Advancing Electrically Heated Pavements for Sustainable Winter Maintenance

Final Report
December 2024

National Concrete Pavement Technology Center

IOWA STATE UNIVERSITY
Institute for Transportation

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16. Abstract

Traditional deicing methods, such as salt application and mechanical removal, incur high costs, require a seasonal workforce, and raise environmental concerns due to water contamination and material degradation. The electrically conductive concrete (ECON) heated transportation infrastructure system offers a more sustainable alternative, utilizing ohmic heating to convert electrical energy into thermal energy, thus preventing ice formation and melting snow on the pavement surface. To facilitate construction of the Iowa City bus stop enhancement project under Iowa Highway Research Board (IHRB) Project TR-789, this research provides key recommendations for ECON production techniques at ready mixed concrete plants to ensure the system's effectiveness and functionality The addition of 0.5 in. long carbon fibers to the truck mixer in stages at the job site is recommended. The recommended maximum truckload for ECON production is 6 yd^3 to prevent fiber balling. Additionally, fresh-stage electrical resistance testing is proposed to facilitate the decision of whether to accept or reject a batch. After electrical evaluation of existing full-scale ECON heated transportation infrastructure systems, small-scale ECON slabs, and small demonstration sites constructed under this study, an operating voltage of 24 volts alternating current (VAC) is advised, and a protective paint layer can be applied to the ECON slab's surface for added safety. These findings offer a framework for ECON heated transportation infrastructure system implementation, supporting safer, more efficient, and environmentally friendly snow and ice removal, essential for maintaining reliable year-round transportation in snowy regions.

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EXECUTIVE SUMMARY

An electrically conductive concrete (ECON) heated transportation infrastructure system is an innovative snow and ice removal solution for cold weather regions. Traditional snow removal practices, including the use of deicing salts and mechanical equipment, present significant challenges because these traditional methods are costly and environmentally harmful. The Iowa Department of Transportation (DOT), for example, spent $15 million in one year on rock salt and brine alone. Deicing salts can pollute natural water sources and harm aquatic ecosystems, and prolonged use can degrade pavement and vehicle materials. Mechanical snow removal equipment demands a seasonal workforce, adding to operational complexity and costs.

An ECON heated transportation infrastructure system addresses these issues by employing ohmic heating, in which electrical energy applied via electrodes embedded in the concrete pavement is converted into thermal energy, melting snow and preventing ice formation. In this system, the concrete mix must achieve a precise level of conductivity while ensuring that safety standards are met, making the ECON production stage the most critical component during the construction phase of this technology. In addition, during the approval process for this technology, electrical regulatory authorities may require electrical safety assurance that must be maintained by this technology during operation so that there is no electrical hazard.

To facilitate construction of the Iowa City bus stop enhancement project under Iowa Highway Research Board (IHRB) Project TR-789, this study's key findings and recommendations focus on ECON production, transportation, and quality control/assurance techniques at ready mixed concrete plants. Carbon fibers, specifically 0.5 in. long fibers, are recommended to provide optimal conductivity without risking performance degradation. The carbon fibers should be added in two stages at the job site to prevent clumping and ensure even distribution within the concrete. Batch sizes should also be limited to 6 yd^3 per truck to further reduce the likelihood of fiber balling. Fresh-stage electrical resistance testing on each batch before it is accepted onsite ensures that the mix meets target specifications.

After electrical evaluation of existing full-scale ECON heated transportation infrastructure systems, small-scale ECON slabs, and small demonstration sites constructed under this study, an operating voltage of 24 volts alternating current (VAC) is advised, and a protective paint layer can be applied to the ECON slab’s surface for added safety. The recommended voltage limits established in electrical installation standards are 30 VAC and 60 volts direct current (VDC), and it is recommended that the system be ungrounded. The recommendation of 24 VAC is derived from the requirement of a typical nominal system voltage that does not exceed 30 VAC.

The ECON heated transportation infrastructure system shows strong potential for maintaining transportation infrastructure in snowy regions, promising to minimize environmental impact, reduce long-term operational costs, and ensure efficient year-round traffic mobility. With these production guidelines and safety protocols, an ECON heated transportation infrastructure system can provide a sustainable, reliable alternative to traditional snow and ice removal, positioning this technology as a key solution for cold region transportation infrastructure.

1 INTRODUCTION

Maintaining year-round traffic mobility is crucial for economic growth and the advancement of civilization. Due to harsh winters with snowstorms, ensuring traffic mobility during cold months is a challenge for transportation agencies in cold regions. Northern parts of the United States, including Alaska, face snowstorms from late October to early April or beyond. From 2019 to 2023, Iowa averaged 32 in. (800 mm) of snowfall annually, with approximately 30 snow events and 66 days of precipitation each winter. During the 2023 fiscal year alone, Iowa experienced 277 hours of adverse winter weather conditions (Iowa DOT 2023), including blowing snow, freezing rain, sleet, frost, and refreezing. Traditional snow and ice removal methods such as applying deicing salts and using mechanical equipment like snowplows remain common approaches for mitigating these effects (Rahman et al. 2024).

Conventional snow removal techniques, however, have notable drawbacks. First, salt application is costly; during the 2023 fiscal year, the Iowa Department of Transportation (DOT) spent $15 million on 130,000 tons of rock salt and 32 million gal of brine (Iowa DOT 2023). Hiring seasonal personnel to manage these efforts is also complex and resource-intensive. Snow removal using traditional methods is often time-consuming, potentially delaying the clearing process. Furthermore, deicing salts—such as rock salt, salt brine, and calcium chloride—pose environmental risks because they contaminate bodies of water, harming aquatic ecosystems. These salts can also deteriorate pavement surfaces and cause corrosion to vehicle bodies, raising concerns about both environmental and infrastructure sustainability (Rahman et al. 2023a).

Innovative snow removal technologies have emerged, including electrically conductive heated pavement systems (HPS), hydronic heating, phase-change materials, and resistive-heating cables (Rahman et al. 2022). Among these, the electrically conductive concrete (ECON) heated transportation infrastructure system has shown substantial promise and is increasingly gaining attention both in the United States and globally.

Operation of an ECON heated transportation infrastructure system is based on the principle of ohmic heating. When electricity is applied to the pavement slab through embedded electrodes, the electrical energy is converted to thermal energy and raises the surface temperature to prevent ice formation or to melt existing snow. Studies on laboratory-scale ECON slabs (Malakooti et al. 2020, Sassani et al. 2018a) reported an energy conversion efficiency of approximately 50% from electrical to thermal energy, findings that were corroborated by recent research using similar tests (Rahman et al. 2024).

However, achieving optimal performance from an ECON heated transportation infrastructure system relies on precise production techniques that consistently meet the necessary electrical properties of ECON. The existing literature lacks knowledge of large-scale ECON production techniques during full-scale implementation. In addition, because the technology is meant to serve the general public, electrical safety evaluation of this technology is mandatory so that when it is encountered by regulatory authorities such as electrical inspectors, these authorities can approve the implementation of this technology within their areas of jurisdiction.

To facilitate construction of the Iowa City bus stop enhancement project under Iowa Highway Research Board (IHRB) Project TR-789, this research aimed to identify suitable production, transportation, and quality control/assurance techniques for ready mixed concrete plant-produced ECON. Under this study, electrical safety evaluation tests were conducted to determine safety protocols for mitigating electrical shock hazards during the system operation of the Iowa City bus stop enhancement project.

2 ECON PRODUCTION, TRANSPORTATION, QUALITY CONTROL/ASSURANCE

2.1 Background

To create enough heat for an effective heated transportation infrastructure system, the surface layer of an electrically conductive pavement must generate a sufficient electric field between its electrodes. For example, when powered at 240 volts alternating current (VAC), the Des Moines ECON heated transportation infrastructure system consumes approximately 35 W/ft^2 of electrical power to generate the required heat (Abdualla et al. 2018). Because standard portland cement concrete (PCC) lacks the necessary electrical conductivity, integrating conductive materials such as conductive fibers is essential to ensure that the system consumes sufficient electrical power and converts a part of it into thermal energy. Research has focused on determining suitable types and quantities of conductive materials. Carbon and steel fibers are the most commonly used conductive additives for ECON applications. At the Des Moines International Airport, an ECON heated transportation infrastructure system utilized carbon fibers at a concentration of 1 vol.%, while the ECON heated bridge deck in Roca Spur, Nebraska, incorporated 1.5 vol.% steel fibers and 20 vol.% steel shavings (Rahman et al. 2022).

Steel fibers can corrode over time, potentially impacting the heating efficiency of the system. To avoid this, carbon fiber—completely noncorrosive—is often preferred in ECON applications, especially in areas susceptible to moisture or salt exposure. However, one key issue encountered in ECON heated transportation infrastructure system projects like those at the Des Moines International Airport and Iowa DOT was that field-produced ECON exhibited a higher electrical resistance than laboratory-produced ECON, even at the same carbon fiber dosage (Rahman et al. 2022). The existing literature reports that field-produced ECON samples have exhibited up to a tenfold increase in electrical resistance compared to laboratory-produced samples (Sassani et al. 2018b) and proposes that the increase in resistance could be a result of carbon fiber degradation due to abrasion during mixing, as fewer fibers were recovered in field samples than in laboratory samples. To test this proposition, five ECON production trials were conducted under Iowa Highway Research Board (IHRB) Project TR-789, Implementing a Self-Heating, Electrically Conductive Concrete Heated Pavement System for the Bus Stop Enhancement Project in the City of Iowa City. It was found that longer mixing times significantly increased electrical resistance, likely due to the abrasive environment altering the carbon fibers from flake forms into small circular bundles (Rahman et al. 2023b). In carbon fiber-reinforced ECON, electrical conductivity depends on the formation of a conductive network among fibers that occurs either through percolation, where fibers form a continuous network, or the tunneling effect, where electrons move between nearby fibers under an electric field. Because a perfect conductive network is challenging to achieve, ECON conductivity typically relies on a combination of percolation and the tunneling effect, but fiber clumping from prolonged mixing can disrupt these connections, increasing resistance.

For an ECON heated transportation infrastructure system, designers must assume a fixed electrical resistance value to determine electrode sizing and spacing. Once ECON is placed, electrode configurations cannot be altered, meaning that production, transport, and placement processes must yield ECON with electrical properties matching design expectations. Although no studies have fully addressed ECON quality from production through placement, further research is necessary to establish production and transport methods that maintain desired conductivity in ECON.

While ready mixed concrete production and transport methods vary widely across plants, they fall into three main categories: (1) transit-mixed plants, (2) shrink-mixed plants, and (3) central-mixed plants. In transit-mixed systems, mixing can be completed at the job site, at the plant, or in transit. Shrink-mixed plants partially mix concrete in a stationary mixer before finishing in a truck mixer, while central-mixed plants complete mixing at a central location before loading concrete for delivery. Plant mixers themselves vary and include tilt-drum, horizontal or dual-shaft paddle, pan, and slurry mixers. Since ECON's electrical resistance can fluctuate with different mixing methods and times, effective production practices may differ by plant type.

This study aimed to develop a suitable ECON mixture proportion for the Iowa City bus stop enhancement sidewalk project and to identify effective production methods for ready mixed concrete plants. At these plants, materials are loaded into a truck mixer from silos, then mixed and transported to the site.

The research investigated the following:

- Optimal carbon fiber length for ECON in ready mixed plants
- Relationship between carbon fiber dosage and ECON's electrical resistance in transit-mixed production
- Mixing process:
  - Ideal stage for adding carbon fiber
  - Necessary mixing time for even fiber distribution
- Transportation process:
  - How to transport ECON from the plant to the site
  - Whether to allow agitation during transit or if a retarder should be added to extend workable time
  - Whether additional mixing at the site is advisable
- Batch size:
  - Impact of batch size on ECON quality
  - Minimum batch volume for trial production and maximum volume for final construction by plant type
- Quality control/assurance procedures to ensure ECON quality

2.2 Methodology

The research was divided into laboratory and plant trials to develop suitable mixture proportions and production techniques for ECON on a large scale, applicable to any ready mixed concrete plant in Iowa. A total of nine laboratory trials, labeled LT-1 to LT-9, were conducted at Iowa State University's Portland Cement Concrete Research Laboratory to refine the mixture designs. These designs were then applied in 12 subsequent plant trials, labeled PT-1 to PT-12.

Two ready mixed concrete plants—Manatt's Inc. in Ames and Croell Inc. in Iowa City, approximately 200 miles apart—were selected to ensure that the developed production methods could be transferred to other independent but similar facilities. Both plants followed a standardized concrete production process. Raw materials were loaded into an 11 yd^3 capacity truck mixer, where the concrete was mixed at 18 to 20 rpm during transport to the job site. Manatt's Inc. (Plant-1) was chosen because of its close proximity to the research team's laboratory, while Croell Inc. (Plant-2) was selected because it is expected to produce ECON for the upcoming IHRB Project TR-789.

The aggregate materials used at each plant were sourced from different locations and displayed distinct gradations. At Plant-1, the mixture consisted of limestone with a nominal maximum size of 1 in. as the coarse aggregate, 3/8 in. gravel as the intermediate aggregate, and natural sand passing through a #4 sieve as the fine aggregate. In contrast, Plant-2 used limestone with a nominal maximum size of 3/4 in. as the coarse aggregate and natural sand passing through a #4 sieve as the fine aggregate, with no intermediate aggregate. Although both plants used similar cementitious materials—Type IL cement and Class C fly ash from the same supplier—their air-entraining and water-reducing admixtures came from different manufacturers.

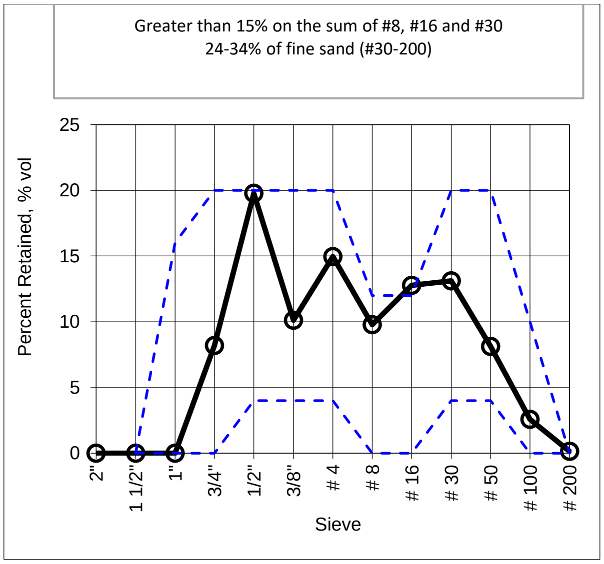
To determine the best carbon fiber length for large-scale ECON production, chopped carbon fibers (Figure 1) measuring 0.5 in. and 0.25 in. were investigated. Data from the Zoltek Corporation indicated that these fibers, made from a polyacrylonitrile (PAN) base, had a carbon content ranging from 91% to 100%, with minimal nitrogen and oxygen components ranging from 0% to 7% and from 0% to 2%, respectively.

Figure 1. Zoltek corporation PX35 chopped virgin carbon fiber

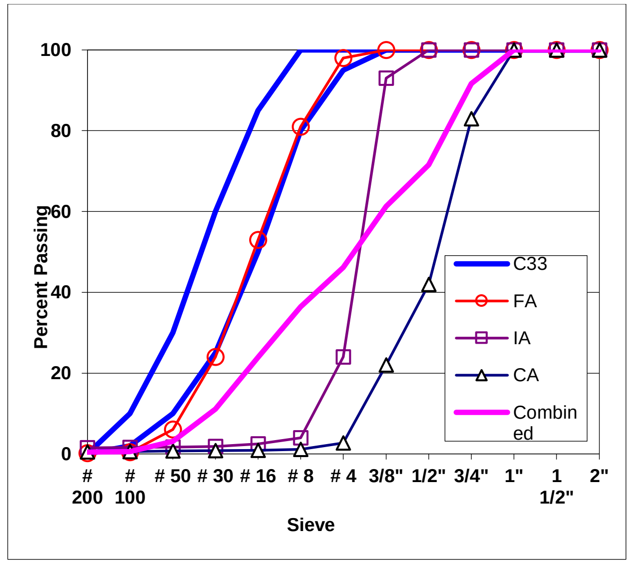
2.2.1 Laboratory Trials

Before the plant trials were conducted, laboratory trials were crucial for determining the optimal mixture proportions given the variation in fiber lengths and material differences between the two plants. The mixture designs followed the performance-engineered mixture (PEM) framework (Wang et al. 2018), which emphasizes selecting aggregate combinations based on their combined gradation to optimize the use of cement paste. For the mixture used at Plant-1, the aggregate proportions were 49% coarse aggregate, 7% intermediate aggregate, and 44% fine aggregate. In contrast, the mixture for Plant-2 utilized a 50/50 ratio of coarse to fine aggregates.

All aggregates used in both plants conformed to ASTM C33 standards, and the research team collected the materials from each plant, ensuring that they were properly stored in sealed containers until their use in the laboratory trials. The combined gradations of the two mixtures, illustrated in Figure 2, conformed to the requirements of the Tarantula curve, with the dashed lines in the figure indicating the defined boundaries. A detailed breakdown of the mixture proportions used in the laboratory trials is provided in Table 1.



(a)



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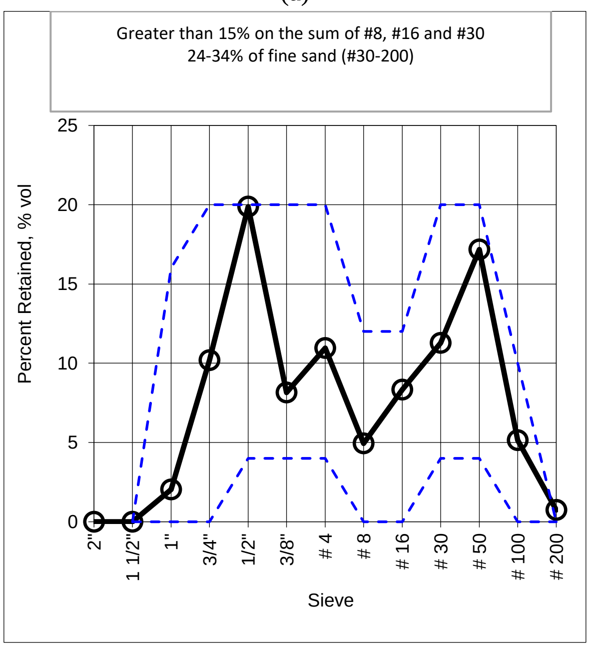

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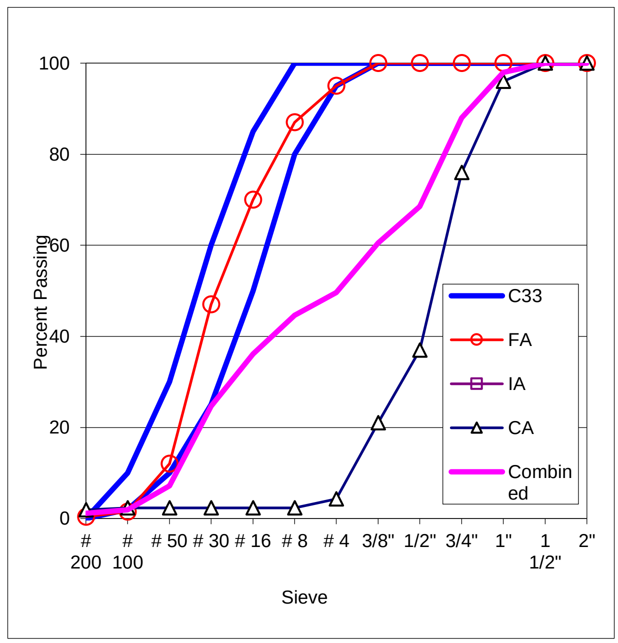


(d)

Figure 2. Plant-1 aggregates' (a) Tarantula curve and (b) individual and combined gradations and Plant-2 aggregates' (c) Tarantula curve and (d) individual and combined gradations

Table 1. Mixture proportions of ECON for laboratory trials at Iowa State University

Mixture ID	w/cm	Cement (lb/yd^3)	Class C Fly Ash (% replacement of cement)	Coarse Aggregate (lb/yd^3)	Fine Aggregate (lb/yd^3)	Intermediate Aggregate (lb/yd^3)	Carbon Fiber (vol.%) (length)
LT-1	0.42	759		1,172	1,151	151	1.25 (0.25 in)
LT-2	0.42	759		1,172	1,151	151	1.25 (0.5 in)
LT-3	0.45	776		1,111	1,111	-	1.25 (0.25 in)
LT-4	0.42	771		1,152	1,152	-	1.25 (0.25 in)
LT-5	0.42	771	15	1,152	1,152	-	1.25 (0.5 in)
LT-6	0.45	696		1,253	1,125	171	0.75 (0.5 in)
LT-7	0.45	705		1,217	1,217	-	0.20 (0.5 in)
LT-8	0.45	666		1,265	1,265	-	0.15 (0.5 in)
LT-9	0.45	666		1,265	1,265	-	0.10 (0.5 in)

* LT = laboratory trials, w/cm = water to cementitious materials ratio

Of the nine trials conducted in the laboratory, five (LT-1 to LT-5) used a carbon fiber dosage of 1.25 vol.%. The main goal of this research was to develop a concrete mixture suitable for application in IHRB Project TR-789. Given that previous studies performed during Des Moines International Airport ECON heated transportation infrastructure system construction (Sassani et al. 2018a), Iowa DOT ECON heated transportation infrastructure system construction (Malakooti et al. 2021), and IHRB Project TR-789 (Rahman et al. 2023b) reported carbon fiber degradation during plant mixing, the research team prioritized reducing the electrical resistance in laboratory samples as much as possible. This approach ensured that even if fiber degradation occurred during plant trials, the electrical resistance would not exceed the target set for the project. As a result, an initial emphasis was placed on a higher fiber content of 1.25 vol.%, nearly double the percolation threshold level identified for ECON with carbon fiber reinforcement (Sassani et al. 2018a). Generally, increasing the carbon fiber content lowers electrical resistance, but above a certain dosage, further additions do not significantly impact resistance—a phenomenon known as the percolation threshold. For ECON reinforced with carbon fibers, this threshold lies between 0.50% and 0.75 vol.% (Rahman et al. 2022). As the study continued, the research team decided to experiment with reduced carbon fiber dosages in later trials (LT-6 to LT-9) using values of 0.75, 0.2, 0.15, and 0.10 vol.%, respectively, so that a correlation could be developed between the carbon fiber dosage and the electrical resistance of concrete plant-produced ECON.

Shorter carbon fibers (0.25 in.) were incorporated in LT-1, LT-3, and LT-4, while 0.50 in. fibers were used in all other laboratory tests. In each case, the carbon fibers were introduced into the mixture during the final stage, along with the final 30% of the batch water—a process termed wet mixing in this research. Materials from Plant-1 were used for LT-1, LT-2, and LT-6, while Plant-2 materials were utilized for all other trials. Since the target application for the ECON mixture was sidewalks that require manual finishing, to achieve the desired 4 in. slump based on the Iowa Statewide Urban Design and Specifications (SUDAS) recommendation, the water-to-cementitious materials (w/cm) ratio was increased to as much as 0.45 to meet this requirement.

Figure 3(a) shows the laboratory-scale drum mixer used for producing ECON. The aggregate materials were sourced from the concrete plants and stored in sealed containers. A day before mixing, representative samples were taken to assess moisture content, and the resulting data were used to adjust the quantities of aggregates and water. From each laboratory trial, three beams (14 in. by 4 in. by 4 in.) were fabricated. Copper mesh electrodes were attached to the two longer ends of each beam, as shown in Figure 3(b). The following procedure was used for the mixing process:

- Step 1: All aggregates were loaded into the drum mixer and mixed for 30 seconds.
- Step 2: The air-entraining agent (AEA) and water-reducing admixture were mixed with one-third of the water then added to the drum mixer.
- Step 3: The ingredients were mixed for 2 minutes.
- Step 4: Cementitious materials and one-third of the mixture water were added gradually.
- Step 5: The ingredients were mixed for 3 minutes.
- Step 6: The carbon fiber and the remaining one-third of water were added to the mixer.
- Step 7: The final mix was carried out for 2 minutes.

(a)

(b)

Figure 3. (a) ECON production using laboratory-scale drum mixer and (b) ECON sample collection at Portland Cement Concrete Research Laboratory, Iowa State University

Electrical resistance (R) in each beam was measured immediately after mixing using a multimeter. The samples were demolded after 24 hours and transferred to a curing room with a water bath at room temperature (72°F). Electrical resistance measurements were taken on the hardened concrete at regular intervals up to 56 days after casting, with the samples kept moist to simulate the environmental conditions expected before and during a snow event. Moist in this case meant that the samples retained moisture on their surface due to exposure in the curing room, replicating real-world conditions. However, the tests were conducted at room temperature (72°F) and in this way differed from the colder conditions the concrete would face during operation.

2.2.2 Ready Mixed Concrete Plant Trials

To identify the optimal carbon fiber length, carbon fiber dosage rate, ECON production methods, transportation methods, and batch volume for a ready mixed concrete plant, the testing plan included ten trial batches distributed between two plants. In the first trial (PT-1) conducted at Plant-1, the mixing sequence proceeded according to the following steps:

- Step 1: At the plant, the truck mixer was loaded with all ingredients, excluding the carbon fibers and 30% of the batch water.
- Step 2: After the initial ingredients were added, the carbon fibers were introduced into the truck mixer, which was running at a slow agitation speed.
- Step 3: The remaining 30% of the batch water was then added, and the truck mixer was rotated at high speed (18 to 20 rpm).
- Step 4: After 3.5 minutes of high-speed mixing, the mixer was switched to a slow agitation mode and left the plant for the job site.

- Step 5: Once the mixer was at the job site, no additional mixing was performed, and the concrete was ready for placement.

Existing research on ECON plant production consistently indicates that adding carbon fiber at an earlier stage of the mixing process—either before incorporating other ingredients or with the aggregates prior to adding water—results in lower-quality ECON when compared to laboratory results with similar mix designs (Rahman et al. 2023b). To address this issue, the present study introduced carbon fiber at a later mixing stage, after all other components had been combined, to minimize fiber degradation by reducing its exposure time in the concrete truck mixer. Since earlier studies (Abdualla et al. 2018, Malakooti et al. 2021, Rahman et al. 2023b) reported carbon fiber degradation in plant production when using fibers 0.25 in. in length, for trial PT-1, 0.5 in. carbon fibers were selected to evaluate whether a sufficient fiber-to-fiber network could still form despite potential degradation. A carbon fiber dosage of 1.25 vol.% was used, with the goal of achieving an electrical resistance similar to that recorded during the laboratory trial (LT-2).

PT-2 was conducted at Plant-2, where the mixing process was adjusted based on the outcomes of PT-1 as follows:

- Step 1: At the plant, the truck mixer received ingredients, excluding the carbon fiber and 30% of the batch water.
- Step 2: Mixing was carried out for 5 minutes at 18 to 20 rpm before the truck left the plant for the job site, and the mixture operated at regular slow agitation during transit.
- Step 3: At the job site, carbon fibers were incorporated into the truck mixer (while the truck mixer was at slow agitation).
- Step 4: The remaining 30% of the batch water was loaded into the truck mixer, and the mixer was subjected to full-speed rotation (18 to 20 rpm).
- Step 5: After 3.5 minutes, the truck mixer was brought to slow agitation speed and the concrete was ready to pour.

The rationale behind this change will be explained later in the discussion of results. Based on the outcome of PT-2, the same ECON production technique was followed in the later trials up to PT-10. However, sensing a fiber distribution issue specifically for trials with low carbon fiber dosages (less than 0.35 vol.%), the research team modified the production technique to ensure uniform fiber distribution. This technique was then adopted in ECON production for the construction demonstration site at the Iowa DOT with 0.4 vol.% carbon fiber (discussed in Chapter 3) and for the preconstruction trial for IHRB Project TR-789 using 0.45 vol.% carbon fiber. The final recommendation regarding ECON production at a ready mixed concrete plant is as follows:

- Step 1: At the plant, the truck mixer is loaded with all ingredients, excluding the carbon fiber and 30% of the batch water.
- Step 2: The mixture is then mixed for 5 minutes at full speed (18 to 20 rpm) before the truck departs for the job site, with the mixer operating at slow agitation during transit.

- Step 3: Upon reaching the job site, 50% of the carbon fiber is added to the truck mixer while it operates at slow agitation.
- Step 4: Another 15% of the batch water is added, and the mixer is rotated at full speed (18 to 20 rpm) for two minutes.
- Step 5: The mixer is then slowed down, and the remaining 50% of the carbon fiber is added while the truck operates at slow agitation.
- Step 6: The final 15% of the batch water is added, and the mixer is rotated again at full speed (18 to 20 rpm) for two minutes, after which the concrete is ready for pouring.

According to the current ECON heated transportation infrastructure system design methodology, the required electrical resistance of the ECON must be established before determining the electrode size and spacing (Abdualla et al. 2016). However, reaching the target electrical resistance is challenging due to fiber degradation. During the laboratory trials, the research team focused initially on achieving the lowest possible electrical resistance, ensuring that it would remain below the desired limit after degradation during plant production. However, if an ECON slab system consumes more electrical power than the available capacity, it could malfunction and fail to generate the expected heat (Rahman et al. 2024). Under IHRB Project TR-789, a study was conducted to develop a comprehensive ECON HPS design methodology. Drawing from the existing literature and insights from the study under IHRB Project TR-789, the team set a target 28-day electrical resistance of 15 Ω for a beam sample measuring 14 in. by 4 in. by 4 in. with copper mesh electrodes attached to the longer ends. After reviewing the results from PT-1, the team decided to lower the carbon fiber dosage to reach the target resistance, reducing it to 1 vol.% for PT-2.

A detailed breakdown of the mixture proportions used in the ready mixed concrete plant trials is shown in Table 2.

Table 2. Mixture proportions of ECON for ready mixed concrete plant trials

Mixture ID	w/cm	Cement (lb/yd^3)	Class C Fly Ash (%replacement of cement)	Coarse Aggregate (lb/yd^3)	Fine Aggregate (lb/yd^3)	Intermediate Aggregate (lb/yd^3)	Carbon Fiber (vol.%)	Plant
PT-1	0.42	759	15	1,172	1,151	151	1.25	Manatt's
PT-2	0.42	771		1,178	1,178	-	1.00	Croell
PT-3	0.42	696		1,253	1,117	169	0.60	Manatt's
PT-4	0.45	705		1,209	1,209	-	0.60	Croell
PT-5 (6 yd^3)	0.45	705		1,209	1,209	-	0.60	Croell
PT-6	0.45	705		1,213	1,213	-	0.40	Croell
PT-7	0.45	666		1,265	1,265	-	0.15	Croell
PT-8	0.45	666		1,263	1,263	-	0.25	Croell
PT-9	0.45	666		1,261	1,261	-	0.35	Croell
PT-10	0.45	666		1,262	1,262	-	0.30	Croell

* PT = plant trials, w/cm = water-to-cementitious materials ratio, yd^3 = cubic yards

In PT-3, using the same mixing sequence as for PT-2, ECON was produced at Plant-1. Since the target electrical resistance was not met with 1 vol.% carbon fiber, the dosage was further reduced to 0.6 vol.% in PT-3. However, because the team was satisfied with the mixing process performance adopted in PT-2, the same process was followed for PT-3 to confirm its effectiveness across different ready mix plants. The target resistance was achieved in PT-3, so PT-4 was conducted at Plant-2 to ensure that the same resistance could be reached using Plant-2's materials and facilities. This was critical because Plant-2 was selected to produce ECON for IHRB Project TR-789.

The batch volume for PT-1 through PT-4 was 3 yd^3. To verify that the wet mixing process could ensure uniform carbon fiber distribution during large-scale ECON production, PT-5 was conducted with a 6 yd^3 batch at Plant-2. For PT-6 through PT-10, the batch volume was reduced back to 3 yd^3. These trials, held at Plant-2, utilized varying carbon fiber dosages to establish a correlation between the carbon fiber dosage and the 28-day electrical resistance of plant-produced ECON.

The concrete produced in the plant trials was used to construct pavement slabs for either a sidewalk or parking lot at the Iowa DOT facilities in Ames and Iowa City (Figure 4). The purpose of this site construction was to validate the task of developing design guidelines for ECON heated transportation infrastructure system under IHRB Project TR-789.

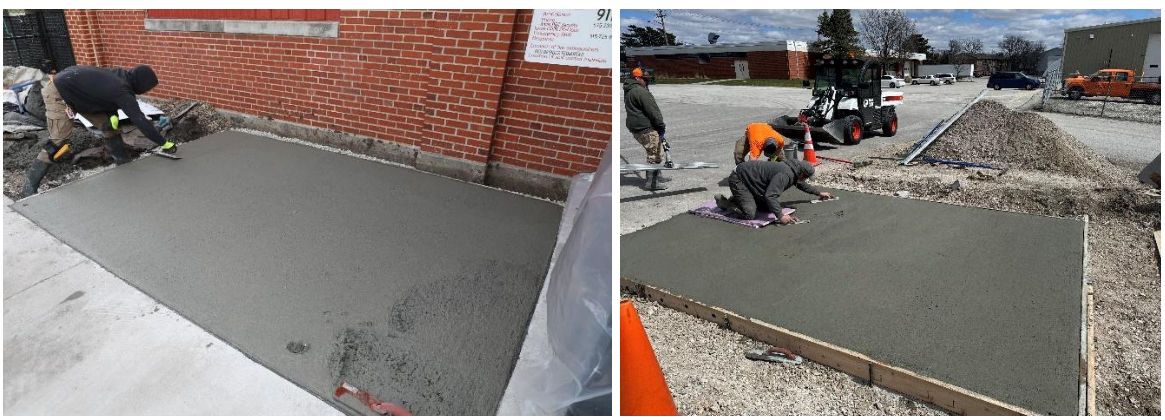


Figure 4. Small-scale ECON HPS pavement slab preparation

Similar to the laboratory trials, beam samples were fabricated during the plant trials to evaluate performance (Figure 5). Fresh-stage electrical resistance (R) measurements were taken from beam samples collected onsite immediately after ECON production for all trials. However, for PT-1, where carbon fiber was added at the plant, the concrete underwent additional mixing due to the slow rotation of the truck mixer during transit. To account for potential degradation, the research team collected additional samples from the plant for this trial to compare and evaluate differences in electrical resistance. After measuring the fresh-stage electrical resistance, the samples were left onsite for a day to harden sufficiently before being transported to the Iowa State University laboratory curing room without risking damage. Electrical resistance measurements were taken on the hardened concrete at regular intervals for up to 56 days after casting, with the samples kept moist to simulate the environmental conditions expected before and during a snow event. Moist in this case meant that surface moisture was maintained on the samples due to exposure in the curing room, mimicking real-world conditions. However, the tests were conducted at room temperature (72°F) and in this way differed from the colder conditions the concrete would experience during actual operation.

Figure 5. ECON sample collection from ready mixed concrete plant trials

2.3 Results and Discussion

2.3.1 Laboratory Trials

Figure 6 shows the electrical resistance data obtained at both the fresh and 28-day stages across all of the laboratory trials. The results demonstrated an inverse relationship between carbon fiber dosage and electrical resistance, with the most noticeable increase occurring at dosages below 0.75 vol.%. Mixtures containing longer carbon fibers also consistently showed lower electrical resistance compared to those with shorter fibers, regardless of the source of the other materials. A statistical analysis was performed to assess whether the differences in electrical resistance between various trials were statistically significant. F-tests on all laboratory samples revealed that the null hypothesis (H0) could be rejected ($p\text{-value} < 0.0001 < 0.05$) with a confidence level of 95% ($\alpha = 0.95$), meaning that at least one laboratory trial had a mean electrical resistance distinct from the others.

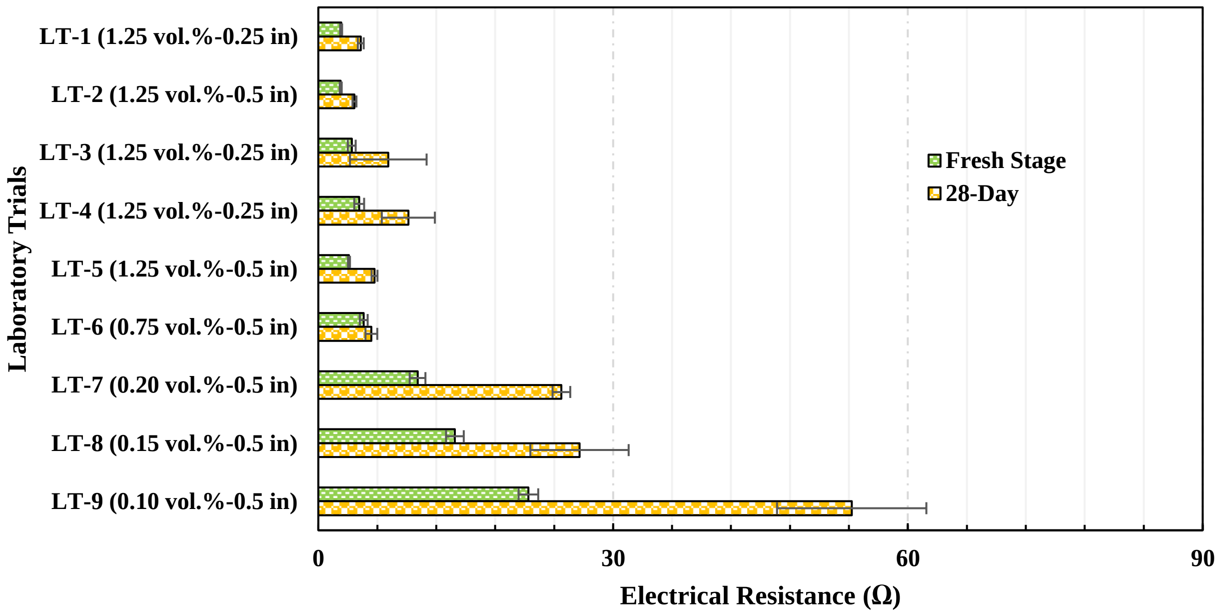


Figure 6. Laboratory trial samples' electrical performance

To further break down the differences between the laboratory trials, Tukey's Honest Significant Difference (HSD) method was applied to the 28-day data. Tukey's HSD is a post hoc test used after an analysis of variance (ANOVA) to determine which group means are significantly different from one another. Two group means (μ_i, and μ_j) are considered significantly different if the absolute difference between their sample means ($\overline{y_{i.}} - \overline{y_{j.}}$) exceeds the HSD value calculated using Equation 1.

$$\mathrm{HSD} = \frac{\mathrm{q}_\alpha(\mathrm{a,N{-}a})}{\sqrt{2}}\sqrt{\mathrm{MS}_{\mathrm{Error}}(\frac{1}{\mathrm{n_i}} + \frac{1}{\mathrm{n_j}})} \tag{1}$$

In this equation, $q_\alpha(a, N - a)$ represents the critical value from the studentized range distribution, *a* refers to the number of groups, and *(N-a)* denotes the degrees of freedom for the error term. The terms $n_i$and n_j correspond to the sample sizes of the respective groups. When the groups have the same sample size, Equation 1 simplifies to Equation 2:

$$\mathrm{HSD} = \mathrm{q}_\alpha(\mathrm{a, N - a})\sqrt{\frac{\mathrm{MS_{Error}}}{\mathrm{n}}} \tag{2}$$

Figure 7 summarizes the results of this analysis, showing that the mean electrical resistance for LT-9 was significantly different from those in all other trials at the 95% confidence level. Conversely, the mean resistance values for LT-1 through LT-6 did not significantly differ from one another. Similarly, the LT-7 and LT-8 values were statistically similar, but those from LT-1 to LT-6 differed.

Batch	LT-9	LT-8	LT-7	LT-4	LT-3	LT-5	LT-6	LT-1	LT-2
Least Sq. Mean Electrical Resistance (Ω)	54.3	26.60	24.70	9.20	7.10	5.70	5.40	4.30	3.70

Figure 7 Tukey's HSD analysis on all the laboratory trial samples (trials of different colors are significantly different)

The findings from the Tukey's HSD test indicate that the length of the carbon fiber did not impact the electrical resistance at a dosage rate of 1.25 vol.%. Additionally, despite variations in the aggregates and admixtures used at different plants, electrical resistance remained consistent for the same carbon fiber dosage across all trials. An important takeaway from this analysis is that above a 0.75 vol.% carbon fiber dosage, there is no substantial reduction in electrical resistance, because the conductive network is already established at this dosage level, aligning with the percolation threshold theory widely recognized in the literature (Sassani et al. 2018a).

2.3.2 Ready Mixed Concrete Plant Trials

Figure 8 shows the electrical resistance data obtained at both the fresh and 28-day stages across all of the ready mixed concrete plant trials. In plant trial PT-1, the key objective was to evaluate whether adding carbon fibers during the final stage of mixing (wet mixing) could result in electrical properties comparable to those achieved in laboratory conditions at the same carbon fiber dosage. A secondary goal was to assess whether the carbon fibers were uniformly distributed throughout the mix. The average fresh-stage electrical resistance for samples taken immediately after production at Plant-1 was measured to be 5.0 Ω, with a standard deviation of 0.1. By the 28-day mark, the resistance had increased to 10.2 Ω, with a standard deviation of 0.5. These values were approximately double those recorded in laboratory trial LT-2, which utilized the same materials, including 0.5 in. fibers at a 1.25% volume dosage. However, the low standard deviation in resistance across the samples suggests good fiber distribution, especially considering that samples were taken from various points within the truckload.

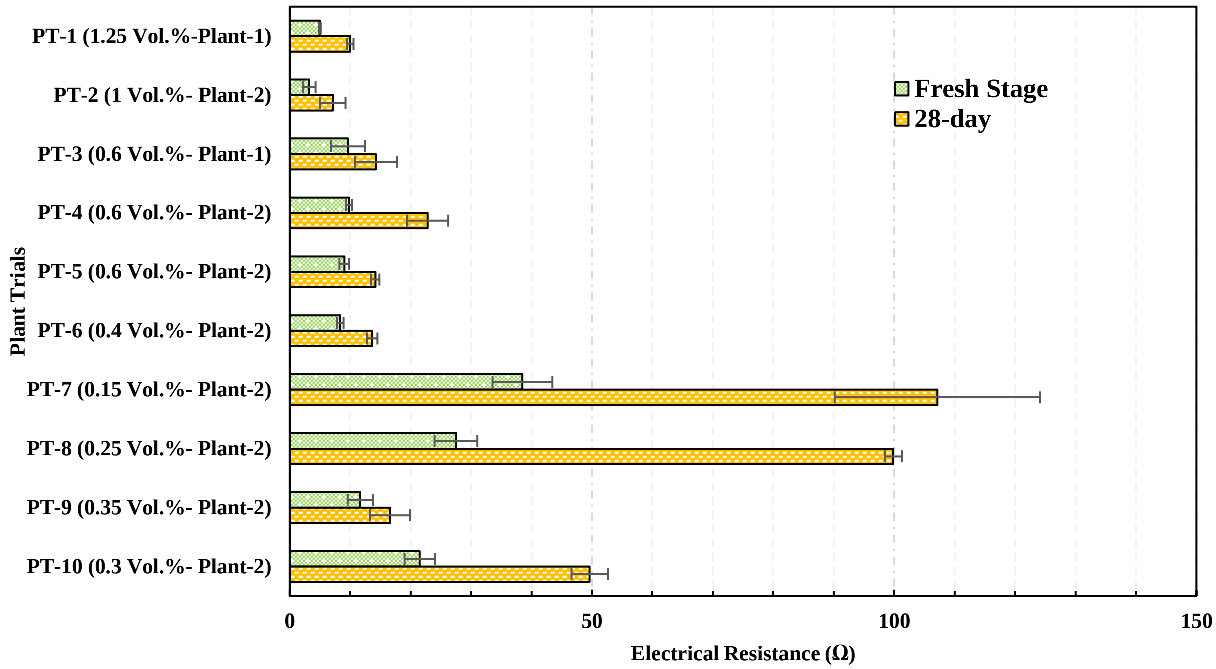


Figure 8. Ready mixed concrete plant trial samples' electrical performance

While the electrical resistance values in PT-1 were roughly twice those recorded in LT-2, the increase was far less significant than reported in previous studies, where plant-produced ECON exhibited up to a tenfold rise in resistance compared to laboratory-produced samples (Malakooti et al. 2020, Rahman et al. 2023b, Sassani et al. 2018b). This smaller increase could be due to minor degradation of the carbon fibers inside the truck mixer.

The ECON produced at Plant-1 was transported for 20 minutes to the job site, with the mixer running at a slow agitation speed during the trip. The samples collected at the job site exhibited a much higher average fresh-stage electrical resistance of 95 Ω, with a standard deviation of 8, and a 28-day resistance of 635 Ω, with a standard deviation of 15. The main difference between the samples from the plant site and job site was the extended mixing time during transit, confirming that prolonged mixing leads to fiber degradation, in turn increasing electrical resistance.

In light of the results from PT-1, the research team determined that for further ready mixed concrete plant trials, to minimize fiber degradation during transit, carbon fiber should be added directly at the job site rather than at the plant. Consequently, as mentioned earlier, a different mixing procedure was employed in PT-2 than in PT-1, with the carbon fiber being introduced onsite for PT-2.

A key factor in ECON's electrical performance is that neither excessively high nor low electrical resistance is suitable for heating pavement applications. If the resistance exceeds the target, the system will consume less power than designed, leading to slower heating. Conversely, if the resistance is too low, the system may draw more power than required, risking damage to the system and potentially rendering it inoperable (Rahman et al. 2024). Since PT-1, which used

1.25 vol.% carbon fiber, resulted in a 28-day electrical resistance below the target of 15 Ω, the research team reduced the carbon fiber content to 1 vol.% for PT-2.

The 28-day mean electrical resistance for PT-2 was measured to be 7.14 Ω, with a standard deviation of 2.5. While this result confirmed that introducing carbon fiber at the job site is a viable method for future ECON production, the lower-than-expected resistance prompted further reductions in fiber dosage. Subsequent tests for LT-6 and LT-7, which used 0.75 vol.% and 0.2 vol.% carbon fiber respectively, produced resistance values ranging from 5.40 Ω to 24.70 Ω (Figure 6). Based on these results, the team adjusted the dosage to 0.6 vol.% for PT-3, yielding an electrical resistance of 14.24 Ω, closer to the target value.

Given that Plant-2 was chosen for ECON production for the construction project carried out under IHRB Project TR-789, it was essential to verify that the developed mixing process was adaptable to the ready mixed concrete plant in Iowa City. To this end, PT-4 (3 yd^3) and PT-5 (6 yd^3) were conducted at Plant-2 using 0.6 vol.% carbon fiber. The larger volume of PT-5 aimed to evaluate both whether uniform fiber distribution could be achieved and whether the ECON quality would remain consistent. While PT-5 showed no noticeable variation in 28-day resistance compared to PT-3, the PT-4 samples exhibited a higher 28-day resistance due to increased air content, despite achieving a fresh-stage resistance similar to that of PT-3 and PT-5. When ECON is in a fresh state, the moisture content allows for sufficient electron flow between electrodes, but once the concrete hardens, the electrical resistance depends primarily on the carbon fiber network and internal concrete structure. Higher air content can hinder electron flow, leading to increased resistance. For PT-4, a higher w/cm ratio was used to meet the workability requirement of the hand-finished sidewalk project. The increase in air-entraining admixture resulted in higher air content, necessitating adjustments for PT-5, subsequently achieving the desired results.

In PT-6 through PT-10, the team explored different carbon fiber dosages to establish a correlation between fiber content and electrical resistance. Figure 9 shows a considerable increase in resistance below a certain carbon fiber dosage for both the plant and laboratory trial batches. As observed in PT-1, the plant trial samples generally had twice the resistance of their laboratory counterparts, indicating a different percolation threshold for carbon fiber in plant-produced ECON.

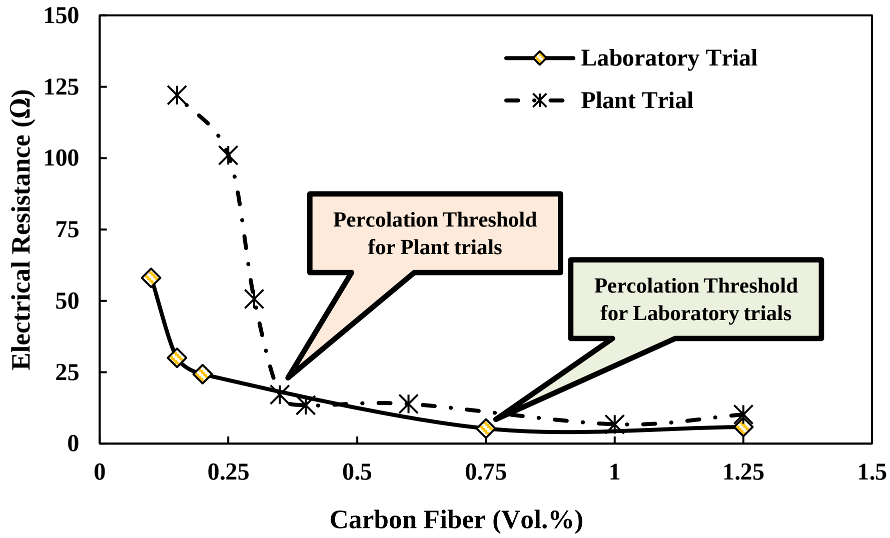


Figure 9. Percolation threshold of carbon fiber in ECON

An F-test conducted across all plant trials rejected the null hypothesis (H0) (p-value $< 0.0001 < 0.05$), indicating a significant variation in mean electrical resistance among plant trials. Analysis using Tukey's HSD method revealed that at a 0.95 significance level, trials with 0.15, 0.25, and 0.30 vol.% carbon fiber had significantly different results compared to other trials (Figure 10). As a result, the percolation threshold for carbon fiber in plant-produced ECON was determined to be 0.35 vol.%.

Batch	PT-7	PT-8	PT-10	PT-4	PT-9	PT-3	PT-5	PT-6	PT-1	PT-2
Least Sq. Mean Electrical Resistance (Ω)	107.12	99.84	49.62	22.84	16.58	14.24	14.16	13.66	10.00	7.14

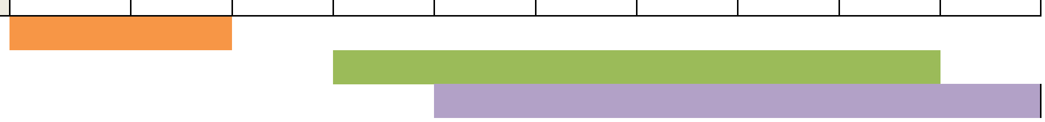


Figure 10. Tukey's HSD analysis on all of the ready mixed concrete plant trial samples (trials of different colors are significantly different)

2.4 ECON Quality Control/Assurance

A critical challenge during ECON field construction was determining how to assess concrete quality to decide whether to accept or reject a batch. While traditional methods for evaluating fresh PCC quality focus on workability and air content, assessing ECON quality requires consideration of not only these factors but also electrical properties. However, the existing literature does not provide guidance on this.

To address this gap, the research team analyzed resistance data gathered during this study as well as data from two previous studies (Rahman 2023, Rahman et al. 2023b). The increase in electrical resistance over time for approximately 100 samples was analyzed. The electrical resistance was measured at various stages—fresh, 1 day, 7 days, 14 days, 21 days, 28 days, and 56 days—and the natural logarithm (ln) of the data was taken to facilitate comparison. To calculate the factor increase in resistance over time, each reading was divided by the fresh-stage value. Figure 11 shows the average resistance factor increase for all samples at different ages. The data revealed that electrical resistance in ECON grows exponentially during the first 7 days, after which the increase slows, with no significant rise observed after 28 days.

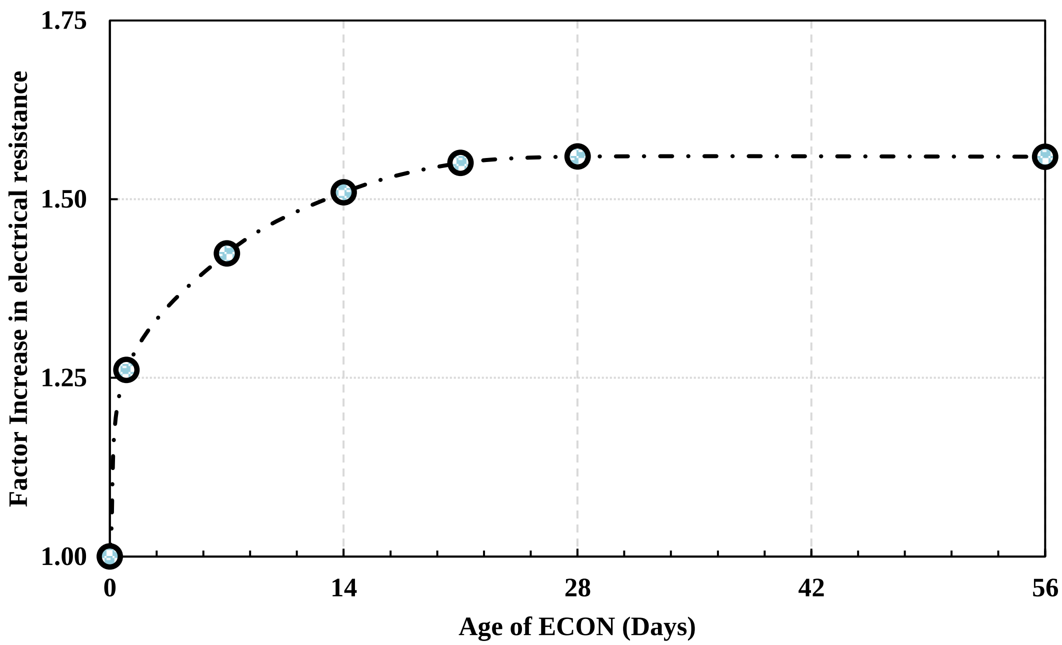


Figure 11. Factorial increase in electrical resistance of ECON with age

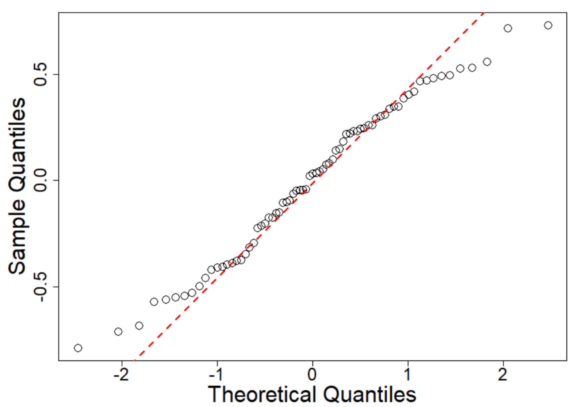
When designing components such as electrode spacing and wiring configurations for ECON heated transportation infrastructure systems, engineers must consider the appropriate level of electrical resistance to estimate the system's power requirements. Since no significant resistance increase was noted beyond 28 days, this 28-day resistance value can be considered the design resistance for determining other design parameters. Therefore, creating a statistical prediction model for 28-day electrical resistance based on fresh-stage measurements is essential for quality control/assurance during ECON production and placement.

To develop such a model, the data set of approximately 100 samples was randomly divided into two parts: 80% for model development and 20% for accuracy testing. Given the exponential nature of the resistance increase, the natural logarithm of the data was used to develop a linear model. Equation 3 presents the model for predicting 28-day resistance (Y) based on fresh-stage resistance (X) for an ECON beam of 14 in. by 4 in. by 4 in, with copper mesh electrodes on the long sides. The coefficient C1 is 1.04 with a 95% confidence interval (CI) of 0.86 to 1.25, and

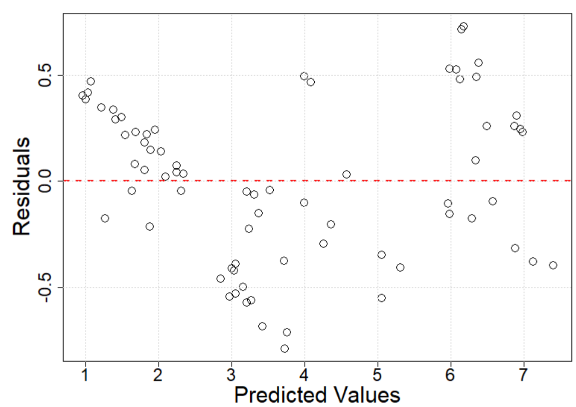
C2 is 1.41 with a CI of 1.35 to 1.47. When applied to the 20% test data, the model yielded a coefficient of determination (R^2) of 0.97.

$$Y = C_1 \times X^{C_2} \tag{3}$$

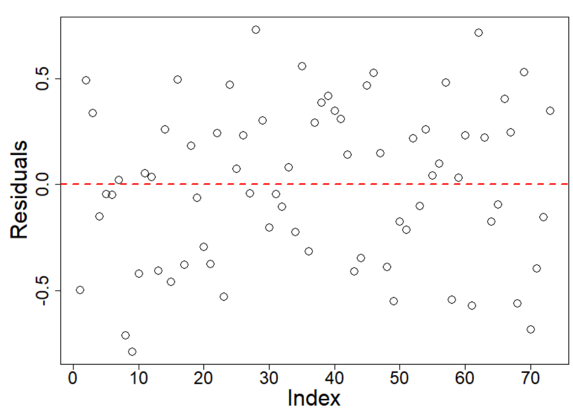
During model development, three key assumptions were made regarding the data set: normality, constant variance, and independence. Based on Figure 12a and considering the data set size, normality was generally upheld, with only minor deviations at the tails. Figure 12b indicates that the variance was relatively consistent throughout, suggesting no violation of constant variance. Since no discernible pattern was observed in Figure 12c, independence was confirmed. Equation 3 can be utilized in electrical resistance testing of fresh concrete beams as a tool for quality control and assurance. For example, if the target 28-day electrical resistance for an ECON heated transportation infrastructure system project is 50 Ω, the fresh-stage electrical resistance measured at the plant or job site should range between 12 Ω and 20 Ω (based on the confidence intervals of the model coefficients), as shown in Table 3. Any batch outside of this range should be rejected. Future research should aim to develop a model based on a more extensive data set for improved robustness.



(a)



(b)



(c)

Figure 12. R output to assess potential violations of assumptions in the 28-day electrical resistance prediction model: (a) normality, (b) constant variance, and (c) independence

Table 3. Calculation of desired range for fresh stage electrical resistance for the hypothetical example

C_1	C_2	Required Fresh Stage Electrical Resistance (Ω)
0.86	1.35	20
0.86	1.47	16
1.25	1.35	15
1.25	1.47	12

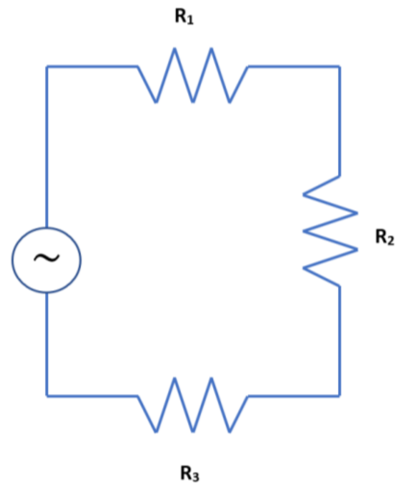
3 ECON HEATED TRANSPORTATION INFRASTRUCTURE SYSTEM'S ELECTRICAL SAFETY

3.1 Background

Because ECON technology is encountered by regulatory authorities, such as electrical inspectors, permitting guidelines and applicable inspections must be included in the planning. Some delays by regulatory authorities could occur before acceptance of such installations due to these authorities' unfamiliarity with the technology and the potential risks arising from exposure to the general public.

Because ECON heated transportation infrastructure system technology is exposed to people in a wet contact environment, electrical safety in terms of both shock and burn hazards must be considered. According to the existing literature (Fish and Geddes 2009), the electrical resistance of human skin ranges from 1,000 Ω to 100 kΩ, depending on factors such as moisture (dry or wet conditions) and contact area. The electrical resistance of internal bodily systems, including the nervous system, blood vessels, and muscles, is significantly lower (around 300 Ω) due to the presence of wet and salty tissues.

If a person touches the surface of an ECON slab with bare skin at two points from any part of the body, such as hands or feet, completing an electrical circuit, there is a potential risk of electrical shock. The main barrier to the flow of hazardous current and shock injury would be the skin resistance at the two points of contact. The possible contact paths could be two bare hands, two bare feet, two other exposed body parts, or some combination of these. If the power system to the ECON system is grounded, another possible path would be contact with the ECON slab and any grounded metal or the earth. A wet surface and/or wet skin will reduce the skin resistance and increase the hazard. If the surface or contact voltage of the ECON slab is high enough to overcome the skin resistance, it may allow an unsafe current to pass through the human body. In this scenario, the human body can be modeled as shown in Figure 13, where the total body resistance is the sum of the internal body resistance (R2) and two external skin resistances representing the two points of contact (R1 and R3). The overall electrical resistance of a human body can vary from 2.3 kΩ to 200.3 kΩ.



Fish and Geddes 2009

Figure 13. Current flow model through human body touching ECON HPS with at least two points of external skin contact

According to the literature (Fish and Geddes 2009), any current below 1 mA at 60 Hz AC power is barely perceptible to humans, while 16 mA is the maximum current that an average person can tolerate and still “let go” without suffering significant injury. The threshold for ventricular fibrillation that can cause fatal heart irregularities is approximately 100 mA. Safety standards set protective devices such as ground fault circuit interrupters (GFCI) to open when 5 mA could be passing through the body. Considering 16 mA as the maximum limit for current passing through the human body, the maximum surface voltage measured on any ECON surface is approximately 36 VAC in dry conditions.

Contrary to various criteria presented in some literature, the National Electric Code (NEC) and Underwriters Laboratories (UL) have established different standards for defining safe contact voltage limits. These standards generally follow internationally adopted standards for protection from electric shock hazards. According to the NEC and UL, there is no risk of electrical shock if the surface voltage of the ECON slab is below 30 VAC for dry contact. Should the voltage exceed this threshold, NEC and UL limit the maximum leakage current to 0.5 mA. For electrical products that have wet contact, such as products used outdoors and exposed to weather, the safe voltage limit is 15 VAC, and the limit for leakage current remains same. Currently, the NEC and UL have no specific criteria for ECON heated transportation infrastructure systems. Recent changes have been enacted to the NEC, and UL is in the process of possibly developing applicable requirements into a standard. However, at this time, treating an ECON heated transportation infrastructure system as an electrical product in a wet environment (considering the expected meltwater from snow and ice) is the approach being used for assessing electrical safety. This perspective seems to be a logical path until the NEC and UL establish criteria specifically tailored to ECON heated transportation infrastructure systems.

To measure leakage current, UL 101, Standard for Safety for Leakage Current for Utilization Equipment (Sixth Edition, dated July 31, 2017), refers to the circuit model in Figure 14, which includes resistors (R1, R2, and R3 with values of 1,500 Ω, 500 Ω, and 10k Ω) and capacitors (C1 and C2 with values of 0.22 μF and 0.022 μF), designed for AC frequencies up to 100 Hz. This network is used for measuring the startle reaction current for humans.

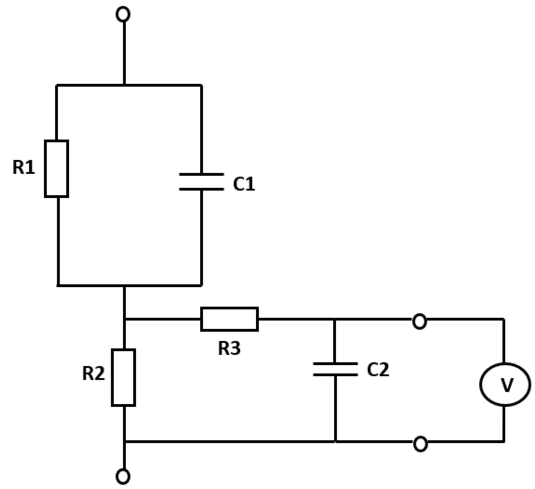


Figure 14. Leakage current measuring circuit for AC at frequencies up to 100 Hz

To ensure the compliance of the ECON heated transportation infrastructure systems constructed for IHRB Project TR-789 with NEC and UL specifications, an electrical safety assessment was conducted. This involved measuring surface voltage and leakage current at existing ECON heated transportation infrastructure system sites at the Des Moines International Airport and the Iowa DOT main offices in Ames. Subsequent tests were performed on laboratory-scale ECON slabs and on a demonstration sidewalk for the ECON heated transportation infrastructure system at another Iowa DOT facility in Ames. The evaluations were carried out in collaboration with cdcmello Consulting LLC and UL field evaluation staff. The testing aimed to assess potential safety risks and propose solutions to mitigate any issues identified from the testing data acquired.

3.2 Methodology

3.2.1 Testing Existing Full-Scale ECON Heated Transportation Infrastructure System Sites

Two existing ECON heated transportation infrastructure system sites, the main offices of the Iowa DOT and the Des Moines International Airport, were visited by individuals from cdcmello Consulting LLC, the UL field evaluation group, and the Iowa State University research team.

For the Iowa DOT ECON heated transportation infrastructure system site located in Ames, Iowa, testing was planned on the selected spots shown in Figure 15. Prior to testing, the Iowa State University research team marked the electrode locations with the use of an ultrasonic tomograph MIRA 3D device, which detects the location of metal embedded inside concrete surfaces in a nondestructive way (Figure 16).

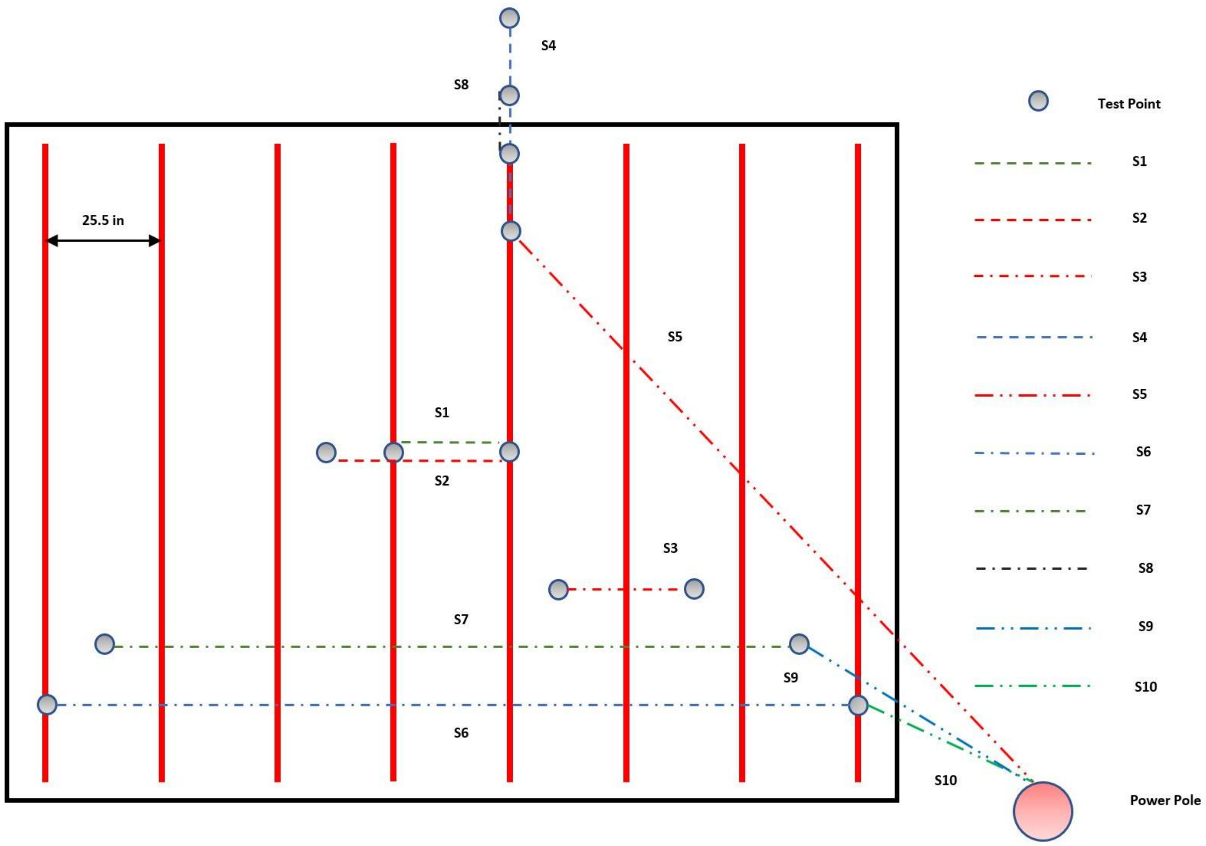


Figure 15. Electrical safety evaluation test plan for the Iowa DOT ECON heated transportation infrastructure system site in Ames, Iowa

Figure 16. Electrode location marking by the Iowa State University research team

The Iowa DOT ECON heated transportation infrastructure system uses a 208/120 VAC three-phase power supply and has 10 segregated ECON slabs. Due to some operational issues, testing was only completed on the slab having 8 flat electrodes (1 in. by 1/8 in.) spaced 25.5 in. apart. This slab had the highest power density consumption considering the electrical properties of the slabs (Malakooti et al. 2021). Ten scenarios were created considering the possible electrical shock hazard in real life if a human were to complete an electrical circuit (Table 4).

Table 4. Electrical safety evaluation test scenarios for the Iowa DOT ECON heated transportation infrastructure system site in Ames, Iowa

Scenario	Explanation
S1	Both test points directly above the inside electrodes (spacing 25.5 in.)
S2	One test point directly above the inside electrode and the other midpoint between two inside electrodes (spacing 38.25 in.)
S3	Midpoint between two inside electrodes (spacing 25.5 in.)
S4	One test point directly above the inside electrode and the other on the ground earth surface (spacing 18 in.)
S5	One test point directly above the inside electrode and the other connected to the ground rod at the service transformer power pole
S6	Test points directly above the electrodes located at the two outside electrodes (spacing 14.875 ft)
S7	Test points on the midpoints between the outer electrodes on either side (spacing 12.75 ft)
S8	One test point directly above the inside electrode and the other on the ground earth surface (spacing 12 in.)
S9	One test point directly above the outside electrode and the other connected to the ground rod at the service transformer power pole
S10	One test on the midpoint between the outer electrodes and the other connected to the ground rod at the service transformer power pole

At the Des Moines International Airport ECON heated transportation infrastructure system site, testing was planned on the selected spots shown in Figure 17. The Des Moines International Airport ECON heated transportation infrastructure system uses a 240 VAC three-phase power supply and has two ECON slabs, each consuming a power density of approximately 35 W/ft^2 (Abdualla et al. 2018). Testing was conducted on one of the two slabs having six angled electrodes (1.5 in. by 1.5 in. by 1/8 in.) spaced 36 in. apart. Eight scenarios were created considering the possible electrical shock hazard in real life were a human to complete an electrical circuit (Table 5).

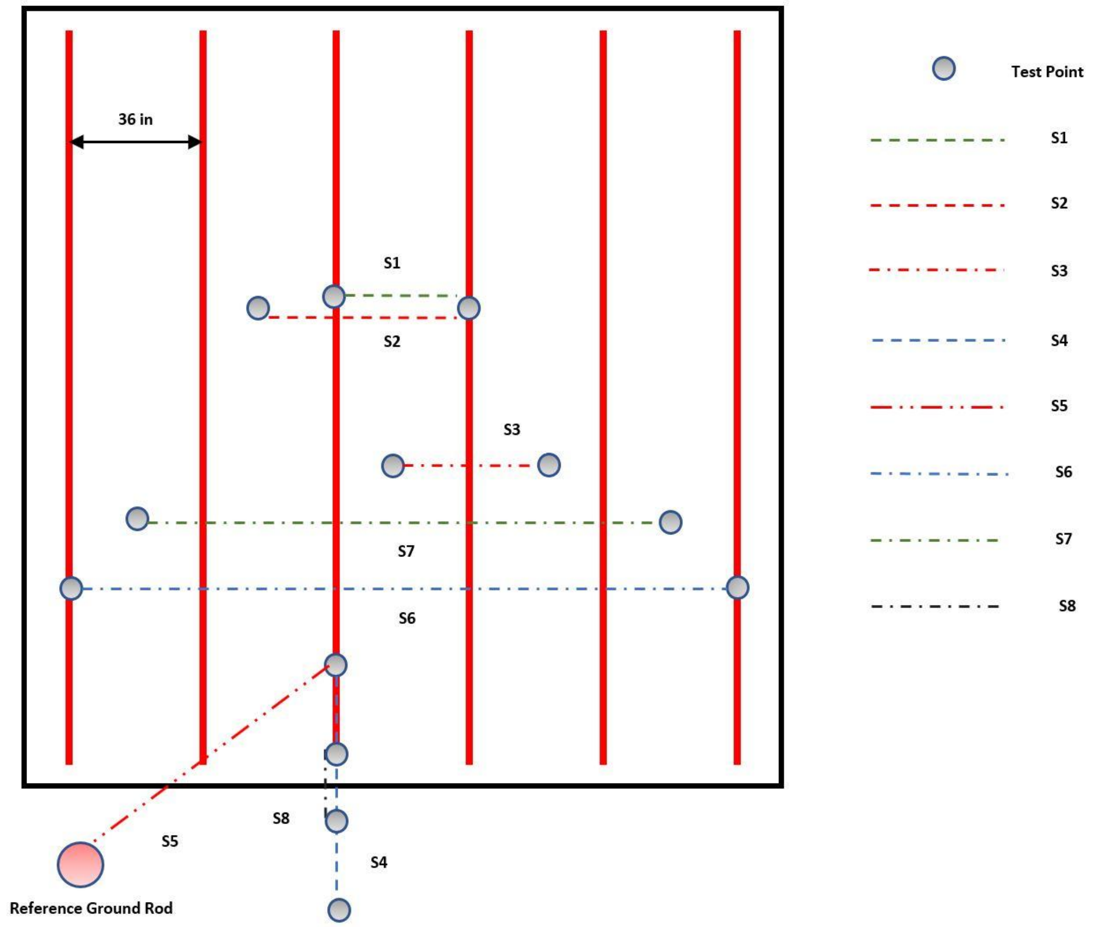


Figure 17. Electrical safety evaluation test plan for the Des Moines International Airport ECON heated transportation infrastructure system site

Table 5. Electrical safety evaluation test segments for the Des Moines International Airport ECON heated transportation infrastructure system site

Scenario	Explanation
S1	Both test points directly above the inside electrodes (spacing 36 in.)
S2	One test point directly above the inside electrode and the other midpoint between two inside electrodes (spacing 54 in.)
S3	Midpoint between two inside electrodes (spacing 36 in.)
S4	One test point directly above the inside electrode and the other on the ground earth surface (spacing 18 in.)
S5	One test point directly above the inside electrode and the other connected to the ground rod through a builder circuit-breaker panel
S6	Test points directly above the electrodes located at the two outside electrodes (spacing 15 ft)
S7	Test points mid-point between the outer electrodes on either side (spacing 14 ft)
S8	One test point directly above the inside electrode and the other on the ground earth surface (spacing 12 in.)

To replicate foot contact by a human, sponges wrapped with aluminum foil were used (Figure 18). Concrete bricks were placed on the sponges, ensuring suitable contact of the foil to the ECON surface so that the whole setup mimicked a scenario in which a human is touching the ECON slab surface. Measurements were taken on the wet slab both before and after spraying saltwater solution on the slab. To prepare the saltwater solution, 0.67 oz of $CaSO_4$ salt was mixed into 1 US gal of distilled water, a mixture taken from applicable UL standards for this type of testing. Figure 19 shows the data collection process during the site visits. Voltage was measured using multimeters (calibrated). To measure leakage current, a custom-made leakage current network constructed in accordance with UL 101 and UL 61010-1 was used (Figure 20). This is a standard network specified in several UL standards and International Electrotechnical Commission (IEC) standards.

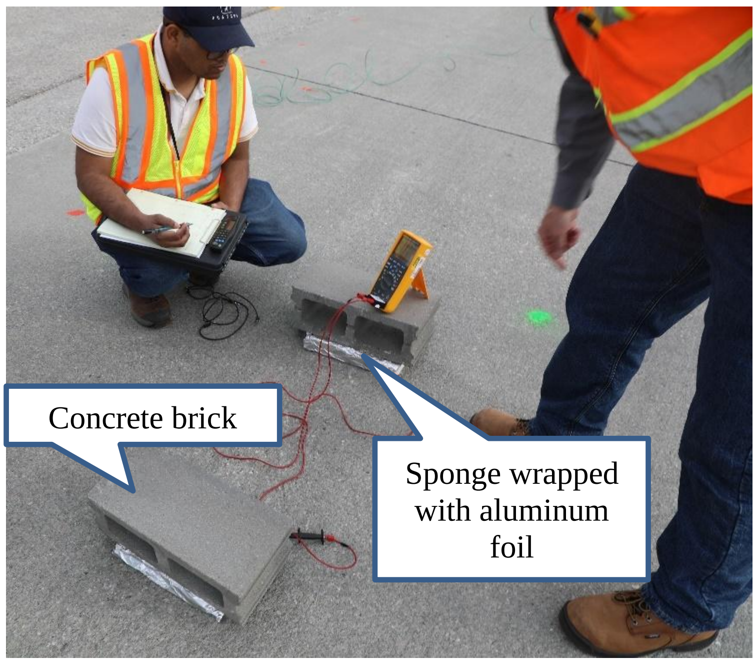


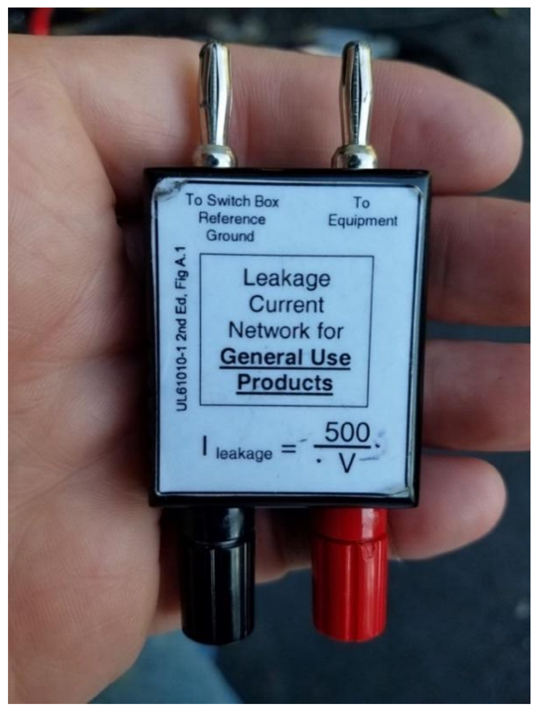
Figure 18. Sponge-brick setup for electrical safety evaluation

(a)

(b)

Figure 19. Electrical safety evaluation: (a) Iowa DOT and (b) Des Moines International Airport ECON heated transportation infrastructure system

(a)



(b)

Figure 20. Leakage current tester: (a) inside and (b) front view

3.2.2 Testing Laboratory ECON Slab Sample

Crack development in concrete pavement is inevitable, raising potential concerns related to the effects of cracks on surface contact voltages. While the ECON heated transportation infrastructure system is in operation, if a crack occurs, melt water from snow can soak the crack and introduce conductive contaminate materials, potentially leading to an electrical shock hazard. An additional electrical safety evaluation on ECON slabs with simulated cracks was therefore necessary to understand possible electrical safety issues. For this study, the Iowa State University research team constructed an ECON slab (2 ft by 2 ft by 6 in.) with two embedded angled electrodes (2 in. by 2 in. by ¼ in.) spaced 16 in. apart (Figure 21). With 24 VAC applied, the slab consumed approximately 40 W/ft^2 of power.

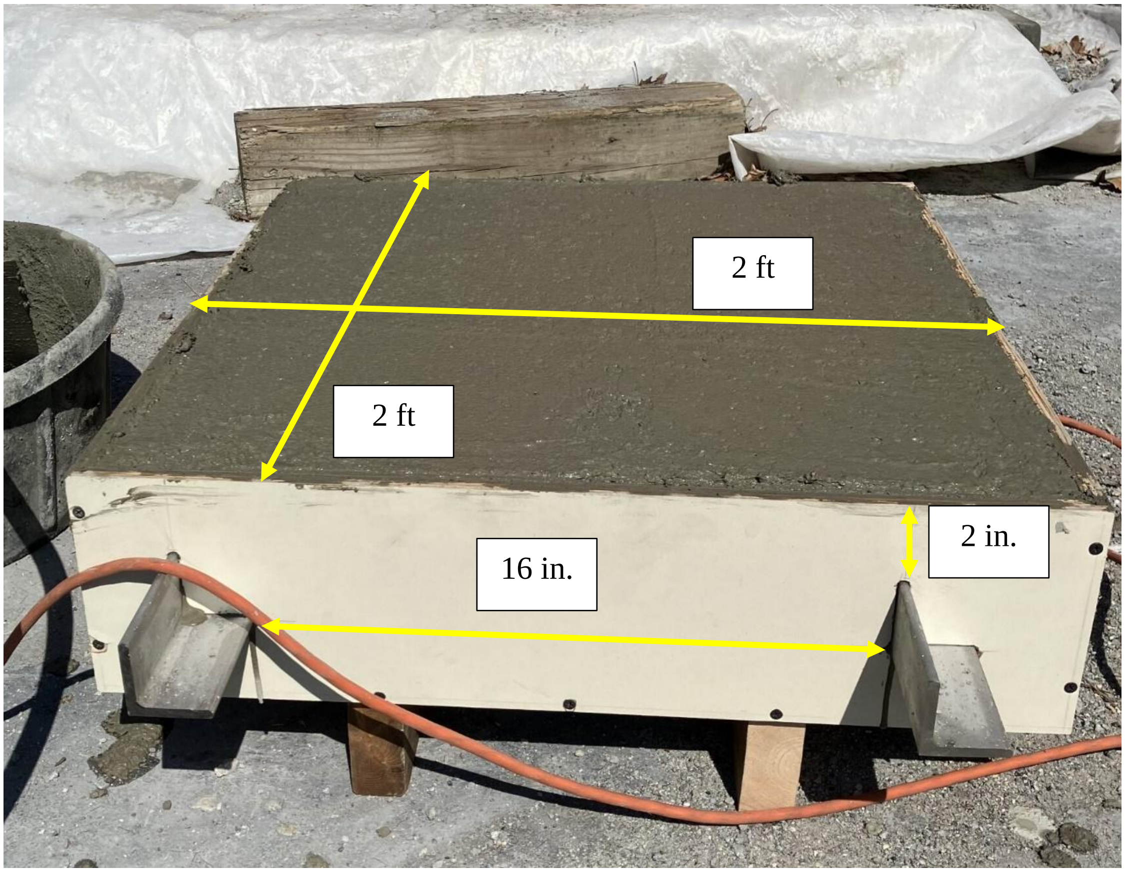


Figure 21. Laboratory-scale ECON slab

Measurements were taken in three stages. First, before introducing any cracks, electrical surface voltage measurements were taken on section 1-1 and section 2-2 (Figure 22). Electrical measurements were taken on section 1-1 for scenario S1 (a human stepping directly above the electrodes along section 1-1) and on section 2-2 for scenario S3 (a human stepping directly above the electrodes along section 2-2). Only surface voltage testing using a multimeter (calibrated) was conducted at this stage. A sponge-brick setup similar to that shown in Figure 18 was used (Figure 23a) to replicate human feet, and testing was conducted as shown in Figure 23b. Measurements were taken only under wet conditions after soaking with saltwater at this stage.

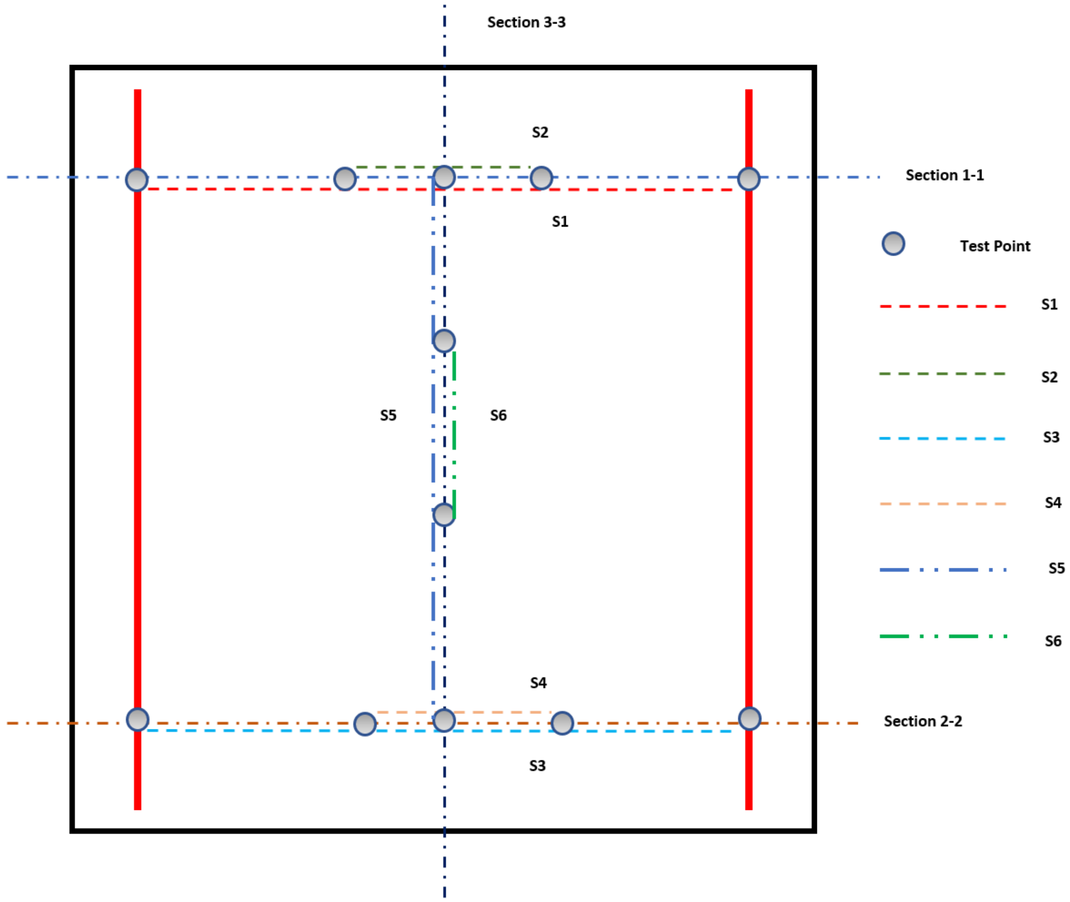


Figure 22. Electrical safety evaluation plan for laboratory-scale ECON slab

(a) (b)

Figure 23. Electrical safety evaluation: (a) sponge-brick setup and (b) surface voltage measurements

Next, a series of sawcuts was made perpendicular to the electrodes and across the full slab width. The first cut was at a 1 in. depth. The second cut in the same location was at a 1 1/2 in. depth, and the last cut was at a 2 in. depth. After each cut, the electrodes were energized at 24 VAC, and surface voltage measurements were completed. The 2 in. deep crack was introduced along section 1-1 to evaluate the effect of crack development perpendicular to the electrodes. The reason for introducing the ultimately 2 in. deep crack was to expose the electrode surfaces while considering the electrodes' placement depth, as shown in Figure 21. For the crack along section 1-1, measurements were taken for scenario S1 (a human stepping directly above the electrodes along section 1-1) and scenario S2 (a human stepping between two points inside the electrodes along section 1-1). In addition, measurements were taken for scenario S3 (a human stepping directly above the electrodes along section 2-2) and scenario S4 (a human stepping between two points inside the electrodes along section 2-2). Both surface voltage and leakage current measurements were taken in all cases before and after soaking with a saltwater solution. For leakage current measurements, the customized leakage current tester shown in Figure 20 was used.

In the final stage, a second crack (2 in. deep) was introduced along section 3-3 (Figure 22) to evaluate the potential shock hazard when a crack occurs in the direction parallel to the electrodes. For this crack, measurements were taken for scenarios S1, S2, S3, and S4. In addition, measurements were taken for scenario S5 (a human stepping along section 3-3 with footsteps 18 in. apart) and scenario S6 (a human stepping along section 3-3 with footsteps 4 in. apart). Both surface voltage and leakage current measurements were taken in all cases before and after soaking with a saltwater solution.

3.2.3 Testing ECON Sidewalk at Iowa DOT District 1 Office

To accomplish a task under IHRB Project TR-789, an ECON demonstration sidewalk was constructed near the Iowa DOT District 1 office in Ames with various electrode configurations (Figure 24). To construct the site, 3 yd^3 of ECON were produced at Manatt's Inc. in Ames, and 0.4 vol.% of 0.5 in. long carbon fiber was used. The fresh-stage electrical resistance for a 14 in. by 4 in. by 4 in. beam with copper mesh electrodes was 8 Ω, and the 28-day electrical resistance was 12 Ω. Electrical safety evaluations were conducted by energizing the four angled electrodes (2 in. by 2 in. by ¼ in.) with 24 VAC, since this particular electrode shape and size was recommended for the construction carried out under IHRB Project TR-789. The electrodes were placed 2 in. below the top surface of the ECON and spaced at 27.5 in. The power consumption was approximately 31 W/ft^2.

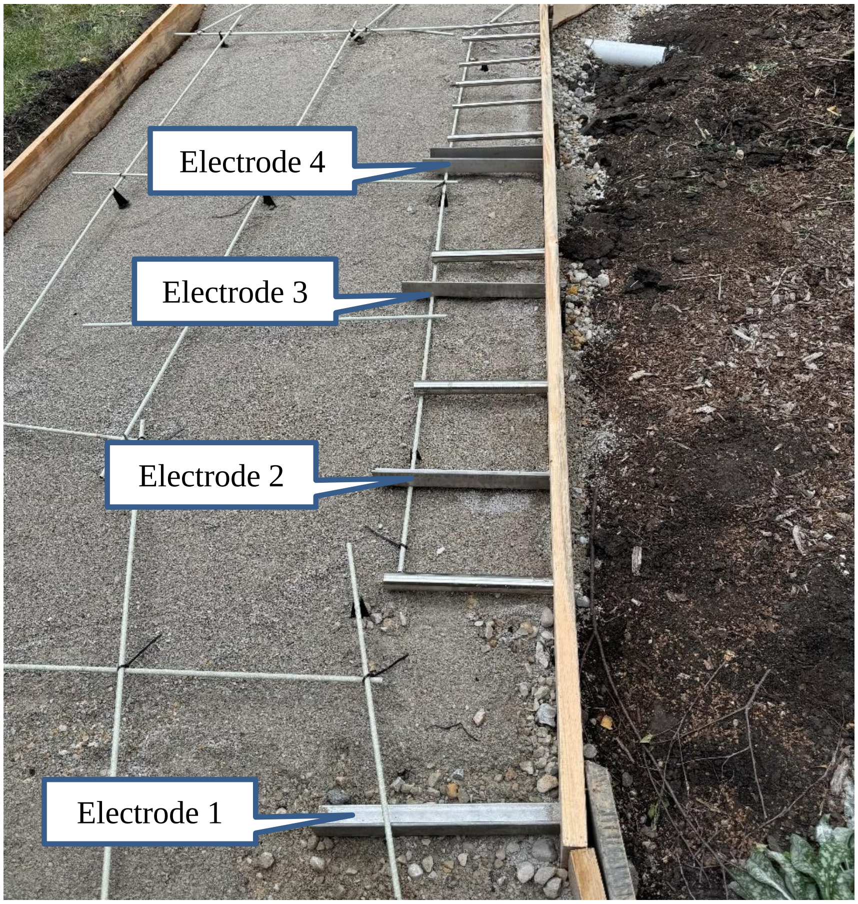


Figure 24. Electrode layout for the ECON demonstration sidewalk site

Measurements were taken before and after soaking the slab surface with saltwater. The electrical safety evaluation plan for this site considered the nine scenarios shown in Figure 25 and Table 6. For this site, only surface voltage measurements were taken (Figure 26).

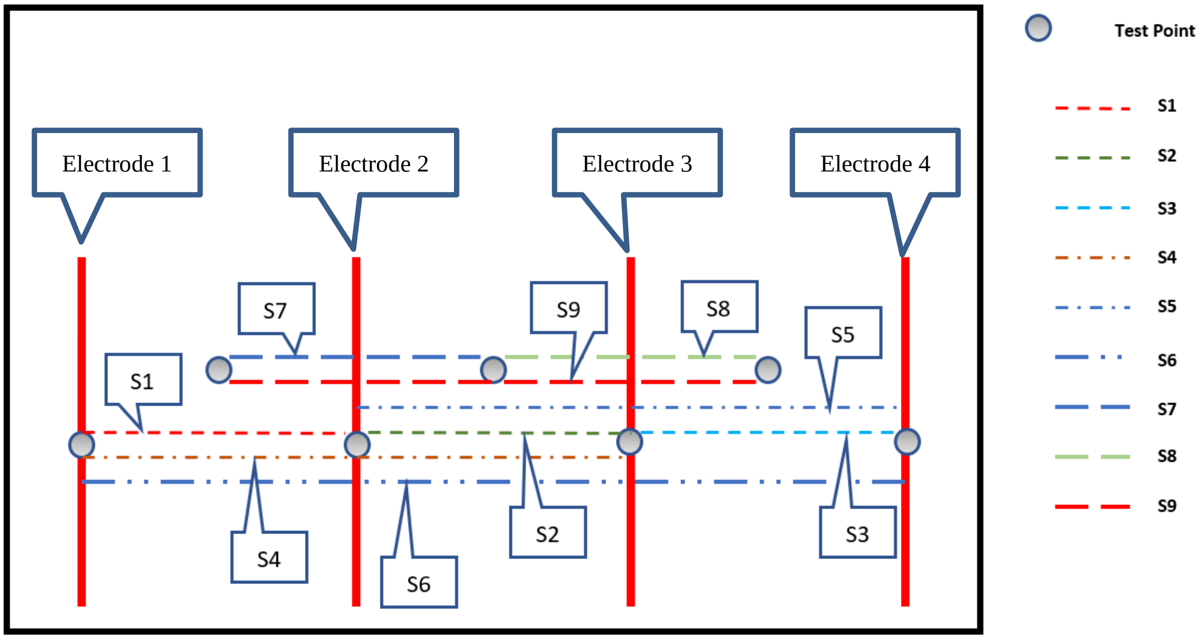


Figure 25. Electrical safety evaluation plan for the ECON demonstration sidewalk site

Table 6. Electrical safety evaluation test scenarios for the ECON demonstration sidewalk site

Scenario	Explanation
S1	Test points directly above electrodes 1 and 2 (spacing 27.5 in.)
S2	Test points directly above electrodes 2 and 3 (spacing 27.5 in.)
S3	Test points directly above electrodes 3 and 4 (spacing 27.5 in.)
S4	Test points directly above electrodes 1 and 3 (spacing 55 in.)
S5	Test points directly above electrodes 2 and 4 (spacing 55 in.)
S6	Test points directly above electrodes 1 and 4 (spacing 82.5 in.)
S7	Test point between electrodes 1 and 2 and electrodes 2 and 3 (spacing 27.5 in.)
S8	Test point between electrodes 2 and 3 and electrodes 3 and 4 (spacing 27.5 in.)
S9	Test point between electrodes 1 and 2 and electrodes 3 and 4 (spacing 55 in.)

Figure 26. Surface voltage measurement on the ECON demonstration sidewalk site

3.3 Results and Discussion

3.3.1 Existing Full-Scale ECON Heated Transportation Infrastructure System Sites

Table 7 presents the electrical safety evaluation test results for the ECON heated transportation infrastructure system site at the Iowa DOT main offices in Ames, Iowa. Of all the scenarios, scenarios S1, S2, and S3 most closely resemble situations where a human completes an electrical circuit by directly touching at least two contact points of an ECON slab. Since the results show that the surface voltage measurements for all three cases were always below the defined safe limit of 15 VAC established by the NEC and UL, the higher leakage currents that were measured do not have any significance. Similar findings were observed for scenario S7. However, in the case where a human touches the ECON slab surface and completes an electrical circuit by touching a ground surface, as in scenarios S4 and S8, the measured electrical surface voltages were higher than the defined safe voltage limit. Furthermore, the leakage current test results also exhibited higher values than the UL-defined safe leakage current limit of 0.5 mA. Similar observations were made for scenarios S5, S6, S9, and S10.

Table 7. Electrical safety evaluation test results for the Iowa DOT ECON heated transportation infrastructure system site in Ames, Iowa

Scenario	Before Saltwater Application		After Saltwater Application	
	Surface Voltage (VAC)	Leakage Current (mA)	Surface Voltage (VAC)	Leakage Current (mA)
S1	11.9	5.7	14.2	25.7
S2	0.4	0.2	3.1	5.6
S3	6.1	2.9	5.2	9.3
S4	63.9	2.8	58.5	91.0
S5	86.0	43.4	85.8	154.8
S6	18.2	8.9	N/A	N/A
S7	11.3	5.5	N/A	N/A
S8	27.5	5.3	26.8	46.8
S9	80.3	40.6	N/A	N/A
S10	97.8	49.4	N/A	N/A

Based on electrical field theory, in a simplified scenario with two electrodes under a 120 VAC voltage potential, the electric field distribution would resemble the setup in Figure 27. According to this theory, the maximum voltage potential is observed when measuring between points very close to the electrodes, and the voltage potential gradually decreases between them. For example, if one test point lies on an equipotential line of 80 V and another on a line of 40 V, the resulting voltage potential would be 40 V, lower than the voltage measured closer to the electrodes.

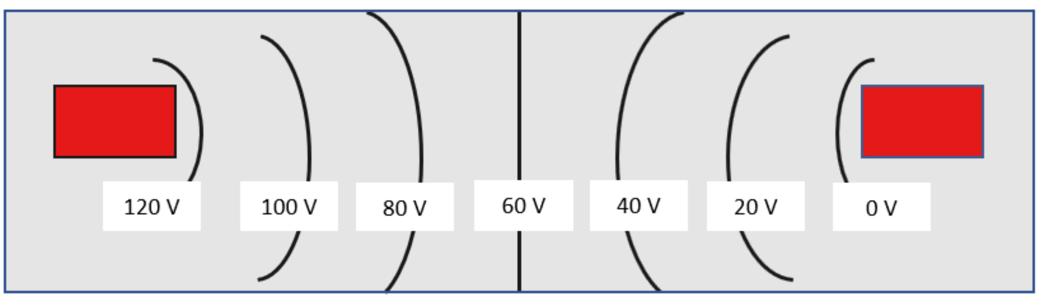


Figure 27. Typical electrical field for ECON slab

However, in this case, the measurements for scenario S1 (11.9 VAC before saltwater application and 14.2 VAC afterward) appear unusually low for an applied 120 VAC, even with the increased complexity introduced by multiple electrodes compared to Figure 27. According to electrical field theory, the readings for scenario S4 should be higher than those for scenario S8 (because voltage potential decreases with distance), so the low reading for scenario S1 indicates a system malfunction.

In contrast, for the Des Moines International Airport ECON HPS at 240 VAC, the surface voltage for scenario S1 is higher than for other scenarios, suggesting proper system functionality. However, from an electrical safety perspective, the surface voltage measurements and leakage currents exceed the UL safe limits, indicating a potential shock hazard. Since some Iowa DOT ECON HPS test cases and all Des Moines International Airport ECON HPS test cases exceeded the safe voltage and leakage current thresholds, neither a 120 VAC nor a 240 VAC supply voltage can be considered electrically safe for ECON HPS application.

Table 8. Electrical safety evaluation test results for the Des Moines International Airport ECON heated transportation infrastructure system site

Scenario	Surface Voltage (VAC)	Leakage Current (mA)
S1	141.2	254.0
S2	83.5	150.4
S3	58.9	106.0
S4	62.7	112.8
S5	80.4	145.0
S6	114.3	203.4
S7	23.5	42.6
S8	31.0	56.8

3.3.2 Laboratory ECON Slab Sample

The research team selected a 24 VAC input for testing the laboratory ECON slab sample in order to align with the NEC and UL safe voltage thresholds, specifically 30 VAC for general outdoor products and 15 VAC for products in wet environments. The decision to use 24 VAC was based on the practicality and accessibility of industrial-grade 24 VAC transformers, which are more readily available than other custom low-voltage options. By avoiding nonstandard or customized transformers, the team minimized potential procurement delays that are common in the electrical equipment industry due to often lengthy lead times. This choice ensured both compliance and practicality for potential field applications.

The results of the electrical safety evaluation, shown in Table 9, indicate that the surface voltage readings for scenario S1 were consistently higher than those for scenario S2, which is expected due to the greater distance for scenario S1.The introduction of a 2 in. crack along section 1-1 led to a slight increase in surface voltage, likely because the crack exposed part of the electrode surface, increasing the voltage measurements.

Table 9. Electrical safety evaluation test results for laboratory ECON slab

Scenario	No Crack	2 in. Crack (Section 1-1)				2 in. Crack (Section 3-3)	
	Surface Voltage (VAC)	Surface Voltage (VAC)		Leakage Current (mA)		Surface Voltage (VAC)	Leakage Current (mA)
	After Saltwater Application	Dry	Wet	Dry	Wet	Wet	Wet
S1	16.5	19.2	18.6	0.3	20.5	18.7	20.7
S2	N/A	8.2	9.8	0.8	10.2	9.9	10.7
S3	17.2	19.0	18.9	0.2	20.5	19.0	20.8
S4	N/A	10.6	9.6	0.7	10.4	10.7	10.3
S5	N/A	N/A	N/A	N/A	N/A	0.2	0.4
S6	N/A	N/A	N/A	N/A	N/A	0.8	0.6

In both scenario S1 and scenario S3, the surface voltage with the 2 in. crack exceeded the 15 VAC threshold for wet environments but remained under the 30 VAC limit for general outdoor use. Conversely, the surface voltages for scenarios S2 and S4 stayed within safe limits regardless of the environmental classification. For scenarios S1 and S3, the leakage currents under wet conditions were significant when considering the ECON heated transportation infrastructure system as an appliance in a wet environment, though they remained under 0.5 mA in dry conditions.

Introducing another 2 in. crack along section 3-3 did not impact voltage or current readings, implying that only those cracks perpendicular to electrodes could pose an electrical safety hazard. Prompt maintenance would be necessary to address any such cracks to ensure electrical safety.

3.3.3 ECON Sidewalk at Iowa DOT District 1 Office

Table 10 presents the surface voltage measurements for a small-scale ECON heated transportation infrastructure system set up at the Iowa DOT and tested with a 24 VAC input. This setup, utilizing four active electrodes, more closely replicates the anticipated electrical field conditions of a full-scale ECON heated transportation infrastructure system than the laboratory sample with only two electrodes. In wet conditions, the surface voltage measurements remained below 15 V for all scenarios except S6. While this test point voltage was 16.1 volts, 1.1 volts above the set surface voltage limit, scenario S6 involved a hypothetical case of a person simultaneously touching two points on the ECON surface that are 82.5 in. apart, far greater than a typical human stride. Given this context, the operation of the ECON HPS at 24 VAC would be considered safe.

Table 10. Electrical safety evaluation test results for small-scale ECON heated transportation infrastructure system site (at the Iowa DOT)

Scenario	Surface Voltage (VAC)
S1	14.8
S2	12.7
S3	13.7
S4	2
S5	0.8
S6	16.1
S7	0
S8	0.2
S9	0.1

4 CONCLUSIONS AND RECOMMENDATIONS

The following recommendations can be made for the successful construction of the Iowa City bus stop enhancement project under Iowa Highway Research Board (IHRB) Project TR-789 and to mitigate electrical shock hazards during the system operation:

- Carbon fiber is recommended for ECON production because its noncorrosive nature ensures long-term performance. A fiber length of 0.5 in. minimizes the increase in electrical resistance caused by fiber degradation during ECON production in a ready mix truck mixer.
- For IHRB Project TR-789, a dosage of 0.40 vol.% (12.2 lb/yd^3) of 0.5-inch carbon fiber is recommended, aiming for an electrical resistance between 10 and 20 Ω at 28 days in a 14 in. × 4 in. × 4 in. beam with copper mesh electrodes. Alternative recommended options are (1) to use 0.45 vol.% (13.7 lb/yd^3) of 0.5-inch carbon fiber for constructing the northside slabs and 0.40 vol.% (12.2 lb/yd^3) of 0.5-inch carbon fiber for constructing the southside slabs and (2) to use 0.45 vol.% (13.7 lb/yd^3) of 0.5-inch carbon fiber for all slabs.
- Carbon fiber should be added at the job site in two steps; such a technique removes the chances of fiber degradation and, at the same time, ensures uniform carbon fiber distribution.
- The maximum truckload of a single batch of ECON in a ready mix truck mixer should be limited to 6 yd^3 to reduce the chances of fiber balling and poor distribution of carbon fiber.
- Before accepting any batch of ECON at the job site, fresh-stage electrical resistance measurements should be conducted and matched against the target to ensure an efficient and functional ECON heated transportation infrastructure system. Specifically, for IHRB Project TR-789, the fresh-stage electrical resistance measured for a 14 in. by 4 in. by 4 in. beam with copper mesh electrodes should fall within 4 to 10 Ω.
- A 24 VAC electrode supply voltage is recommended for the operation of ECON heated transportation infrastructure systems to avoid any electrical shock hazard. An ungrounded supply system is also recommended. The bare concrete and ECON system must represent the primary safety aspect with regard to shock and burn hazards.
- As an added feature, a protective paint layer can be applied on the ECON slab surface as an added measure to ensure electrical safety. This, however, cannot be relied upon as the primary safety system due to the necessity of continued maintenance to ensure that no concrete exposure occurs.

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