Proposed Improvements to the Construction of Electrically Conductive Concrete Pavement System based on Lessons Learned

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ABSTRACT

The construction of electrically conductive concrete (ECON) pavement systems include several additional processes which make it different from the construction of regular rigid pavement systems. These can include the use of embedded electrodes, and two-lift concrete construction with different concrete mix designs. This study focuses on the lessons learned from constructing ECON slabs using these methods at the Des Moines International Airport and Iowa Department of Transportation Headquarters, as the first full-scale implementations of a carbon fiber-based ECON pavement system. Based on these efforts, a set of best practices is proposed to help minimize the time required to prepare the setup for placing ECON as the top lift of the pavement. These practices mainly include improvements in scheduling and decision making for the installation time and location of system components including electrodes, conduits, control unit, and sensors, and choosing appropriate both electrical and sensor wires' length, along with the instrumentation process. Applying these best practices improves the quality of the ECON pavement system, decreases the required labor, simplifies the project management process, and results in significant savings in money and construction time.

INTRODUCTION

Electrically conductive concrete (ECON) heated pavement systems (HPS) have recently gained attention as an alternative to conventional methods of snow and ice removal (Gopalakrishnan et al. 2015; Sassani et al. 2018). This self-heating system uses electricity to generate heat through the Joule heating process to increase the pavement surface temperature to melt snow and ice (Sadati et al. 2018). This alternative method of snow and ice removal improves the quality of the pavement maintenance in winter weather conditions since it can be used to prevent snow accumulation on the pavement. This is also convenient since the system can be controlled remotely (Sadati et al. 2018). However, ECON HPS requires a special design and construction procedure, different from regular rigid pavement systems, which includes two-lift paving and installation of additional components (Abdualla et al. 2018a). Two-lift paving for concrete pavement systems has been studied previously. Hu et al. (2019) studied the possibility of optimizing the concrete mix for the top lift of the pavement while the bottom lift is made of a less expensive material. This two-lift design is reported to result in improved skid resistance and reduced noise level. It is concluded that although two-lift paving construction generally has a higher cost associated with the additional equipment, labor and scheduling efforts, the cheaper bottom lift material can compensate for that increased cost. Swarna et al. (2019) developed a finite element models of two-lift wet-on-dry concrete pavements and simulated thermal and structural loads for evaluating the performance of this system. It was concluded that, compared to conventional pavement construction, the two-lift construction with more inexpensive material can result in the desired structural adequacy.

The current ECON HPS technology should be constructed in two lifts, the top lift being constructed two to three days after the first. Therefore, the two-lift construction for this system is wet on dry concrete construction. The bottom lift is regular concrete and, generally, accounts for the bulk of the required thickness based on the traffic level and the structural adequacy. The top lift is made of ECON material which is more expensive and provides the medium for developing electric current by applying a voltage difference to generate heat through a resistive heating process (Abdualla et al. 2016; Sadati et al. 2017). The typical electrical resistivity range of air-dried normal portland cement concrete (PCC) is between 6.54×10^5 and 11.4×10^5 Ω-cm, (Malakooti 2017; Malakooti et al. 2018) while this range for ECON is between 50 and 3000 Ω-cm. Low electrical resistivity of ECON allows the electricity to flow from the electrode to ECON layer. Electrodes, which are connected to a power source, are required inside the ECON layer to provide the voltage difference (Malakooti et al. 2019). Therefore, after the construction of the bottom lift with the regular concrete, electrodes should be placed, and then the top lift of ECON should be poured to have the electrodes embedded in this electrically conductive layer. To monitor the thermal performance of the system and also to automate its operation, thermometers should also be installed inside the pavement layers. It should be noted that, if the project is a pavement reconstruction, and the existing pavement has an adequate structural strength, ECON can be constructed as an overlay. There are also additional steps required to secure the electrical system components including power and sensor wires. There is also a need for an electrical power source for operating the ECON HPS slabs and an enclosure which can host the switches and the control system (Abdualla et al. 2018b). The location for installation of a power source and an enclosure should be considered in the planning phase. The additional steps required for the construction of ECON HPS compared to the construction of regular rigid pavement systems should be studied in order to optimize the process by optimizing the construction time and cost. Therefore, the current study focuses on several detailed construction techniques that can significantly impact the project in the design and scheduling steps.

The objective of this paper is to recommend best practices for the construction process of ECON HPS based on construction projects at DSM and IA DOT. Therefore, this paper discusses the lessons learned during the planning meetings and construction as best practices which would potentially result in saving time and reducing the cost of the construction of ECON HPS. There are two recent projects that have worked on evaluating the construction of full-scale ECON HPS slabs in the field. The first is the construction of ECON HPS test slabs in the general aviation section of Des Moines International Airport (DSM), located in Des Moines, Iowa, in November 2016. The second is the construction of ECON HPS test slabs at Iowa Department of Transportation Headquarters (IA DOT) located in Ames, Iowa, in October 2018. These two construction projects provide helpful insights to acquire a set of best practices for optimizing the construction process of such systems. The lessons learned are discussed in this paper. The lessons mentioned in this paper are learned during and after the construction of the two aforementioned projects. The significance of developing such best practices can be recognized considering that design and construction of ECON HPS is a collaborative effort involving engineers and experts from both the civil and electrical engineering fields. Therefore, it is necessary to provide a common ground between the teams that are involved in the project well ahead of actual construction.

The remainder of this paper is presented in three sections. The first section contains the brief description on the construction projects of ECON HPS test slabs at DSM and IA DOT. In the second section, the lessons learned from these projects are explained, and the last section includes the acquired conclusions and recommendations.

FIELD CONSTRUCTION PROJECTS

The ECON HPS test slabs constructed at DSM and IA DOT are described briefly in this section. The constructed slabs at DSM and IA DOT were designed with different sizes and electrode configurations.

Des Moines International Airport Test Slabs

Two slabs were constructed at DSM in November 2016 (Figure 1) to evaluate the design and construction process of carbon fiber-based ECON HPS and test the system performance in terms of its heating capacity and energy use. The material and equipment used for this project are reported by Abdualla et al. (2018c). The constructed slabs were 3.8 m wide and 4.57 m in length, and the total concrete thickness was 19 cm, which was made of 9 cm ECON for the top layer and 10 cm regular concrete for the bottom layer. Abdualla et al., (2018a)., provided a detailed explanation of the construction techniques and the system requirements for these ECON HPS slabs. The control and the data acquisition systems were installed in a nearby existing airplane hangar, which belongs to DSM airport. The voltage applied to each pair of electrodes was 240 V; an existing electrical power supply system was used to operate the slabs.

Figure 1. Construction of two ECON HPS test slabs at Des Moines International Airport, November 2016

Iowa Department of Transportation Test Slabs

Ten ECON HPS test slabs were constructed at IA DOT in October 2018. The ECON and regular concrete material and concrete placing equipment used for this project are the same as the DSM project reported by Abdualla et al. (2018c). Ten test slabs were constructed, each having a unique electrode configuration design. The electrode configuration design parameters considered were electrode spacing, cross section shape, and dimensions. The configuration design and the electrode number, shape and size for each slab are presented in Table 1. The slabs were each 3.66 m wide and 4.57 m long and the concrete layer was 25 cm made of 8 cm of ECON as the top layer and 17 cm of regular concrete as the bottom layer. The tested electrode cross section shapes included solid circular (2 cm, 2.5 cm diameter), hollow circular (2.5 cm diameter), and rectangular (2.5 cm by 0.6 cm). The electrode spacing included two slabs with 90 cm, four slabs with 65 cm and, four slabs with 50 cm spacing on center. The constructed pavement before and after placing the ECON layer are presented in Figure 2.

Table 1. Electrode number, shape and dimensions used in the ten test slabs at IA DOT

Test Slab #	Number of electrodes (spacing)	Size of electrode cross section	Electrode type & shape
1	10 (500 mm)	Diameter: 20 mm	Smooth circular bar
2	10 (500 mm)	Width and Thickness 25 mm x 3 mm	Flat bar
3	10 (500 mm)	Diameter: 25 mm	Hollow circular bar
4	10 (500 mm)	Diameter: 25 mm	Smooth circular bar
5	8 (650 mm)	Diameter: 20 mm	Smooth circular bar
6	8 (650 mm)	Diameter: 25 mm	Smooth circular bar
7	8 (650 mm)	Width and Thickness 25 mm x 3 mm	Flat bar
8	8 (650 mm)	Diameter: 25 mm	Hollow circular bar
9	6 (900 mm)	Diameter: 20 mm	Smooth circular bar
10	6 (900 mm)	Diameter: 25 mm	Smooth circular bar

(a) (b)

Figure 2. Electrically conductive concrete (ECON) heated pavement system test slabs at Iowa DOT: (a) before pouring the ECON layer and (b) after pouring the ECON layer, October 2018

A new electrical power source was installed near the construction site by City of Ames electricians to provide the required electricity for the operation of ECON HPS test slabs. There were two options for the amount of voltage that can be applied to each pair of electrodes embedded inside the constructed test slabs at IA DOT. The system can either be operated by connecting to a single-phase 120 V or alternatively a three-phase 208 V. This electrical power source was sized based on the estimated peak power demand for the slabs during the design. A structure was also installed to host an enclosure besides the test slabs which contains the circuit breakers, switches, slabs control system, and other electrical equipment and data collectors for sensors.

LESSONS LEARNED

It is necessary to have planning meetings prior to the construction of ECON HPS to understand the system requirements since the design and construction of ECON HPS is a collaboration between teams that consist of both civil and electrical engineers. In this planning meetings the location of the construction site should be studied. The required power demand determined during the design stage should be discussed and the availability of power supply system should be confirmed. This may require involving the electrical power supply authorities at the construction location, depending on the level of power determined to be needed. Moreover, if there are no existing structures that can be used to install an enclosure, the construction of such structure near the ECON HPS slabs should be considered in an appropriate location as a priority. Further detailed recommendations on the construction of ECON HPS slabs are provided in the following sub-sections.

Construction Process

Installing the electrodes and electrical connections are essential steps during the construction of ECON HPS. After constructing the regular concrete layer, there are generally approximately two to three days required to install the electrodes and sensors before pouring the ECON layer. This time is required for both i) having a regular concrete layer with adequate strength for installing the electrodes, and ii) installing the electrodes along with connecting them to the power source. It is estimated that placing each electrode and connecting it to the power wires would require approximately 15 minutes for two skilled workers on average. The regular concrete layer would already have sufficient strength when pouring the ECON layer. The surface of the regular concrete should be roughened and prepared for pouring ECON layer. This helps to provide a better bond between the ECON and regular concrete layers.

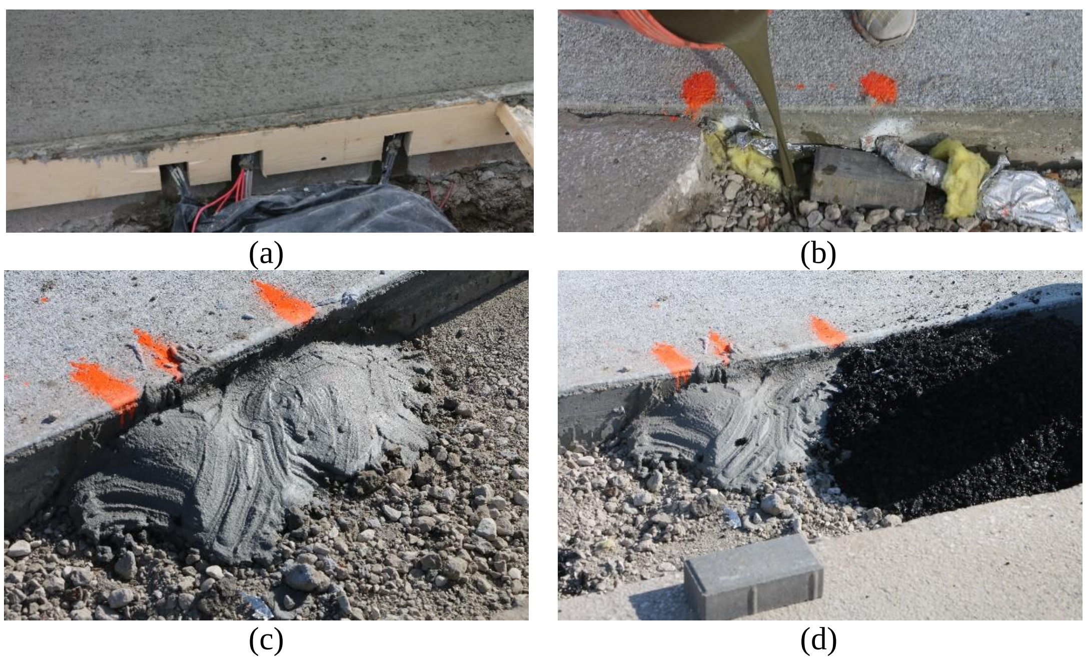
In addition to the pavement layers, the construction team should plan for the installation of the electrical equipment and carefully measure the distance between the control room and the installed electrodes and sensors. Location of the enclosure for the electrical control system is particularly important when determining the length of sensors and power wires. The wires should be sized carefully; if they are short, this may result in additional costs to support providing sufficient length; if they are too long, they should be trimmed which a time consuming and labor-intensive task. In order to prevent delays and minimize the cost, construction team should have meetings to make sure that all involved parties including, pavement material engineers, electricians, and instrumentation teams have a clear view of the entire construction process from the beginning.

Preparation for Conduit Placing

The sensor and power wires should be protected using proper conduits embedded in the base layer of the pavement. If the conduits are installed in the base layer below the slabs, the wiring should be performed before pouring the regular concrete layer. If the conduits are placed at the sides of the slabs, the wiring can be performed after pouring the regular concrete and anchoring the electrodes to its surface. The conduits installed besides the slabs for IA DOT project are shown in Figure 2a.

Preparation for installing power wires and sensor wires

In addition to sizing the wires to the proper length, the distribution of wires on the regular concrete layer surface should also be well-monitored. The wires should not be bundled on the surface that would potentially form voids inside the ECON layer. It is important to distribute the wires on the regular concrete surface and if necessary anchor them to the surface. The construction team should ensure that the wires are well distributed on the surface to minimize their adverse impact on the desired bond between ECON and regular concrete layers. Wires should also be well protected against the other construction steps following the wire installation. The wires and the protection layers utilized in the IA DOT project, are shown in Figure 3. The wires that were left outside the slabs (Figure 3a), before they entered the conduits, were covered with appropriate insulation layers (Figure 3b and Figure 3c). This layer protected the sensor and power wires from being exposed to high temperatures caused by pouring hot mix asphalt to cover the conduits (Figure 3d).



(a) (b) (c) (d)

Figure 3. Images of the wires and the protection layers utilized in the IA DOT project: (a) sensor and power wires imbedded in ECON layer, (b) preparation for pouring hot mix asphalt concrete, (c) additional concrete layer to provide structural support, and (d) hot mix asphalt covering the protected wires

To minimize the impact of loading and shear force on the wires outside the slabs, the wires with the protection layer shown in Figure 3b were buried under a regular concrete layer and a concrete piece was also placed under them as an additional support. This regular concrete layer provides bound to the pavement concrete layer and supports the wires against a shear force that would potentially damage them at the point they enter the concrete slabs. This protective concrete layer is shown in Figure 3c and Figure 3d.

To have a better protection against the potential shear load, it is recommended that when the openings are made for the wires in the concrete formwork (Figure 3a), the construction team should allow additional concrete on the wires. This additional concrete piece is a part of the concrete slab, hence, can resist against the shear force, and would act as a support for the wires to prevent any potential damage.

CONCLUSIONS

Two construction projects for electrically conductive concrete (ECON) heated pavement system (HPS) test slabs are reviewed and the lessons learned during each are provided as a set of best practices to optimize the construction time and cost. The test slabs were constructed at the DSM International Airport and the IA DOT headquarters. These pavement construction project were generally performed in two lifts, with the regular concrete as the bottom lift followed by a thin ECON layer as the top lift. The ECON layer is poured after 2-3 days of paving the bottom lift. The surface of the bottom lift should be prepared, ensuring a strong bond between the layers. The recommendations for ECON HPS construction projects based on the current experiences are summarized as follows:

- Engineers and experts from both civil and electrical engineering fields that are involved in the construction project should have discussions in planning meetings prior to the construction to provide a common ground for all the involved parties and prevent the potential conflicts which would result in delaying the project.
- System requirements should be determined based on the design and the construction site should be well-studied to confirm that requirements (e.g., power source capacity) are met. The availability of power supply system and a control room is inevitable for successful operation of ECON HPS.
- The location of the control room and the power supply system with regards to the ECON HPS slabs should be taken into consideration when sizing the sensor and power wires.
- The wires on the surface of the regular concrete should be well distributed not to form voids in ECON layer or adversely impact the desired bound between ECON and regular concrete layers.
- The construction team should carefully check the potential for damaging the wires at any location that the wires are not buried in concrete or are outside of the conduits. Such wires should be covered with appropriate material and also should be protected against external loads that can damage them.

The acquired list of best practices during the aforementioned construction projects can be used in the future to improve the performance of the construction team. Moreover, the potential for other methods of placing conduits, e.g., below the concrete slabs, are not studied here and can be investigated as the future work.

ACKNOWLEDGEMENTS

The authors would like to thank the Iowa Department of Transportation (DOT) and Iowa Highway Research Board (IHRB) for providing the matching fund for this research project that is sponsored by Federal Aviation Administration (FAA). The authors 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 the Iowa DOT facility manager and Iowa DOT electricians, the FAA technical monitor and Mr. Gary L. Mitchell at the American Concrete Pavement Association are gratefully acknowledged for their guidance, support, and direction throughout the research. The authors would like to express their sincere gratitude to other research team members in ISU Program for Sustainable Pavement Engineering and Research (PROSPER) 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.

REFERENCES

Abdualla, H., Ceylan, H., Cetin, K. S., Kim, S., Taylor, P. C., Mina, M., Cetin, Bora Gopalakrishnan, K., and Sadati, S. (2018a). “Construction Techniques for Electrically Conductive Heated Pavement Systems.” *Construction and Environmental Engineering Conference Presentations and Proceedings*, 551–561.

Abdualla, H., Ceylan, H., Kim, S., Gopalakrishnan, K., Taylor, P. C., and Turkan, Y. (2016). “System requirements for electrically conductive concrete heated pavements.” *Transportation Research Record*, 2569, 70–79.

Abdualla, H., Ceylan, H., Kim, S., Mina, M., Cetin, K. S., Taylor, P. C., Gopalakrishnan, K., Cetin, B., Yang, S., and Vidyadharan, A. (2018b). “Design and Construction of the World’s First Full-Scale Electrically Conductive Concrete Heated Airport Pavement System at a U.S. Airport.” *Transportation Research Record*, (November).

Abdualla, H., Ceylan, H., Kim, S., Mina, M., Cetin, K. S., Taylor, P., Gopalakrishnan, K., Cetin, B., Yang, S., Sassani, A., and others. (2018c). *Design and Construction of the First Full-Scale Electrically Conductive Concrete Heated Airport Pavement System at a US Airport*.

Gopalakrishnan, K., Ceylan, H., Kim, S., Yang, S., and Abdualla, H. (2015). "Self-Heating Electrically Conductive Concrete for Pavement Deicing: A Revisit." *Transportation Research Board 94th Annual Meeting.*, No. 15-4764.

Hu, J., Siddiqui, M. S., Fowler, D. W., and Whitney, D. (2019). "Potential Technical and Cost Benefits of Two-Lift Concrete Paving." *Airfield and Highway Pavements*.

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

Malakooti, A., Abdualla, H., Sassani, A., Ceylan, H., and Kim, S. (2019). "Effect of Electrode Geometry and Size on Heating Performance of Electrically Conductive Concrete (19-02535)." *Transportation Research Board (TRB) 99th Annual Meeting*, Washington, D.C.

Malakooti, A., Maguire, M., and Thomas, R. J. (2018). "Evaluating Electrical Resistivity as a Performance based Test for Utah Bridge Deck Concrete (CAIT-UTC-NC35)." *Rutgers University. Center for Advanced Infrastructure and Transportation*.

Sadati, S. M. S., Cetin, K., and Ceylan, H. (2017). "Numerical Modeling of Electrically Conductive Pavement Systems." *Congress on Technical Advancement 2017*, ASCE, Duluth, MN, 1–10.

Sadati, S. M. S., Cetin, K., Ceylan, H., Sassani, A., and Kim, S. (2018). "Energy and thermal performance evaluation of an automated snow and ice removal system at airports using numerical modeling and field measurements." *Sustainable Cities and Society*, Elsevier, 43(August), 238–250.

Sassani, A., Arabzadeh, A., Ceylan, H., Kim, S., Sadati, S. M. S., Gopalakrishnan, K., Taylor, P. C., and Abdualla, H. (2018). "Carbon fiber-based electrically conductive concrete for salt-free deicing of pavements." *Journal of Cleaner Production*, Elsevier Ltd, 203, 799–809.

Swarna, S. T., Hossain, K., Reddy, M. A., and Pandey, B. B. (2019). "A mechanistic and economic analysis of two-lift concrete pavements." *Road Materials and Pavement Design*, Taylor & Francis, 0(0), 1–19.