conducting the simulations in Pavement ME design software version 2.3. The major design inputs including design life, traffic volume, climate, etc. were considered constant as shown in Table 2. Simulations were conducted for the NMDOT paving mixes, already tested for CTE and the strength properties. Level 1 inputs were used for laboratory tested data and level 3 inputs were used for default CTE values. The performance parameters including transverse cracking, joint faulting and international roughness index (IRI) were analyzed with respect to the variability of the input schemes.

Table 2. Inputs for Simulation.

Parameter	Value
Design Life	30 years
Design Thickness	10 in
Dowel Diameter and Spacing	1.25 in @ 12 in
Joint Spacing	15 ft
Slab Width	12 ft
Climate Station	Albuquerque, NM
Initial IRI	63 in/mile
Terminal IRI	172 in/mile
Threshold Transverse Cracking (% of Slabs)	15 %
Terminal Mean Joint Faulting	0.12 in
Reliability	90%
Modulus of Rupture of Concrete	Per CA-ID
Elastic Modulus of Concrete	Per CA-ID
Poisson's Ratio	0.2
Aggregate Type	Per CA-ID
Traffic ESALS	29×10^6
Number of Lanes	2
Base Course	Non-stabilized
Base Course Thickness	6 in
Base Course Resilient Modulus	40000 Psi

Table 3. Climatic Details of Simulated Region.

Weather Station	Albuquerque, NM
Mean Annual Air Temperature (^{0}F)	57.81
Mean Annual Precipitation (in)	9.05
Freezing Index (^{0}F - days)	42.82
Average Annual Freeze/Thaw Cycles	75.85
Remarks	Moderate Region

SIMULATION RESULTS

The analysis of simulation results was conducted to quantify the effects of CTE inputs on JPCP performance indicators.

Effects on Transverse Cracking: The comparison for transverse cracking is presented in Figure 3, which shows that there is significant variation in transverse cracking between the simulation results of tested CTE values and default CTE values. The difference in transverse cracking is in the range of 4.7 to 16.6% which is highly significant. With these results, it is evident that the pavement must be designed with the accurately tested CTE inputs for the paving mix to be used so that the designed pavement can last for the entire service life.

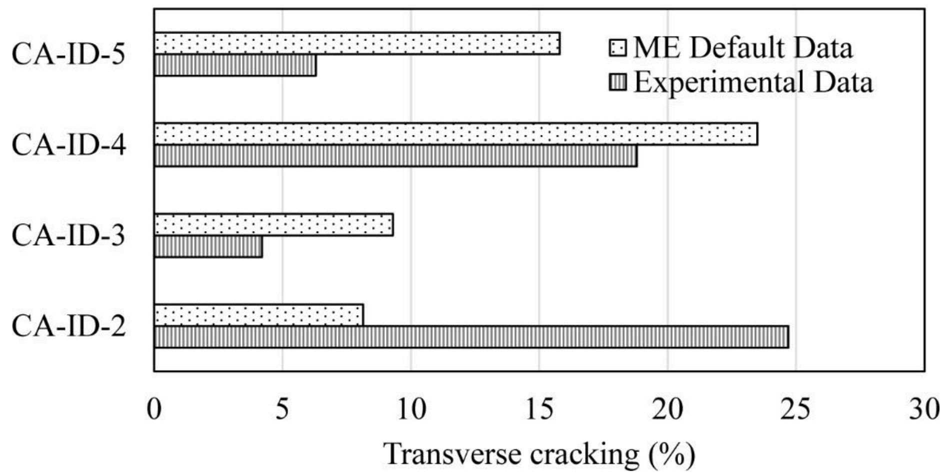

Figure 3. Impact of CTE input levels on transverse cracking.

Effects on Joint Faulting: The comparative summary for joint faulting for the tested and default CTE inputs is presented in Figure 4. It is evident that there is significant impact on joint faulting between the two input levels. The difference in joint faulting values ranges up to 0.03 in.

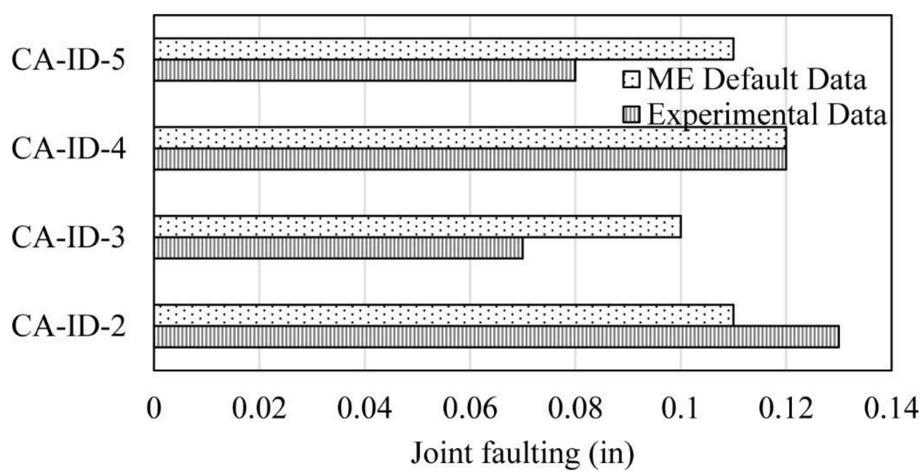

Figure 4. Impact of CTE input levels on joint faulting.

Effects on Pavement Roughness: The comparison is presented in Figure 5, which shows that there is significant variation in IRI between the two CTE input levels. The difference ranges between 6.5 to 26.4 in/mile. The high values correspond to the difference in transverse cracking and faulting as IRI is dependent on transverse cracking and faulting parameters along with other factors. These results necessitate the importance of using tested CTE inputs while designing a concrete pavement.

EFFECTS OF JOINT SPACING ON JPCP PERFORMANCE

The effects of joint spacing on pavement performance parameters were evaluated by conducting simulations with tested CTE inputs used for all the paving mixes and varying the joint spacing between 12 to 17 feet. The results show that there is significant impact of joint spacing on all the performance parameters. The maximum impact of joint spacing is on transverse cracking with % change of up to 34.3% with unit change in joint spacing, while joint faulting is affected with % change of up to 16.7%. This shows that joint spacing has significant effects on JPCP performance and by modifying the joint spacing the adverse effects of higher CTE concrete can be minimized.

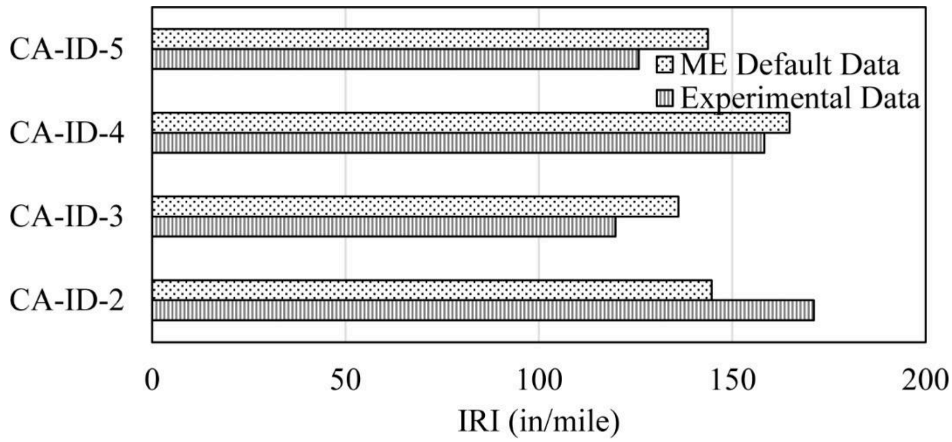

Figure 5. Impact of CTE input levels on IRI.

Comparison of Effects of Joint Spacing: The comparison of the effects of joint spacing on cracking, faulting and IRI are shown in Figure 6, 7, and 8 respectively. The results show that joint spacing has significant impact on all the performance parameters and as the joint spacing increases the pavement distresses also increases with all other design factors being constant. Thus, pavement performance improves when joint spacing is reduced with less transverse cracking, less faulting and lower IRI values.

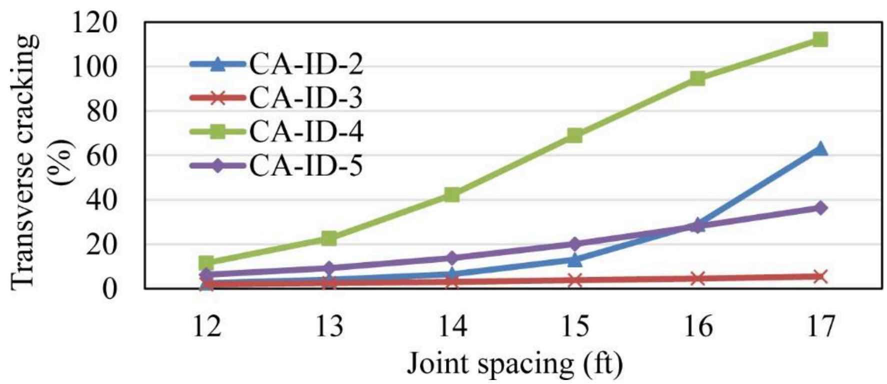

Figure 6. Impact of joint spacing on transverse cracking.

CONCLUSIONS

The experimental data indicated that coarse aggregate mineralogy has the most significant impact on the CTE of paving concrete. The main cause of this dependence is that coarse aggregate has the highest proportion in the concrete constituents. The tested CTE values differ from the average ME default CTE values which may result in inaccurate pavement design. Simulation results proved that CTE inputs have a significant impact on the performance predictions of JPCP thus the paving mix to be used should be tested for CTE before the design phase. It is also highlighted that the adverse effects of high CTE values can be minimized by reducing the transverse joint spacing.

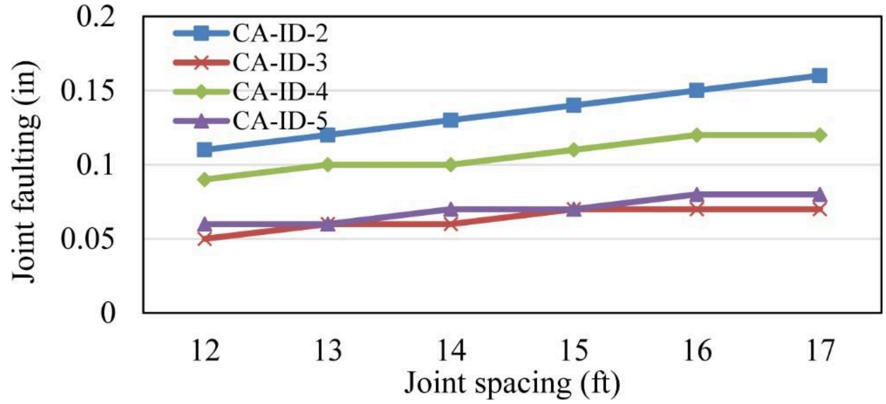

Figure 7. Impact of joint spacing on faulting.

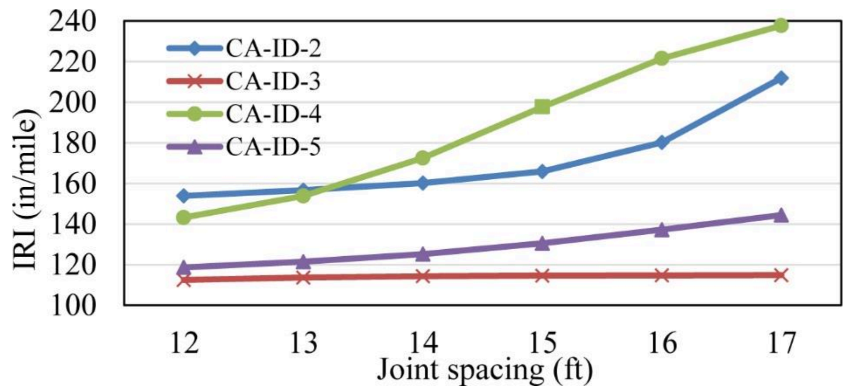

Figure 8. Impact of joint spacing on pavement roughness.

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

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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.

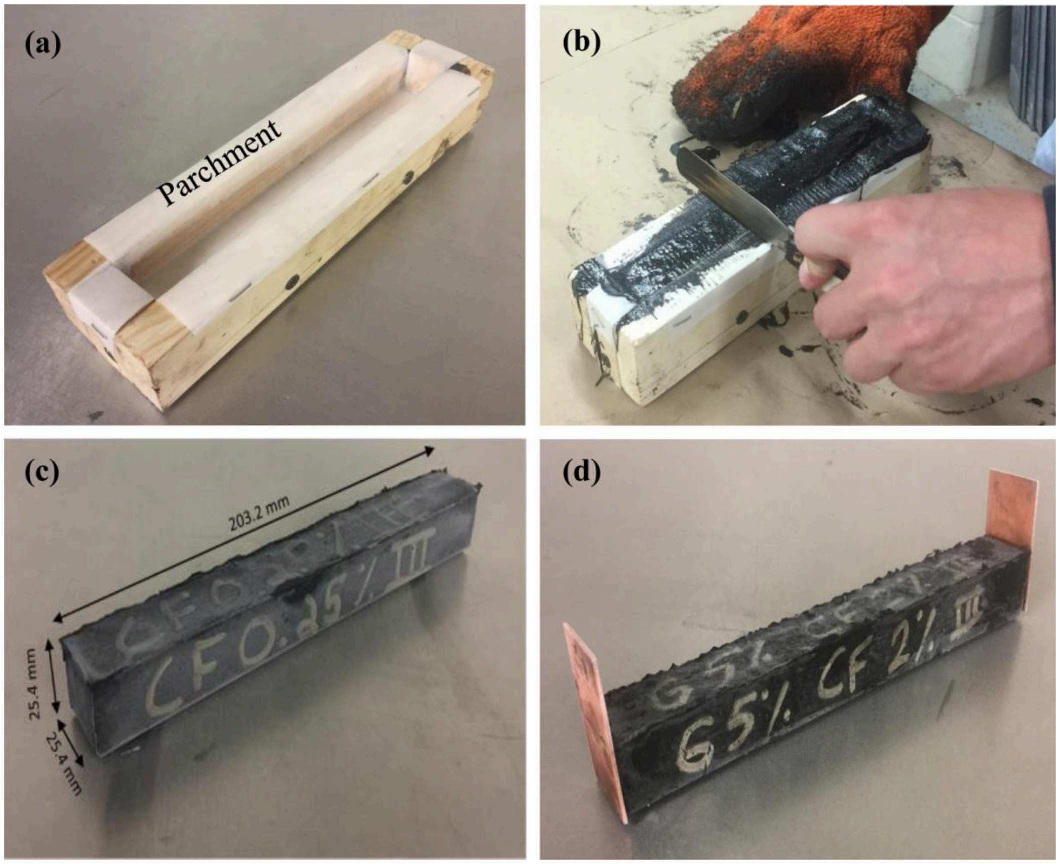

Figure 1. Preparation of prismatic asphalt mastic specimens: (*a*) wooden mold for casting the asphalt mastic specimens, (*b*) hand compacting and leveling the asphalt mastic specimens, (*c*) demolded asphalt mastic specimen, (*d*) an asphalt mastic specimen with attached copper electrodes.

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*).

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):

$$\rho = \frac{RS}{L} \quad (1)$$

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 and 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).

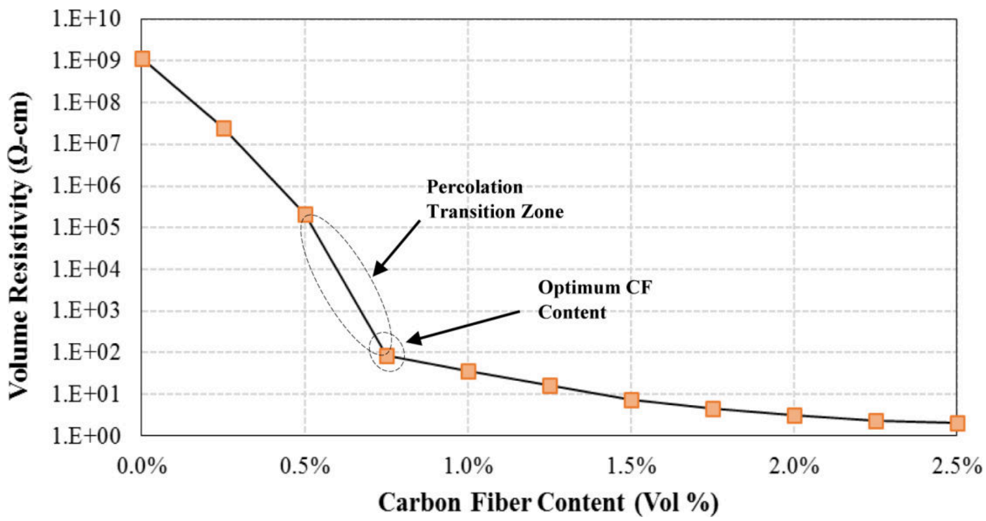

Figure 2. Relationship between electrical resistivity and CF volume content.

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