7-11-2018

Investigating the Heat Generation Efficiency of Electrically-Conductive Asphalt Mastic Using Infrared Thermal Imaging

Ali Arabzadeh
Iowa State University, arab@iastate.edu

Halil Ceylan
Iowa State University, hceylan@iastate.edu

Sunghwan Kim
Iowa State University, sunghwan@iastate.edu

Alireza Sassani
Iowa State University, asassani@iastate.edu

Kasthurirangan Gopalakrishnan
Iowa State University, rangan@iastate.edu

Investigating the Heat Generation Efficiency of Electrically-Conductive Asphalt Mastic Using Infrared Thermal Imaging

Abstract

One of the emerging technologies for producing sustainable ice-and snow-free pavements is the use of electrically-conductive surface courses, e.g., electrically-conductive asphalt concrete (ECAC) that can melt ice and snow through resistive heating. Modifying the mastic in asphalt concrete with electrically-conductive materials is a promising approach for producing high-quality ECAC. The objective of this study is to evaluate electrical conductivity and heat generation efficiency of electrically-conductive asphalt mastic (ECAM) specimens at a below-freezing temperature—simulating the harsh weather conditions in North America during the wintertime. To this end, asphalt mastic was electrically modified with carbon fiber (CF) at varying volume contents. The ECAM specimens were then powered by 60V AC during a time window of 10 minutes so that their heat generation capacity could be characterized through infrared thermography (IRT). Based on the resistivity measurements and thermal data analysis, the most reasonable CF content enabling rapid heat-generating ECAM was identified; this has future implications with respect to achieving efficient highway, bridge, and airport pavement operations during wintertime.

Disciplines

Construction Engineering and Management | Structural Engineering | Structural Materials

Comments

This is a manuscript of a proceeding published as Arabzadeh, Ali, Halil Ceylan, Sunghwan Kim, Alireza Sassani, and Kasthurirangan Gopalakrishnan. "Investigating the Heat Generation Efficiency of Electrically-Conductive Asphalt Mastic Using Infrared Thermal Imaging." In *International Conference on Transportation and Development* (2018): 206. doi: 10.1061/9780784481554.021. Posted with permission.

Investigating the Heat Generation Efficiency of Electrically-Conductive Asphalt Mastic Using Infrared Thermal Imaging

Ali Arabzadeh[1], Halil Ceylan[2], Sunghwan Kim[3], Alireza Sassani[4], and Kasthurirangan Gopalakrishnan[5]

[1]Ph.D. Candidate, Iowa State University; email: arab@iastate.edu
[2]Professor, Iowa State University; Phone: 515-294-8051; Fax: 515-294-8216; email: hceylan@iastate.edu (**Corresponding Author)**
[3]Research Scientist, Iowa State University; email: sunghwan@iastate.edu
[4]Ph.D. Candidate, Iowa State University; email: asassani@iastate.edu
[5]Research Associate Professor; Iowa State University; email: rangan@iastate.edu

ABSTRACT

One of the emerging technologies for producing sustainable ice-and snow- free pavements is the use of electrically-conductive surface courses, e.g., electrically-conductive asphalt concrete (ECAC) that can melt ice and snow through resistive heating. Modifying the mastic in asphalt concrete with electrically-conductive materials is a promising approach for producing high-quality ECAC. The objective of this study is to evaluate electrical conductivity and heat generation efficiency of electrically-conductive asphalt mastic (ECAM) specimens at a below-freezing temperature - simulating the harsh weather conditions in North America during the wintertime. To this end, asphalt mastic was electrically modified with carbon fiber (CF) at varying volume contents. The ECAM specimens were then powered by 60V AC during a time window of 10 minutes so that their heat generation capacity could be characterized through infrared thermography (IRT). Based on the resistivity measurements and thermal data analysis, the most reasonable CF content enabling rapid heat-generating ECAM was identified; this has future implications with respect to achieving efficient highway, bridge, and airport pavement operations during wintertime.

INTRODUCTION

Presence of “contaminants” such as ice, snow, or slush on the paved areas of airfields causes hazardous conditions that can lead to airplane incidents, possibly even accidents. Moreover, snow storms usually reduce airport traffic volume by causing flight delays or cancellations or, in the worst case scenario, they can lead to airport closures (FAA 2016). To mitigate such ground-related winter problems, an airport operator can find appropriate approaches that saves time, minimize costs and efforts associated with ice and snow removal from the surface of runways, taxiways, aprons, etc (FAA 2016). The use of deicing chemicals and deployment of snow removal equipment are conventionally practiced methods for winter maintenance of airfield paved areas; such methods are typically costly and time-consuming (Anand et al. 2017;

Shen et al. 2017). However, with the aid of emerging technologies, it is possible to overcome such financial and time-related problems. For example, preventive approaches such as superhydrophobic (super water-repellent) asphalt concrete (Arabzadeh et al. 2016) or superhydrophobic portland cement concrete (PCC) (Arabzadeh et al. 2017) have been studied for curbing ice formation or preventing snow accumulation on the paved areas of airfields. It is also possible to produce airfield pavements made of electrically-conductive concrete (ECON) (Sassani et al. 2017) that can effectively melt ice, snow, or slush present on paved areas of airfields.

Similar to ECON, electrically-conductive asphalt concrete (ECAC) is another emerging alternative technology for mitigating the winter ground-related problems. ECAC has been successfully used for self-healing (Liu et al. 2010; Liu et al. 2012) and self-sensing/monitoring purposes (Liu and Wu 2011; Huang et al. 2013). In addition to self-healing and self-sensing, ECAC has gained attention because of its excellent ice and snow melting capability achieved through electro-thermal effects (Wu et al. 2012). The most efficient way for achieving ice and snow melting capability in asphalt mixtures, which are themselves electrically-insulating, is through addition of electrically-conductive materials (Pan et al. 2015). This facilitates the passage of current when asphalt concrete as part of a circuit is subjected to an applied voltage. The more conductive the asphalt mixture, the lower the resistivity and the higher the current passing through it. According to Ohm's law, the generated current, through conduction (Wu et al. 2012), produces heat in asphalt concrete (Liu et al. 2010) through resistive heating, enabling it to melt ice, snow, and slush. There are different methods for evaluating heat generation efficiency in electrically-conductive asphalt mixtures among which infrared (IR) thermography, using a thermal camera, can result in development of highly accurate graphs (temperature versus time) for electrically-conductive asphalt mixtures subjected to electric current (García et al. 2009).

For the first time, in 1995 an ECAC snow-melting system called Snowfree® was installed on a portion of a taxiway at the Chicago O'Hare International Airport (Derwin et al. 2003). The conductive material used in Snowfree® was only synthetic graphite powder incorporated into the asphalt mixture at a high volume content of 25% (Derwin et al. 2003). Although the implemented ECAC could successfully melt ice and snow, the FAA deemed that the operating costs were too high, so to date no airport has used this technology (Ceylan et al. 2014). In addition to the cost, it seems doubtful that the pavement section could last sufficiently long because of the detrimental effects of graphite powder on mechanical properties of asphalt concrete at the high dosage rate of 25% (Liu and Wu 2011). With the advancement of technology and the exponentially-increasing use of carbon-based electrically-conductive materials, it seems possible that more electrically-conductive and more mechanically-durable asphalt mixtures could be produced. For example, carbon fiber (CF), produced from either poly acrylonitrile (PAN) or pitch precursors (Chung 2012), is very compatible with asphalt concrete because, like asphalt, it is made of carbon. The melting point of carbon fiber is approximately 1,000ºC , making it suitable for use in hot-mix asphalt (Abtahi et al. 2010). In addition to chemical and thermal compatibility, CF also contributes to increased cracking resistance and increased fatigue life (Abtahi et al. 2010; Lee et al. 2005) in asphalt concrete. Also, it is believed that CF, with an approximate resistivity of 10^{-3} Ω cm, is the best conductivity enhancing material for use in asphalt concrete (Wu et al. 2005)

In this study, asphalt mastic specimens were modified with CF to produce electrically-conductive asphalt mastic (ECAM) specimens for investigating the feasibility of producing highly-efficient asphalt concrete for ice-and snow-free pavement applications. The resistivity of each prepared ECAM specimen was evaluated at a below freezing temperature, a novel feature of this research. Then, based on the resistivity values obtained, the best specimen type at a certain conductive material content was selected and its heat generation efficiency evaluated by performing active infrared thermography (IRT) at a temperature below 0°C, another novel aspect of this research. Finally, based on the active IRT analysis results, it was found that ECAM was capable of generating sufficient heat if modified with the reasonable amount of conductive material. The findings of this study are expected to provide guidance for producing the most heat efficient ECAC for ice-and snow-free pavement applications.

MATERIALS AND METHODOLOGY

Electrically-conductive asphalt mastic (ECAM) specimens were prepared using carbon fiber (CF) to produce a single-phase electrically-conductive material system. A percolation transition zone was identified, and based on the resistivity data analysis, the heat generation efficiency, was evaluated at a volume percentage slightly higher than the optimum volume content of CF.

Asphalt mastic specimen preparation. According to FAA Advisory Circular 150/5370-10G (FAA 2014), the initial asphalt cement performance grade (PG) used in the surface course should be consistent with the recommendations set by State Department of Transportation. As a result, based on the result obtained from Long-Term Pavement Performance (LTPP)-Bind software, it was decided to use PG 58-28, which is a type of performance-based grade bitumen commonly used in Southern Iowa, where Des Moines International Airport is located. The PG 58-28 bitumen used in this study, obtained from Jebro Inc., had the specific gravity (SG) of 1.035.

The mastic specimens prepared for this study were composed of PG 58-28 and both conductive and non-conductive fillers. Conductive filler, obtained from Asbury Carbons Inc., was 3-mm CF. The non-conductive filler was hydrated lime with a SG of 2.3. A bitumen-to-filler weight ratio of 1:1 was held constant for all of the asphalt mixtures. For preparing ECAM specimens, hydrated lime was substituted for CF at volume contents ranging from 0% to 2.5%. Based on the volume content variation of CF, twelve specimen types, each with three replicates, were prepared.

All the mixture components were conditioned in an oven set at 165 °C for 1 hr., then the components were mixed using a Hobart mixer for 5 min., at 60 rpm. The mixtures were then conditioned again in the oven, at 165 °C, for 15 min, following which a spatula (Figure 1*b*) was used to place the prepared asphalt mixtures in wooden molds (Figure 1*a*). The resulting asphalt mastic specimens were conditioned for 2 hr. in a freezer set at 0°C so they could be easily detached from the wooden molds (Figure 1*c*).

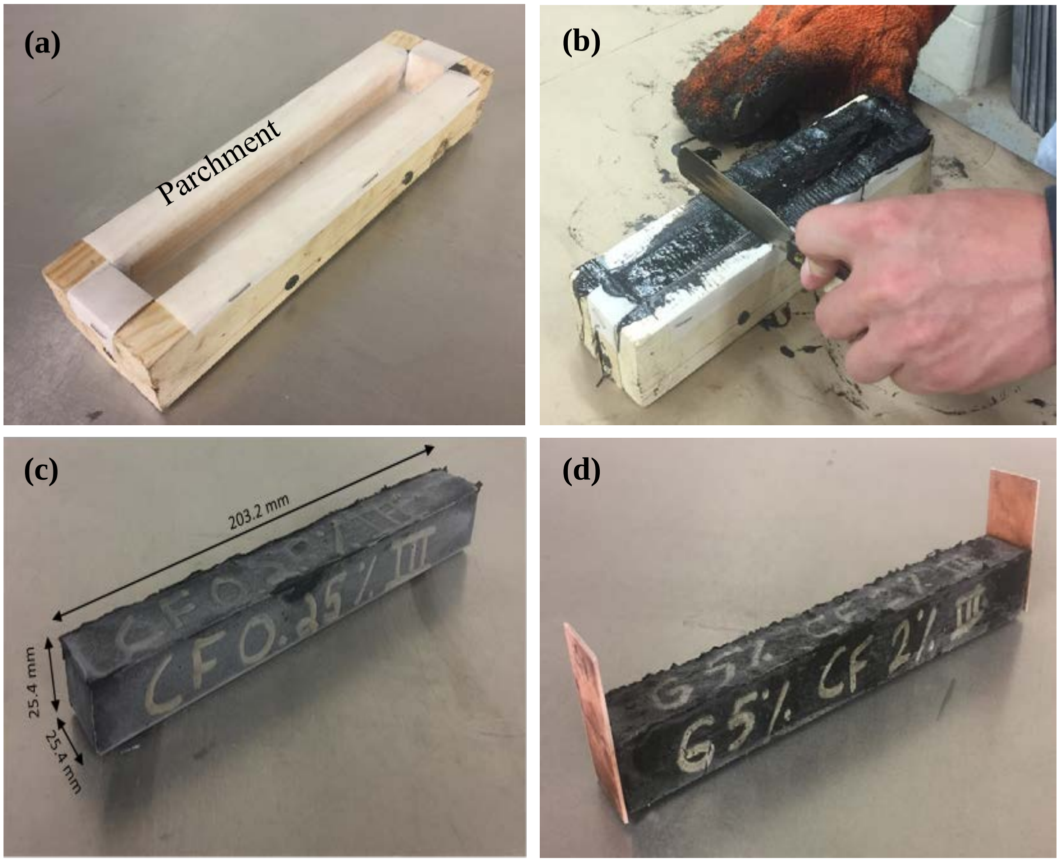

Figure 1. Preparation of prismatic asphalt mastic specimens: (*a*) wooden mold for casting the asphalt mastic specimens, (*b*) hand compacting and leveling the asphalt mastic specimens, (*c*) demolded asphalt mastic specimen, (*d*) an asphalt mastic specimen with attached copper electrodes.

After demolding, the asphalt mastic specimens were slightly warmed up using a blowtorch at the electrode-specimen contact areas, followed by sticking electrodes to the resulting tacky surfaces of the asphalt mastic specimens (Figure 1*d*).

Volume resistivity measurement. The electrical resistivity can be obtained using the Ohm's law (García et al. 2009):

$$\rho = \frac{RS}{L} \tag{1}$$

where ρ is electrical resistivity measured in Ω cm, R is electrical resistance measured in Ω, S is electrode-specimen contact area measured in cm^2), and L is the distance between electrodes measured in cm.

The electrical resistance was measured using the attached copper electrodes (see Figure 1*d*) in an environmental chamber set at -10°C. Before performing the resistivity measurements, all asphalt mastic specimens were preconditioned at -10 °C for at least three hours to produce thermal equilibrium (Arabzadeh and Güler 2014).

The measured and gathered resistance values were converted to resistivity values using Equation 1.

Heat generation measurement. An infrared thermal (IRT) camera was used to evaluate the heat generation efficiency of ECAM specimens at 1 % volume content of CF. Before performing the thermography, all specimens were placed in the environmental chamber and preconditioned at -18 °C, the lowest range at which the IR camera could operate, for at least three hours so they could achieve thermal equilibrium (Arabzadeh 2016). An AC voltage of 60 V at a frequency of 64 Hz was applied to each specimen for the duration of 10 minutes, following which the temperature of each specimen was measured and recorded using the IRT camera. The acquired data were then analyzed and the heat generation efficiency was evaluated.

RESULTS AND DISCUSSION

Volume resistivity data analysis. The resistivity measurements were performed at -10°C and the obtained values from the replicates (each specimen had three replicates) were averaged for each specimen type (see Table 1). The sudden transition (from insulator to conductor, e.g., from 2.12×10^5 to 8.62×10^1) in insulating materials such as asphalt mastic is evidence of existence of a percolation threshold (Weber & Kamal 1997). When the carbon fiber (CF) volume content reaches a threshold value, the first few continuous electrically-conductive paths will be formed, enabling easy travel of charged particles (e.g., electrons) through the sample (Liu et al. 2010), and that is why the resistivity value dropped up to virtually 100% - because of percolation - as the CF content increased from 0.5% to 0.75% (Table 1). To show the percolative behavior of ECAM specimens, it was decided to plot the volume resistivity data as a function of CF content (see Figure 2). Percolation threshold occurs within the percolation transition zone (Figure 2), a zone in which resistivity values drop drastically (e.g., from 2.12×10^5 Ω.cm to 8.62×10^1 Ω.cm), at a high rate, with addition of conductive materials (Liu et al. 2010).

Table 1. Measured Resistivity.

CF Volume Content	Resistivity (Ω.cm)	
	Ave	**SE**
0.00%	1.15E+09	3.94E+08
0.25%	2.46E+07	2.27E+06
0.50%	2.12E+05	4.42E+03
0.75%	8.62E+01	2.20E+01
1.00%	3.75E+01	1.81E+00
1.25%	1.66E+01	4.61E-01
1.50%	7.26E+00	2.98E-01
1.75%	4.62E+00	3.50E-01
2.00%	3.15E+00	2.28E-01
2.25%	2.28E+00	1.06E-01
2.50%	2.05E+00	4.23E-02

As it can be seen in Figure 2, when small amounts of CF are added to asphalt mastic (i.e., 0.5% or less), they tend to be isolated, and current is not able to easily pass through the separated CFs by means of contact resistance. As a result of such small addition of CFs, the resistivity values can drop up to at most 2.12×10^5 Ω.cm (see Table 1 and Figure 2).

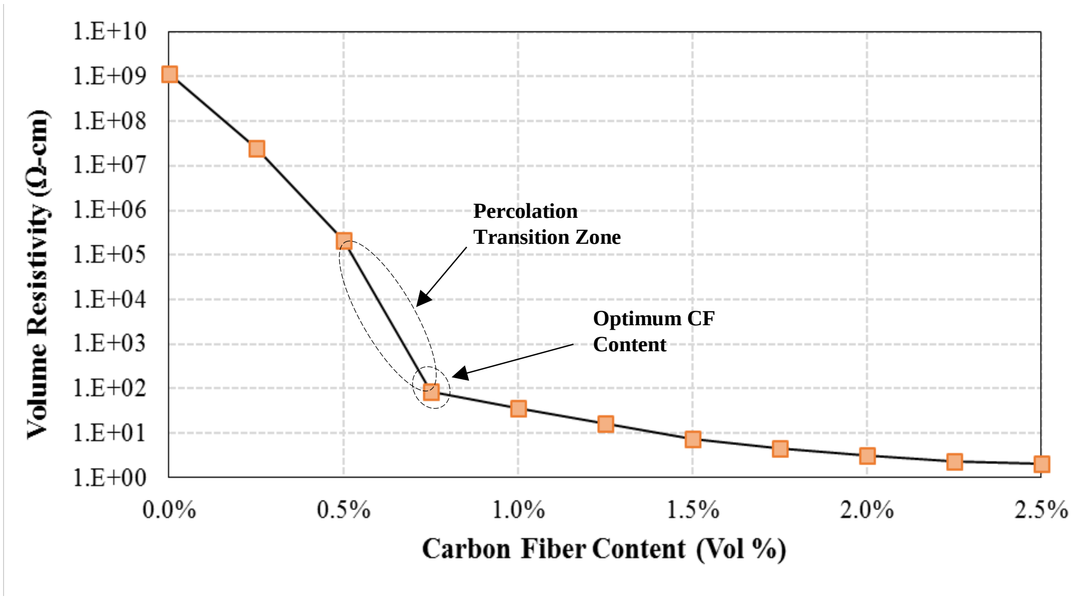

Figure 2. Relationship between electrical resistivity and CF volume content.

Beyond the percolation transition zone (i.e., for the CFs' dosage rates greater than 0.75%), addition of conductive materials results in gradual development and expansion of an electrically-conductive network (Liu et al. 2010) in all dimensions. As a result of such gradual enhancement of electrical conductivity – after the percolation transition zone - , 75% CF (with the resulting 8.62×10^1 Ω.cm resistivity) can be considered optimum conductive material content, beyond which addition of CFs would not be economical. Moreover, according to the literature (Wang et al. 2016), it is not preferred to have an asphalt-based material (such as asphalt concrete, asphalt mastic, etc.) with optimum conductive material content (e.g., 0.75% CF). The ultimate goal in this study is to produce an asphalt mastic which is conductive enough, so that once it becomes a matrix for aggregate system in asphalt concrete, it will generate enough heat to melt ice and snow in cold climatic conditions. As a result of such ultimate goal, and because of possible mistakes associated with construction of pavements paved with hot mix asphalt, it would be better to use conductive materials at a dosage higher than the optimum content (e.g., 1% - which is 0.25% greater than the optimum value of 0.75%).

Heat generation efficiency data analysis. Because of having no concern regarding being in the proximity of percolation transition zone, the ECAM specimen type (having three replicates) modified by 1.00% CF was selected for heat generation analysis. Figure 3, present the thermal data recorded, measured and averaged for one of the replicates of the specimen modified by 1% CF. It is worth noting that the other two replicates had a very similar behavior.

The temperature increase rate is variable in different regions of the developed curve (Figure 3). Within the first 30 sec., i.e., region I, the temperature increases at a decreasing rate which can be due to increase in resistivity values in the temperature range of -18°C to -10°C. In other words, the decreasing rate in temperature increase can be because of high temperature-susceptibility of asphalt mastic's electrical resistivity values in the region I. Although the rate of temperature increase is decreasing between -18°C and -10°C, the fastest temperature increase - considering the average rate - occurs in the first 30 s. After 30 sec., i.e., in region II, the temperature begins to increase at a constant rate until it reaches 4.5°C. This steady temperature increase can be due to moderate temperature susceptibilities in asphalt mastics in the temperature range of -10 to 4.5°C. After 270 sec., i.e., in region III, the temperature increase rate increases with respect to time. Such behavior can be explained by the presence of localized warm regions on/in the specimen (see Figure 4). In these regions asphalt can behave like a Newtonian fluid (García et al. 2015), allowing the bitumen to flow and provide a bigger and better contact area between the fibers that are already in contact. The improved contact between the fibers results in improved heat generation and temperature increase.

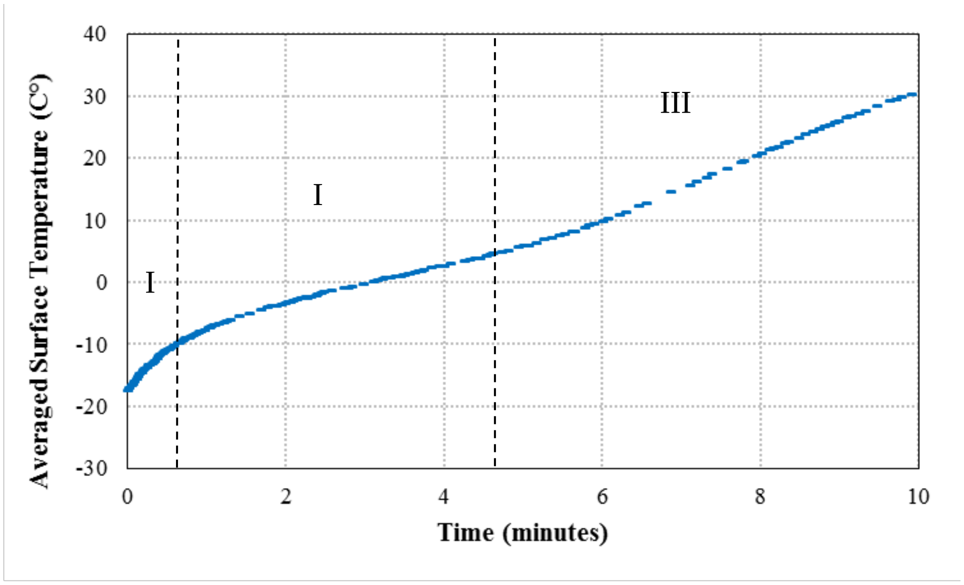

Figure 3. The temperature plot quantifying heat generation in a specimen modified by 1% CF.

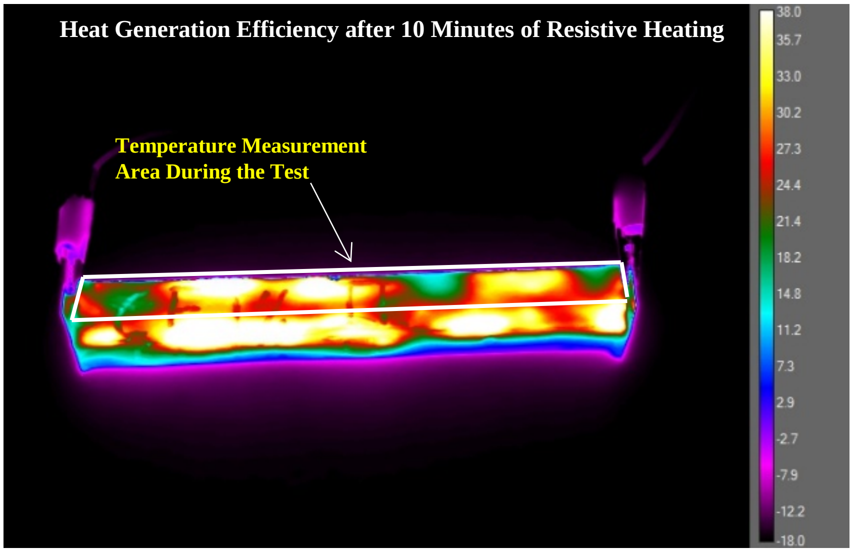

Figure 4. Thermograph obtained from one of the specimens containing 1% CF.

There is no need to reach temperatures beyond the water freezing point, if the drive for producing an electrically-conductive asphalt mastic is solely to melt ice and snow in regions having harsh winters. For example, keeping the surface temperature of asphalt concrete at 5°C will allow the ice to melt, and an asphalt concrete having mastic containing 1% CF, and starting at -18°C, can reach this temperature after 5 with an applied AC voltage of 60V. However, it should be kept in mind that presence of aggregate will have influence on the amount of fibers used for ice melting purpose, because aggregates can cut the conductive paths, or maybe they can improve the dispersion of fibers during mixing process of asphalt concrete at the plant.

CONCLUSION AND RECOMMENDATIONS

The objective of this study was to investigate the feasibility of producing highly-efficient electrically-conductive asphalt concrete for ice-and snow-free pavement applications in areas such as North America. To this end, for conducting this study, asphalt mastic was modified with carbon fiber (CF) at varying volume dosages to produce electrically-conductive asphalt mastic (ECAM) specimens. The resistivity measurements of ECAM specimens were evaluated at a below-freezing temperature, a novel feature of this research. Based on the obtained resistivity values, the best specimen type at a certain conductive material content was selected and its heat generation efficiency evaluated by performing active infrared thermography (IRT) at a temperature below 0°C, another novel aspect of this research. Based on the active IRT analysis results, it was found that the selected ECAM type is capable of generating enough heat if it is modified with reasonable amount of CF content.

Addition of CF to asphalt mastic, at the optimum volume content of 0.75%, considerably decreased the volume resistivity of mastic to virtually 86.2 Ω.cm, and increasing the volume content of carbon fiber to 1% decreased the volume resistivity to 37.5 Ω.cm. Such volume percentage (1% CF) can keep the ECAM specimens from reaching the percolation transition zone, a region at which resistivity values change drastically by a small change in conductive material content - such as fiber loss during preparation of asphalt concrete in the plant. ECAM modified by 1% CF, and powered by an AC voltage of 60 V, could increase the temperature from -18°C to 5°C within 5 min. If the pursuit for producing an electrically-conductive asphalt mastic is solely to melt ice and snow, 5°C is a desirable target temperature which is slightly higher than the water freezing point. It will be beneficial to study the electrical resistivity of ECAM both before and after the glass transition temperature, that can happen at temperatures as low as -25°C (Anderson and Marasteanu 1999). Presence of aggregates (coarse and fine) can change the electrical properties of ECAM which is the matrix for electrically-conductive asphalt concrete (ECAC). As a result of such potential aggregate influence, the percolation threshold for asphalt concrete with different gradations should be investigated. Another important and inevitable step for future studies is to investigate the effect of different carbon fiber lengths and their surface properties on heat generation efficiency and constructability of ECAC technology.

ACKNOWLEDGMENTS

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

REFERENCES

Abtahi, S. M., Sheikhzadeh, M. and Hejazi, S. M. (2010). "Fiber-reinforced asphalt-concrete - A review." *Constr. Build. Mater.*, 24(6), 871–877.

Anand, P., Nahvi, A., Ceylan, H., Pyrialakou, D. V., Gkritza, K., Gopalakrishnan, K., Kim, S., and Taylor, P. C. (2017). *Energy and financial viability of hydronic heated pavement systems*, Final Report No. DOT/FAA/TC-17/47, William J. Hughes Technical Center, Federal Aviation Administration, NJ.

Anderson, D, and Marasteanu, M. (1999). "Physical hardening of asphalt binders

relative to their glass transition temperatures." *Transport. Res. Rec.*, 1661, 27-34.
Arabzadeh, A. (2016). *The influence of different mixture design variables on thermal fatigue cracking of asphalt concrete pavements*, M.S. Thesis, Middle East Technical University, Ankara, Turkey.
Arabzadeh, A., Ceylan, H., Kim, S., Gopalakrishnan, K., and Sassani, A. (2016). "Superhydrophobic coatings on asphalt concrete surfaces." *Transport. Res. Rec.*, 2551, 10-17.
Arabzadeh, A., Ceylan, H., Kim, S., Gopalakrishnan, K., Sassani, A., Sundararajan, S., and Taylor, P. C. (2017). "Superhydrophobic coatings on Portland cement concrete surfaces." *Constr. Build. Mater.*, 141, 393-401.
Arabzadeh, A. and Güler, M. (2014). "Influence of mixture design variables on thermal coefficient of asphalt concrete." *Proc. Int. Conf. on Advances in Civil Engineering*, ACE, 1-6.
Ceylan, H., Gopalakrishnan, K., Kim, S., and Cord, W. (2014). "Heated transportation infrastructure systems: existing and emerging technologies." *Proc., the 12th International Symposium on Concrete Roads*, CD-ROM, September 23-26, 2014, Prague, Czech Republic.
Chung, D. D. L. (2012). *Carbon fiber composites*, 2nd edition, Butterworth-Heinemann,United Kingdom.
Derwin, D., Booth, P., Zaleski, P., Marsey, W., and Flood, Jr . W. (2003). "Snowfree ® heated pavement system to eliminate icy runways." *SAE International*, Technical Paper Number 2003-01-2145.
Federal Aviation Administration (FAA). (2014). *Standards for Specifying Construction of Airports.* FAA Advisory Circular No. 150/5370-10G, Washington, DC.
Federal Aviation Administration (FAA). (2016). *Airport Field Condition Assessments and Winter Operations Safety*. FAA Advisory Circular No. 150/5200-30D, Washington, DC.
García, Á., Schlangen, E., van de Ven, M., and Liu, Q. (2009). "Electrical conductivity of asphalt mortar containing conductive fibers and fillers." *Constr. Build. Mater.*, 23(10), 3175-3181.
García, A., Norambuena-Contreras, J., Bueno, M., and Partl, M. N. (2015). "Single and multiple healing of porous and dense asphalt concrete." *Intell. Mater. Syst. Struct.*, 26(4), 425-433.
Huang, S. X., Sun, C. J., Tang, N., Pan, P., and Wu, S. P. (2013). "Research on construction technology of self-monitoring asphalt concrete." *Appl. Mech. Mater.*, 303, 2485–2489.
Lee, S. J., Rust, J. P., Hamouda, H., Kim, Y. R. and Borden, R. H. (2005). "Fatigue cracking resistance of fiber-reinforced asphalt concrete." *Text. Res.J.*, 75(2), 123–128.
Liu, Q., Schlangen, E., and Van De Ven, M. (2012). "Induction healing of porous asphalt." *Transport. Res. Rec.*, 2305, 95-101.
Liu, Q., Schlangen, E., García, Á., and Van De Ven, M. (2010). "Induction heating of electrically conductive porous asphalt concrete." *Constr. Build. Mater.*, 24(7), 1207–1213.

Liu, X. and Wu, S., (2011). "Study on the graphite and carbon fiber modified asphalt concrete." *Constr. Build. Mater.*, 25(4), 1807-1811.

Pan, P., Wu, S., Xiao, F., Pang, L., and Xiao, Y. (2015). "Conductive asphalt concrete: A review on structure design, performance, and practical applications." *Intell. Mater. Syst. Struct.*, 26(7), 755-769.

Sassani, A., Ceylan, H., Kim, S., Gopalakrishnan, K., Arabzadeh, A., and Taylor, P. C. (2017). "Influence of mix design variables on engineering properties of carbon fiber-modified electrically conductive concrete." *Constr. Build. Mater.*, 152, 168-181.

Shen, W., Ceylan, H., Gopalakrishnan, K., Kim, S., and Nahvi, A. (2017). *Sustainability assessment of alternative snow-removal methods for airport paved surfaces*, Final Report No.DOT/FAA/TC-17/34, William J. Hughes Technical Center, Federal Aviation Administration, NJ..

Wang, H., Yang, J., Liao, H., and Chen, X. (2016). "Electrical and mechanical properties of asphalt concrete containing conductive fibers and fillers. *Constr. Build. Mater.*, 122, 184–190.

Weber, M. and Kamal, M. R. (1997). "Estimation of the volume resistivity of electrically conductive composites." *Polym. Compos.*, 18(6), 711–725.

Wu, S., Mo, L., Shui, Z., and Chen, Z. (2005). "Investigation of the conductivity of asphalt concrete containing conductive fillers." *Carbon*, 43(7), 1358–1363.

Wu, S., Pan, P., Chen, M., and Zhang, Y. (2012). "Analysis of characteristics of electrically conductive asphalt concrete prepared by multiplex conductive materials." *J. of Mater. in Civil Eng.*, 25(7), 871–879.