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DOI
10.1201/9780429457791

Publication date
2018

Document Version
Accepted author manuscript

Published in
Advances in Materials and Pavement Prediction: Papers from the International Conference on Advances in Materials and Pavement Performance Prediction (AM3P 2018), April 16-18, 2018, Doha, Qatar

Citation (APA)
Pavlatos, N., Apostolidis, P., Scarpas, A., Liu, X., & van de Ven, M. (2018). Inductive bituminous mortar with steel and aluminum fibers. In E. Masad, A. Bhasin, T. Scarpas, I. Menapace, & A. Kumar (Eds.), *Advances in Materials and Pavement Prediction: Papers from the International Conference on Advances in Materials and Pavement Performance Prediction (AM3P 2018), April 16-18, 2018, Doha, Qatar* CRC Press. https://doi.org/10.1201/9780429457791

Inductive bituminous mortar with steel and aluminum fibers

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ABSTRACT: This research presents the implementation of a finite element model analysis for assessing the potential of utilizing alternative fibers for the development of inductive bituminous mixes with lower total weight, higher resistance against corrosion, and sufficient induction heating efficiency. Aluminum fibers are selected as the metallic modifier in bituminous mixes against the commonly applied steel fibers in order to develop inductive materials. The main reasons for applying aluminum fibers in bituminous mixes are presented in (Pavlatos et al., Framework for replacing steel with aluminum fibers in bituminous mixes, *Advances in Materials and Pavement Performance Prediction*, Submitted, 2018). A real fiber modified bituminous specimen is reconstructed by means of CT scans and its effective electrical conductivity is calculated assuming steel and aluminum fibers. Since steel fiber modified bituminous mixes have already been used successfully for induction heating, the aim of this work is to demonstrate that aluminum fiber modified bituminous mixes exhibit equally good properties as the steel fiber modified bituminous mixes for induction heating.

1. INTRODUCTION

Road construction and maintenance are two of the major energy consumers in the world (Giustozzi et. 2012), and thus improving the current practices in terms of energy efficiency will support the worldwide effort for achieving sustainable development. Within this framework, national road authorities, contractors and material suppliers have started to explore new technologies to minimize the energy footprint of pavements via developing eco-friendly and long-lasting materials. One of these technologies is the electro-magnetic induction for healing bituminous paving materials (Garcia et al. 2009, Liu et al. 2010, Liu et al. 2012, Liu et al. 2013, Garcia et al. 2013, Apostolidis et al. 2016, Apostolidis et al. 2017). However, the bituminous mixes, which are the most commonly used materials in pavement construction industry, are non-inductive materials. For this reason, inductive particles, mostly steel fibers, are added into the mixes to make them suitable for electro-magnetic induction.

Bituminous mixes modified with steel fibers can be heated locally under a time-variable magnetic field applied by an induction coil. The magnetic field induces eddy currents in fibers within the mortar phase of the mix according to Faraday’s law, and they are heated up based on the principles of Joule’s law. Joule heating, which is also known as ohmic or resistive heating, is a phenomenon through which electric current flows through a material with high electrical conductivity and generates heat (Greenwood & Williamson, 1958, Carslaw & Jaeger, 1959). The generated heat in the material increases the temperature and through the temperature rise the bituminous mortar heats up, so it becomes less viscous and its mechanical properties are recovered.

Apart from allowing for the material healing when coupled with the induction technology, studies have shown the increase of fatigue life in bituminous mixes when steel fibers are added (Liu et al. 2012). However, steel fibers into bituminous materials substantially increase the total weight of plant-produced mixes, resulting in higher production and transportation costs. Lastly, the exposure of steel fiber modified bituminous mixes to various weather conditions results in the corrosion of the steel fibers and thus affects the durability of the material.

2. OBJECTIVES

The present paper assesses the potential of utilizing alternative fibers for the development of inductive bituminous mixes with lower total weight, higher resistance against corrosion, and sufficient electrical properties for having rapid temperature evolution under electro-magnetic induction. Aluminum fibers were selected to replace the steel fibers and the effective electrical conductivity of aluminum and steel fiber composite mixes was determined. Bituminous mortar – mix without the stone fraction – is selected to be studied because it is the bituminous part where the fibers are dispersed and contribute to the ultimate performance of pavements. The bituminous mortar also exhibits the healing capabilities when heated by an external source (e.g. induction heating).

3. GOVERNING EQUATIONS & THEORY

A finite element model has been utilized for the determination of effective electrical conductivity of aluminum and steel fiber modified bituminous mortar. The governing equation is the charge conservation law as described in Equation 1,

$$\frac{\partial \rho_c}{\partial t} + \nabla \cdot \underline{J} = 0 \qquad (1)$$

where ρ_c is the charge density, t is time and $\underline{J}$ is the current density vector. In our case we neglect any charge accumulation as we examine the steady state of the problem.

The current density vector can be described by using Ohm's law in Equation 2,

$$\underline{J} = \sigma\,\underline{E} = -\sigma\,\nabla V \qquad (2)$$

where σ is the electrical conductivity, $\underline{E}$ is the electric field and V is the electric potential.

A potential gradient is applied at opposite sides of the specimen and the current density vector is solved for. The total current that runs through the sample can be calculated by intergrading over a cross-section the projection of the current density on the area. This is done in Equation 3,

$$I = \iint_A \left(\underline{J} \cdot \hat{\underline{n}} \right) dA \qquad (3)$$

where I is the total current that runs through the specimen, dA is an elementary area over which the current density is applied and $\hat{\underline{n}}$ is the normal vector to that area. The specimen is then viewed as an equivalent resistor in an electric circuit as explained in Figure 1 and its resistance is calculated in Equation 4,

$$R = \frac{V}{I} \qquad (4)$$

where R is the equivalent resistance of the specimen and V is the electric potential difference acting on the opposite sides.

As the specimen is a rectangular parallelepiped, the electrical resistance of the specimen is proportional to its resistivity, proportional to its length and inversely proportional to its cross-sectional area. These relationships yield Equation 5,

$$R = \rho_{b,eff}\frac{L}{A} \;\leftrightarrow\; \rho_{b,eff} = R\frac{A}{L} \qquad (5)$$

where $\rho_{b,eff}$ is the effective bulk resistivity, A is the cross-sectional area and L is the length of the specimen. Lastly, the effective bulk conductivity is calculated in Equation 6,

$$\sigma_{b,eff} = \frac{1}{\rho_{b,eff}} \qquad (6)$$

where $\sigma_{b,eff}$ is the effective bulk conductivity.

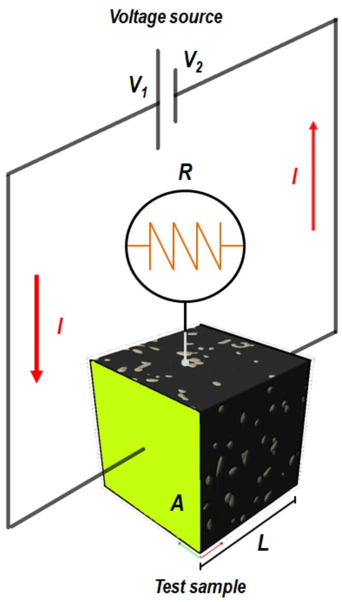

Figure 1. Schematic of electrical conductivity measurements in inductive bituminous mix

4. GEOMETRY, MESH, BOUNDARY CONDITIONS & PARAMETERS

To determine the effective electrical conductivity of these mixes, the 3D finite element mesh of bituminous mortar is generated by using X-ray computed tomography (CT) scans, a completely non-destructive technique for obtaining digital information of features in the interior of opaque objects. The process of reconstructing 3D images of inductive mortars and the CT scans based mesh generation is descripted elsewhere (Apostolidis et al., 2016). The final geometry is a cube with length of 1.18 mm that contains 502.660 elements and 2.285.726 degrees of freedom and it is presented in Figure 2. The generated mesh was imported into the COMSOL Multiphysics for the numerical analyses. For determining the effective electrical conductivity of inductive mortar it is necessary to define the properties of the individual components of the studied composite material. The electrical conductivity magnitudes of the mortar part, steel and aluminum fibers were considered to be 1E-5, 4.8E+6 (ASM International 2000) and 1.7E+07 S/m (ASM International 1990), respectively. The fiber distribution in the studied geometry is demonstrated in Figure 3. A potential gradient of 10 V is applied between the two opposite sides in blue in Figure 4, whereas the remaining four sides are considered as electric insulation. A side acting as electric insulation is translated to a zero normal component of the current density vector on that side.

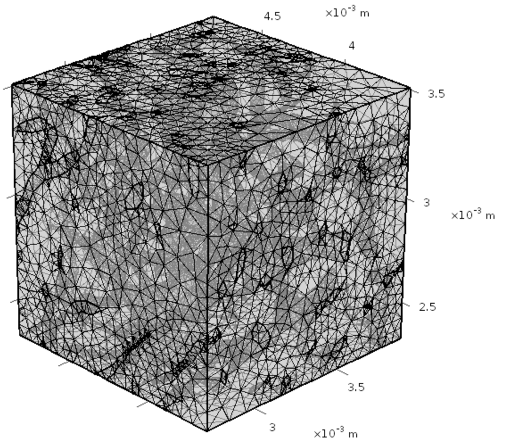

Figure 2. FEM mesh of inductive mortar reconstructed by CT-scans

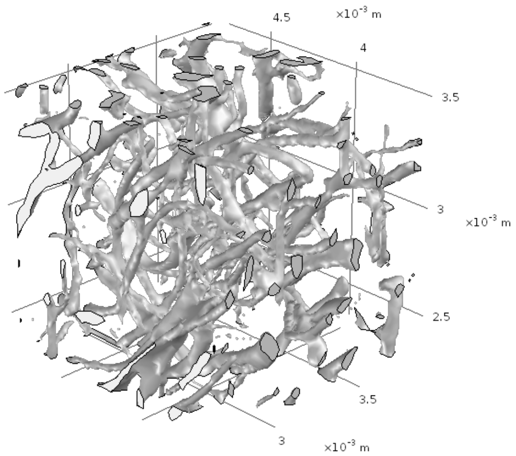

Figure 3. Fibers distribution in inductive mortar

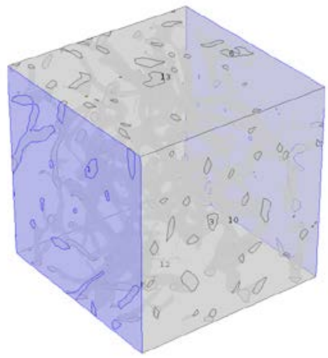

Figure 4. Opposite sides between which the potential difference is applied

5. RESULTS

The current density vector is solved for and the total current is calculated by means of Equation 3 for both the steel and aluminum fiber modified mix. The total current for the steel fiber modified mix is I_{st}=5.58385E-7A and for the aluminum fiber modified mix is I_{al}=5.59455E-7A. Using Equations 4, 5 and 6 the effective bulk conductivity for the steel fiber modified mix $\sigma_{b,eff,st}$=4.73208E-5 S/m and for the aluminum fiber modified mix $\sigma_{b,eff,al}$=4.74114E-5 S/m are calculated. It is evident that the effective bulk conductivity of the composite sample is marginally higher when using aluminum fibers instead of steel fibers. However, in both cases it seems that the bituminous part – with electrical conductivity several orders of magnitude lower – is the limiting factor. The iso-surface plot of the electrical potential is presented in Figure 5, whereas the current density vector in the bituminous part and in the inductive fibers is plotted in Figure 6 and Figure 7 respectively.

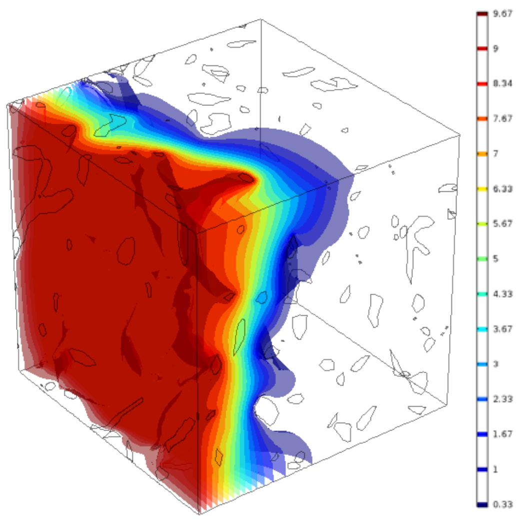

Figure 5. Iso-surface of electric potential (units in V)

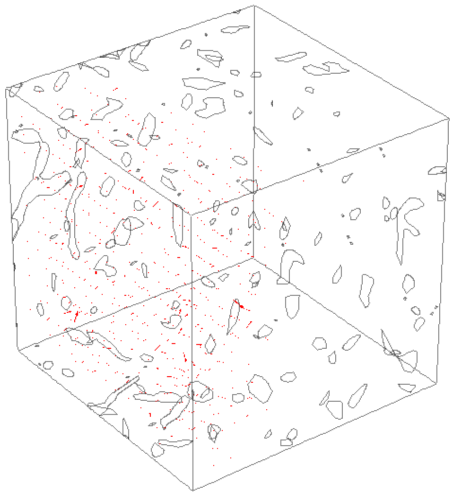

Figure 6. Current density vector in bituminous part

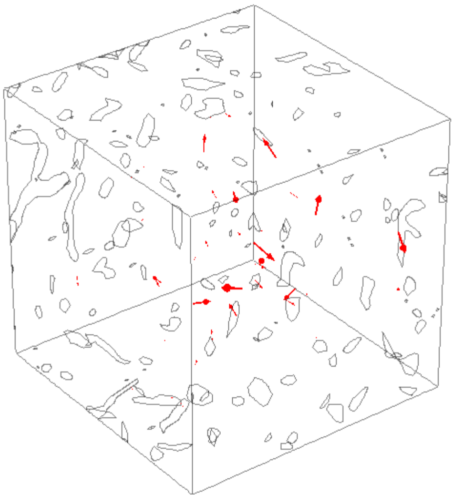

Figure 7. Current density vector in inductive fibers

6. CONCLUSIONS AND FUTURE WORK

In this paper a fiber modified bituminous sample was examined and its effective bulk conductivity was calculated assuming steel and aluminum fibers. From the results it becomes clear that aluminum fibers provide at least as good properties for induction heating as the steel fibers. Therefore, the addition of aluminum fibers sustains the enhanced electrical properties of bituminous mortar, providing at the same time a lower weight composite material with improved resistance against corrosion.

The results for both cases suggest that the effective conductivity of the composite is much closer to the value of the mortar than the value of the metallic fibers. This can be explained by observing Figures 5, 6 and 7. It is evident that initially the electric current is carried by the bituminous part, creating a bottleneck effect. The authors believe that this is the effect of the given geometry as the fiber orientation at the first part of the sample is mostly perpendicular to the external electric field and thus the fibers carry hardly any electric current in that part. This realization reveals the importance of the stochastic nature of the geometry when real-life samples are used.

The current model provides a tool to acquire a quick indication for developing bituminous materials with improved multi-functional properties, such as enhanced healing capacity, anti-corrosive resistance, thermal storage, etc. However, experimental investigation is strongly advised for better understanding of the underlying mechanisms.

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