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Electrically-conductive asphalt mastic: Temperature dependence and heating efficiency

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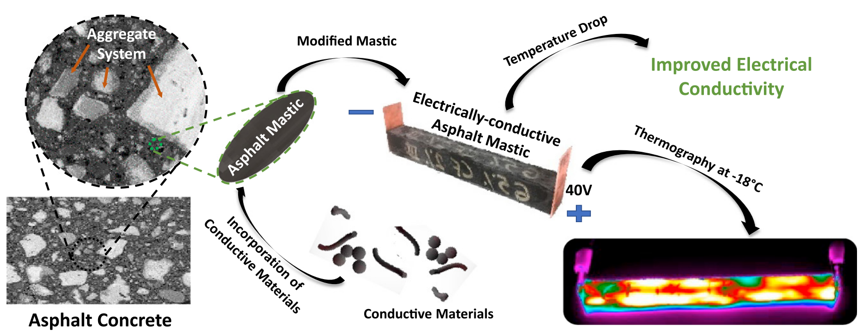
HIGHLIGHTS

- Single-phase and two-phase electrically-conductive asphalt mastics (ECAMs) have comparable resistivities at higher carbon fiber (CF) dosage rates.
- Two-phase ECAM has a higher conductivity than single-phase ECAM at lower CF dosage rates.
- Reduction in temperature enhances electrical conductivity of ECAM indicating heating efficiency of ECAM at freezing temperatures.
- Performing infrared thermography on the surface of ECAM proved the heating efficiency of ECAM within a short time window.

GRAPHICAL ABSTRACT



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ABSTRACT

Asphalt mastic, a pitch-matrix composite, consists of bitumen and mineral fillers (very fine aggregates), that fills the voids created by coarser aggregates in asphalt concrete. In this study, asphalt mastic was modified with carbon fiber (CF) and graphite powder (GP) to produce single-phase (containing only CF) and two-phase (containing both CF and GP) electrically-conductive asphalt mastic (ECAM) for anti-icing and deicing applications. Volume resistivities of ECAMs were measured at two different temperatures and the influence of temperature on electrical conductivity was evaluated, revealing that reduction in temperature enhances the ECAM's electrical conductivity. After analyzing the volume resistivity data for both single-phase and two-phase ECAM specimens, heat generation efficiency of single-phase ECAM was investigated at a conductive material dosage slightly higher than the optimum. The heat generation efficiency was evaluated at a below-freezing temperature by performing active infrared thermography (IRT). Based on the active IRT analysis results, it was found that single-phase ECAM at the selected CF content is capable of generating enough heat for melting ice and snow or preventing accumulation of snow and formation of ice.

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1. Introduction

Electrically-conductive asphalt concrete (ECAC) can be a promising material for anti-icing or de-icing purposes to mitigate winter maintenance problems in critical paved areas such as airports, bridge decks, etc. ECAC can be produced by adding conductive aggregates or fillers to asphalt concrete. Asphalt concrete consists of bitumen, aggregates and fillers, with aggregates providing a skeleton that needs to be covered, while the filler combined with bitumen forms a mastic that fills the interstitial voids created by aggregates [1]. A common way for producing ECAC is incorporating conductive fillers into asphalt concrete [2, 3], i.e., producing an electrically conductive asphalt mastic (ECAM) that fills the voids created by an aggregate system. Because of the key role that ECAM can play in generating a desired amount of heat through resistive heating in asphalt concrete, its resistivity and heat generation capability should be studied in a more isolated way, i.e., when there are no aggregates present [4] to interfere with ECAM performance.

García et al. [5] who studied the heating efficiency of electrically-conductive asphalt mortar (ECAM + sand) for self-healing applications, investigated the heat generation capacity of asphalt mortar through induction heating. They used eddy currents produced by a magnetic field [3] for increasing the temperature in asphalt mortar. Generation of eddy currents needs closed-loop conductive material circuits [5] locally present in asphalt-based materials. However, in conduction heating, for ice- and snow-free pavement applications [6], there is a need for presence of continuous conductive material network(s) in asphalt-based materials connecting one electrode to another, so that the electric current can flow between the electrodes when they are subjected to an electric potential field.

Material-related factors, including types, combinations, and amounts of conductive fillers can influence the volume resistivity of ECAM. García et al. [7], were first to investigate the influence of steel fibers on enhancing the electrical conductivity of asphalt mastic for self-healing applications. They produced an ECAM with a volume resistivity of 200 $\Omega\cdot$cm at an optimum fiber content of 6% by volume of mastic. Although conductive powders can enhance electrical conductivity, it is believed that addition of conductive powders to asphalt concrete containing conducting fibers does not have an appreciable influence on enhancing the electrical conductivity [2]. With advancement in production of conductive fibers and fillers, it seems possible to produce highly-conductive asphalt-based materials capable of generating sufficient heat for ice-and snow-free heated pavement applications.

In addition to material-related factors, external stimuli can influence the electrical conductivity of a composite material such as ECAM [8]. Wu et al. [9], first to investigate the influence of temperature change on electrical resistance of dense-graded ECAC, found that reducing the temperature from 30 °C to 24 °C does not result in any change in resistance of ECAC, although they observed a 12% reduction in resistance when they subjected the same ECAC to a temperature reduction from 38 °C to 30 °C. Resistivity of polymers (such as bitumen) without conducting materials is temperature-dependent [10], and above glass transition temperature ($T_{g\infty}$) - which for bitumen can occur at temperatures as low as −25 °C [11], the volume resistivity of polymers gradually increases with a decrease in temperature [12], i.e., polymers exhibit a negative thermal coefficient (NTC) for $T > T_g$ when they are not modified with electrically-conducting materials. As a result, investigating the effect of temperature on volume resistivity of ECAM at below-freezing temperatures (but still higher than T_g) is of paramount importance, since ECAM would not be a good candidate for ECAC heated pavement applications, if it were not able to maintain its electrical conductivity at low temperatures.

The objective of this study was to produce an electrically-conductive asphalt mastic (ECAM) with efficient heat generation capability, so that when it fills voids created by aggregates, the result is an anti-icing or deicing electrically-conductive asphalt concrete (ECAC) for heated pavement applications. To achieve the objective of this study, asphalt mastic was modified with carbon fiber (CF) and graphite powder (GP) to produce both single-phase (containing only CF) and two-phase (containing CF and GP) ECAM specimens. Volume resistivities were measured at two different temperatures, the influence of temperature on electrical conductivity was evaluated, percolative behaviors were observed, and low resistivity regions were identified. After analyzing the volume resistivity data for both single-phase and two-phase ECAM specimens, it was decided to investigate heat generation efficiency only for single-phase ECAM at a certain conductive material dosage slightly higher than the optimum content. The heat generation efficiency was evaluated at a below-freezing temperature by performing active infrared thermography (IRT). Finally, based on the active IRT analysis results, it was found that single-phase ECAM at the selected CF content is capable of generating enough heat at the selected below-freezing temperature for anti-icing and deicing purposes. Fig. 1 presents more information regarding the procedure followed for accomplishing this study.

2. Experimental

2.1. Materials

The ECAM specimens prepared for this study were composed of performance grade (PG) bitumen and both non-conductive and conductive fillers. The bitumen was PG 58-28 and was obtained from Jebro Inc. The non-conductive filler was hydrated lime (HL), and the conductive fillers, obtained from Asbury Carbons Inc., were flake-type graphite powder (GP) and carbon fiber (CF). Properties of each component type are presented in Table 1.

Electrical conductivity in a composite material such as ECAM, in order of importance, depends on [13, 14]: (a) intrinsic conductivity of conductive additives, (b) the degree of direct contact of conductive additives in an insulating matrix such as asphalt mastic, and (c) the hopping of electrons between the conductive materials which are not in direct contact but are still in close proximities. As a result, according to Table 1, it can be easily interpreted that CF, with the lowest volume resistivity, is the best conductivity enhancement filler followed by GP. The resistivity values reported for CF and GP are obtained from Asbury Carbons Inc., and the resistance of CF, according to Asbury Carbons Inc., is determined by measuring the voltage drop along a single fiber or a fiber bundle, and then the resistivity is calculated based on the geometry of the single fiber or the fiber bundle. The resistivity measurement based on voltage drop is thoroughly explained in ASTM D4496-13 standard. The resistivity of powdered carbonaceous materials such as GP, according to Asbury Inc., can be measured by filling a nonconductive hollow cylinder with GP in which two metallic pistons form a pressure chamber by applying a pressure of 200 Mpa; these pistons are connected to an ohmmeter for measuring the resistance and then calculating the resistivity. HL and PG 58-28 are insulating materials and, as a result, their resistivity values are not reported in Table 1. SG values (see Table 1) are necessary for converting each component's volume to weight and vice versa which helped presenting the mastic design information in Table 2. Sizes of GP, CF and HL can give an understanding about the spatial dominance of CF's when blocked by HL particles. The provided sizes can also be an indication of the ability of CFs to bridge between the GP clusters - in an insulating matrix (asphalt mastic) - enhancing the overall composite's electrical conductivity. Although copper electrode has SG and size values, they are not reported, because these values were not used in this study.

2.2. Specimen fabrication

To identify suitable approaches for enhancing electrical conductivity of asphalt-based materials, ECAM specimens were prepared using two different methods: (a) using CF to produce a single-phase electrically-conductive material system, and (b) using combined CF and GP to produce a two-phase electrically-conductive material system. To alleviate