<td>1.00</td>
</tr>
<tr>
<td>8</td>
<td>D</td>
<td>19.95</td>
<td>5.43</td>
<td>1.19</td>
</tr>
</tbody>
</table>
As is apparent from Table 5-4, the grounding methodology did not significantly reduce the surface current. In addition, an average of one ampere passed through the grounding did not contribute to heating the slab, consequently reducing overall system performance. Therefore, using grounding as a surface current control in the configuration studied in this research is not recommended.

**Insulation Layer**

Another hazard mitigation strategy is to add a thin insulating layer on top of the ECON slabs to act as a barrier to contain the current within the slab and prevent ground personnel from being in direct contact with the surface current. The researchers identified paint as such a potential insulating material because it is low-cost, easily applied, and readily available. For proof of concept, one potential polymer-based paint was chosen because of its durability in field applications; polymers typically have high electrical resistivity, so they can act as an electrical barrier.

To investigate paint as an electrical barrier, one ECON HPS slab and two beams were selected to be painted using a primer and a finish coat applied by following the manufacturer's recommendation. The primer coat was first applied, and the finish coat was applied after complete primer drying. Half of the beam and slab were not painted to provide a control section, as shown in Figure 5-8. The surface voltage was then measured with a multimeter with 120 VAC power supplied to the samples, as shown in Figure 5-9, and the results recorded.
Figure 5-8. Application of paint as an insulation layer on ECON HPS beams

Conductive gel was used on multimeter tips to increase the contact area and obtain a stable reading.

Figure 5-9. Surface voltage measurement reading on ECON HPS slab and beam samples

Table 5-4. Surface voltage measurement on beam and slab samples coated with paint

<table>
<thead>
<tr>
<th></th>
<th>Surface voltage Without paint</th>
<th>Surface voltage with one layer of finish coat</th>
<th>Percent change with one layer of finish coat</th>
<th>Surface voltage with two layers of finish coat</th>
<th>Percent change with two layers of finish coat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>8.9</td>
<td>1.8</td>
<td>-80%</td>
<td>0.1</td>
<td>-99%</td>
</tr>
<tr>
<td>Slab</td>
<td>2.8</td>
<td>0.5</td>
<td>-82%</td>
<td>0.9</td>
<td>-88%</td>
</tr>
</tbody>
</table>
As clearly shown in Table 5-4, even applying only one layer of paint reduced the surface voltage by about 80%, and by using more paint the electrocution hazard can be further reduced. Therefore, applying paint to the ECON HPS surfaces is a viable safety option.

**Conclusions**

The focus of this study was first to investigate the potential electrocution hazard presented by an electrically-conductive concrete (ECON) heated pavement system (HPS) and provide some strategies for mitigating or lowering the risk of electrocution. The findings of this study are as follows:

- A human body equivalent circuit model (HBECM) was developed and used to assess the electrocution potential of the full-scale ECON HPS slabs in operation at DSM International Airport.
- From the literature review, 50 mA was identified as the cut-off value for electrocution safety concerns, and since test results showed that ECON HPS using 240 VAC at DSM International Airport would generate a maximum of 10mA, so ECON HPS is safe for human touch and operation.
- One of the easy strategies to reduce the electrocution hazard in ECON HPS is to reduce the ECON HPS applied voltage in the field as much as possible.
- Using grounding in the configuration studied in this research is not suggested as a surface current control in ECON HPS technology.
- Painting the surfaces of ECON HPS is an effective electrocution-hazard mitigation strategy to reduce surface voltage and increase overall system safety.
References


CHAPTER 6. GENERAL CONCLUSION

Conclusions

The objective of this study was to demonstrate the design, full-scale demonstration, and performance monitoring of the largest operational ECON HPS. Ten ECON HPS test slabs were designed and constructed at the south parking lot of the Iowa DOT headquarters in Ames, Iowa, during October 2018. A PLC system and slab instrumentation using temperature sensors were designed and implemented for remote-control operation and system performance monitoring. Deicing and anti-icing ECON HPS performance was evaluated during the 2018–2021 winter seasons.

The summarized findings of this study are as follows:

- Ten ECON HPS test slabs with various electrode configurations were constructed in the south parking lot of the Iowa DOT headquarters as the largest ECON HPS implementation project. All the test slabs showed promising snow- and ice-free capabilities during various winter weather events.

- Each ECON HPS test slab had a different electrode configuration in terms of electrode shape, size, and spacing. The flat bar, the 1.0 in. (2.5 cm) hollow bar, the 1.0 in. (2.5 cm) solid bar, and the 0.75 in. (1.9 cm) solid bar have the same trend that power density decreases when the number of electrodes increases. However, the flat bar has the highest and the 0.75 in. (1.9 cm) solid bar has the lowest power density among all the different spacing options.

- The power density range for all the slabs was between 10.2 W/ft^2 (109.8 W/m^2) and 45.6 W/ft^2 (491.5 W/m^2), with an average of 24.6 W/ft^2 (265.1 W/m^2). The power density normalized to the resistivity of each ECON HPS slab ranged between 0.42 W/ft^2 (4.6 W/m^2) (slab 8S-0.75) and 8.6 W/ft^2 (93.1 W/m^2) (slab 8F-1).
• Increasing the electrode diameter in circular solid bars resulted in an increase in power density in all electrode spacing.

• The power density was decreased in the flat bar and 1.0 in. (2.5 cm) circular solid bar slabs by decreasing the electrode spacing (increasing the number of the electrodes used in each slab).

• Based on the theory, the laboratory studies, and the FE models, the temperature increase rate of an electrode is influenced by its surface contact area (perimeter).

• A theoretical formulation was developed to describe the ECON HPS thermal behavior.

• An increase in electrode size resulted in an increase in energy conversion efficiency.

• FWD testing showed that the average heated pavement deflections were about 10% lower than those of regular concrete pavement slabs, indicating that the heated slabs were stiffer with a higher modulus.

• The slope of the temperature increase rate versus the perimeter curve for different electrodes was found to be identical in both water and ECON prototype slab tests.

• Flat-bar orientation (vertical versus horizontal) did not significantly change the heating performance of the electrodes according to water tests.

• The PLC exhibited better control flexibility than Arduino board microcontrollers in terms of autonomous control, expandability, and control capability.

• A human body equivalent circuit model (HBECM) was developed and it was used to assess the electrocution hazard of the full-scale ECON HPS slabs in operation at DSM International Airport.

• From the literature review, 50 mA is identified as the cut-off value for safety concern of electrocution and test results showed that ECON HPS using 240 VAC at DSM International
Airport will generate a maximum of 10mA. Therefore, ECON HPS is safe for human touch and operation.

- One of the easy strategies to reduce the electrocution hazard in ECON HPS is to reduce the ECON HPS applied voltage in the field as much as possible.
- It is not suggested to use grounding in the configuration that was studied in this research as a surface current control in ECON HPS technology.
- Painting the surfaces of ECON HPS can be an effective electrocution hazard mitigation strategy to reduce the surface voltage and increase the overall system safety.

**Recommendations for Implementation and Future Research Directions**

The findings of this study facilitate the design of an ECON HPS and provide detailed information on the construction steps. The following recommendations have been drawn from this study to facilitate the design and construction of future ECON HPS implementations:

- A designed, programmed, and implemented PLC system was found to be a promising and robust remote-control system to be used in ECON HPS technology.
- Testing electrodes in water for monitoring the temperature increase rate is a faster, repeatable, nondestructive, and cost-effective method for identifying favorable electrode sizes and comparing electrode performance for an ECON HPS.
- Considering initial costs of the electrodes, flat-bar and smaller-diameter electrodes were found to be more cost-effective than the larger electrodes due to the lower cost of smaller-sized electrodes relative to the temperature increase rates associated with them.
- Use of 20% fly ash Class C replacement and removal of methylcellulose and DCI admixtures helped improve the slump to 3.9 in. (10 cm) during the Iowa DOT project ECON placement.
• If sensors are to be incorporated into the ECON HPS design, their tips and cables must be electrically insulated and thermally operational.

• Using multiple voltages with the PLC control device gave ECON HPS users control over snow- and ice-melting speed.

• Premature cracking due to the use of an angle-shaped electrode can be eliminated by incorporating circular or flat-bar electrode shapes.

• The paths followed by water produced as the result of melting ice and snow from the heated slabs to the drainage outlet must be heated to eliminate ice formation near the heated slabs.

• The best operational practice of heated pavements is to turn the system on before the snow event starts so that snow accumulation will not occur and operation time and consequent operation cost will decrease.

Other applications and the rationale for prioritization among critical areas of Iowa transportation infrastructure systems for ECON HPS implementations, identified as being of interest to the Iowa DOT and Iowa county and city engineers, are discussed as follows:

• **Bridge decks**
  
  o Bridges are the first locations in a highway system to freeze during the winter season. Thin layers of black ice and frost form on top of the bridge deck, potentially resulting in vehicles sliding off the bridge and causing fatal crashes. Many highway agencies dedicate portions of their winter maintenance budget for deicing these locations (so-called frost run) for mitigating this hazard. Entrance and exit ramps in the highway system are also potential winter hazards, due to higher vehicle speeds and potential of sliding off the ramp.
o Given these frost-run operations are typically on bridges located over a body of water, resulting in a direct chloride load into the water system, heated-bridge technology can mitigate direct chloride load into nearby water bodies.

o During this study, several highway agencies, such as those in Iowa and Wisconsin, have expressed strong interest in implementation of heated-bridge technology.

- **Rest areas**
  o Rest areas, specifically in interstate highway systems, experience high foot traffic throughout the year, and they are typically located in areas that would not be easily accessible to winter maintenance crews to clear the snow and ice in a timely manner.
  
o ECON HPS technology is in full compliance with the Americans with Disabilities Act (ADA) mission to ease the commute of individuals with disabilities, especially during the winter season. Based on data from the U.S. Bureau of Labor Statistics, about 25% of ice- and snow-related falls occur in parking lots. Snow and ice can cause significant hardship for individuals with disabilities, and implementing heated pavement on parking lots and ramps could be a way to mitigate this hardship. In addition, the Iowa DOT has received dedicated funding for ADA-compliance projects that can be used to further implement ECON HPS, facilitating the contribution of people with disabilities to our society.

The versatility of the ECON HPS technology demonstrated for roadway application in this study is such that it can be custom-designed and optimized for each specific transportation infrastructure application depending on need and interest. This versatility stems from the fact that the ECON HPS technology can be implemented as either a conductive concrete surface for a new construction project or a conductive concrete overlay on top of an existing structure for a
rehabilitation project. However, the ECON HPS design requirements and considerations are somewhat different for each specific application, warranting detailed research investigations before being fully implemented in each situation. Therefore, pursuit of future research directions from this study is recommended to develop and implement custom-designed and optimized ECON HPS technology for each prioritized application area identified (i.e., bridge decks and rest areas).