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A Numerical Simulation of Electrical Resistivity of Fiber-Reinforced Composites, Part 2: Flexible Bituminous Asphalt

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Abstract: Asphalt concrete pavements are vulnerable to freeze-thaw cycles. Consecutive cracking and penetration of corrosive agents can expedite the degradation of asphalt pavements and result in weight loss and reduced strength. Fiber reinforcement in flexible bituminous asphalt bridge cracks limits the crack width and enhances the toughness of the composite. Furthermore, steel fibers facilitate asphalt heating during maintenance and repair operations. Electrical resistivity is a vital parameter to measure the efficiency of these operations and to identify the state of degradation in fiber-reinforced asphalt concrete. The significant difference between conductivities of steel fibers and bituminous matrix warrants in-depth investigations of the influence of fiber reinforcement on the measured surface electrical resistivity of placed pavements. Numerical simulations endeavor to predict the resistivity and associated deviations due to randomly distributed fiber reinforcement. Results and discussions reveal the sources and magnitudes of fiber geometry and content adjustments. Outcomes investigate associated errors for practical applications.

Keywords: finite element method; fiber-reinforced composites; electrical resistivity; electrical conductivity; material durability; sustainable development; infrastructure resilience; asphalt concrete

1. Introduction

The sustainable development of resilient infrastructure warrants the application of high-performance materials to extend the service life of engineering systems, such as pavements infrastructure, and to minimize input energy and greenhouse gas emissions [1–5]. Extensive resources required to maintain and operate pavement systems signify the importance of planning for sustainability and resilience [6–8].

1.1. Durability of Bituminous Asphalt Composites

Asphalt pavements are vulnerable to thermal and chemical environmental conditions. Combinations of volume changes due to freeze–thaw cycles, cracking due to strength loss, and penetration of water and deicing chemicals in asphalt result in progressive weight loss and degradation of structural capacity. Physical and mechanical properties of the aggregate and bituminous matrix and their interaction within the interfacial zone determine materials resistance against these degradations [9,10]. The application of sustainable materials, such as recycled aggregates, is a common practice to enhance the performance and extend the service life of the pavement with adequate resilience against risks [11]. An evaluation of the asphalt performance includes investigating specific material characteristics, such as permeability, porosity, chemical stability, environmental conditions (including the presence of chemicals and salts, water flow, and pressure), and applied cycles of freezing and thawing [12]. Using proper types and gradations of aggregates tends to reduce permeability...
and limit damages due to the accumulation of water, salt, and chemical agents in mixture voids [12–16].

1.2. Fiber-Reinforced Asphalt

Fiber reinforcement is an established technique to control cracking in composite materials, such as concrete and asphalt pavements [17]. In addition, conductive fibers can facilitate conductive heating as an efficient method to alleviate freezing conditions and enhance healing mechanisms [18–22]. Electrically conductive cementitious or asphalt concrete pavements utilize steel and graphite fibers to achieve required conductivity in critical applications, including airports and bridge decks [23–25]. Slender steel fibers are more efficient than graphite powders due to higher conductivity values and the ability to bridge crack widths [26]. However, additives such as graphene and slag are often used to reduce required heating energy without changing the heating rate [27]. Fibers are placed directly in the hot mix asphalt [28], with proportioning adjustments to increase the bituminous contents [29]. Application of fibers from virgin or recycled sources may also change the air voids and other physical and mechanical properties of the mixture, determining the durability of the pavement [30–41].

The electrical resistivity of the asphalt is an efficient measure of the conductive heating efficiency of the pavement, which is enhanced by conductive fibers [37,42–44]. The surface electrical resistivity is an adaptable method for sensor-based structural health monitoring [45]. The bituminous asphalt is an insulative material with an electrical resistivity of $10^{11}$ to $10^{13}$ Ω·m. The electrical resistivity of asphalt concrete is slightly lower than bitumen within the range of $10^7$ to $10^9$ Ω·m. The addition of steel and carbon fibers can substantially reduce this value in the $10^1$ to $10^5$ Ω·m range [44]. The external heating using electromagnetic induction or microwave radiation relies on the electrical resistivity of the pavement to achieve proper temperature and polarization effects [40,46–52]. The optimum temperature depends on various external conditions, such as time and damage [53,54], as well as internal parameters, such as viscosity and mixture properties [40,47,52–56]. The heating capacity of the bitumen has a substantial impact on the healing properties of the asphalt composite. This capacity, which additives can adjust, influences the level of energy required to begin the healing process in bitumen [34,57–59]. Porosity also facilitates the healing and recovery of asphalt mixtures [34,60]. High thermal energy absorption of fibers compared to bituminous matrix and aggregates facilitates this process [52]. However, the practical range of fiber contents is typically 6 to 8 percent by volume to avoid clustering during mixing procedures [61]. Figure 1 displays selected observed data which indicate fiber contents and measured electrical resistivity of the composite bituminous asphalt materials (Table 1). The scattered observations warrant numerical studies in order to understand the trends of electrical resistivity measures concerning fiber type, content, and geometry.

Figure 1. Selected experimental data on fiber content and electrical resistivity.

| Fiber Type                                      | Electrical Resistivity (Ω·m) |
|-----------------------------------------------|------------------------------|
| Low-Carbon Steel Fiber                        | $1.0 \times 10^1$           |
| Micron-Scale Steel Fiber                      | $1.0 \times 10^0$           |
| Stainless Steel Shaving                       | $1.0 \times 10^{-1}$        |
| Steel Fiber                                   | $1.0 \times 10^{-2}$        |
| Steel Wool                                    | $1.0 \times 10^{-3}$        |
Table 1. Selected experimental studies on the electrical resistivity of fiber-reinforced asphalt.

| Reference                | Specimen                                                                 | Fibers                                                                 |
|--------------------------|--------------------------------------------------------------------------|------------------------------------------------------------------------|
| Wang et al. (2016) [26]  | (AC-13) with 13.2 mm nominal maximum aggregate, and Shell-70 binder,     | Low-carbon steel, 0.10 ± 0.02 mm diameter, with a smooth face          |
|                          | equivalent to PG 64-22                                                   |                                                                        |
| Huang et al. (2009) [62] | Gravel with a nominal maximum size of 12.5 mm, and PG 64-22 binder       | Micron-scale Beki-Shield GR steel fiber, 8 micron diameter, and 6 mm long |
| Norambuena et al. (2018) [30] | Coarse aggregate or gravel (S.G. 2.779), fine aggregate or sand (S.G. 2.721), and filler (S.G. 2.813), and 5.3% bitumen content by aggregates mass | Low-carbon steel wool fibers (S.G. 7.180)                               |
| Norambuena et al. (2018) [30] | Coarse aggregate or gravel (S.G. 2.779), fine aggregate or sand (S.G. 2.721), and filler (S.G. 2.813), and 5.3% bitumen content by aggregates mass | Austenitic stainless steel shavings (S.G. 7.980)                        |
| Liu et al. (2010) [42]   | Quarry material (Bestone, Bremanger Quarry, Norway) between 2.0 and 22.4 mm (S.G. 2.770), crushed sand between 0.063 and 2 mm (S.G. 2688), and 70/100 bitumen (S.G. 1.032) | Steel fiber, 0.0296–0.1911 mm diameter                                 |
| Liu et al. (2010) [42]   | Quarry material (Bestone, Bremanger Quarry, Norway) between 2.0 and 22.4 mm (S.G. 2.770), crushed sand between 0.063 and 2 mm (S.G. 2688), and 70/100 bitumen (S.G. 1.032) | Steel wool, 0.00635–0.00889 mm diameter                                |

S.G.: Specific Gravity. PG: Performance Grade.

2. Materials and Methods

A multi-physics finite element model using COMSOL simulates the numerical solution to the electrical resistivity of asphalt concrete (Figure 2) [63–65]. Random distribution of fibers within the asphalt prototype is generated using a pre-processor MATLAB routine [66]. The modeled prototype is a 100 mm-diameter cylinder with a height of 65 mm. The electrical resistivity is $4.5 \times 10^{11} \ \Omega \cdot m$ for the homogenized matrix and $2.4 \times 10^{-7} \ \Omega \cdot m$ for fibers. Models incorporated two aspect ratio (length to diameter) values of 200 (F1) and 100 (F2) (Table 2). The distribution of fibers in asphalt can be considered random [67]. The finite element model contains nearly 340 solid objects within the modeled cylinder [68]. Figure 3 shows a sample section view of the prototype.

Table 2. Dimensions of fibers.

| Model | Length, mm | Diameter, mm |
|-------|------------|-------------|
| F1-1  | 60         | 0.3         |
| F1-2  | 80         | 0.4         |
| F2-1  | 60         | 0.6         |
| F2-2  | 80         | 0.8         |
In addition, a series of samples with various fiber dispersion was analyzed to verify the reliability of electrical resistivity results concerning the random distribution of fibers. For this purpose, a total of 15 samples with the same fiber content were examined to assure the normal distribution of fibers within the prototype. Shapiro–Wilk and Kolmogorov–Smirnova rates were 0.861 and 0.148, respectively, which were more significant than 0.05, indicating a normal distribution of numerical analysis results. The values of Kurtosis and Skewness were $-0.372$ and $-0.886$, respectively, which were between 2 and $-2$, confirming the normal distribution of the results (Figure 4). Hence, variations in the random dispersion of fibers do not cause bias, skew, or instability in calculated electrical resistivity measures.

Figure 2. A sample finite element model of fiber-reinforced asphalt concrete prototype.

Figure 3. Simulated fiber dispersion through a section view at a 30 mm height.
The model follows Wenner’s method using four electrodes at an equal spacing in a row as shown with dots in Figure 2, with two external electrodes transmitting the specified current and two internal electrodes measuring the electrical resistance. Equation (1) expresses the surface electrical resistivity in Wenner’s method:

$$\rho = 2\pi sR,$$ (1)

where $\rho$ is the surface electrical resistance, $R$ is the electrical resistance, and $s$ is the distance between electrodes. The model imposed a simulated current of 1 A/m$^2$ at a spacing of 30 mm. The electrical potential formulation follows Poisson’s equation combining the Gauss’ law and continuity equation:

$$-\nabla \cdot (\sigma \nabla V - J^e) = Q_i,$$ (2)

where $\sigma$ is the electrical conductivity, $V$ is the electric potential, $J^e$ is the volume of external current, and $Q_i$ is the current at the source.

3. Results

Imposed electrical current is one ampere per square meter at electrodes spaced 10 mm at the top surface of the asphalt prototype (Figure 5). The concentration of the current density in green color is evident at the contact points of electrodes. Purples lines indicate the electric current flow within the body of the prototype, and black lines show fibers.

Figure 6 indicates that increasing steel fiber content reduces the surface electrical resistivity. Table 3 provides a summary of reduction rates using exponential regressions. Disregarding a few outliers, it is evident from results that a higher aspect ratio of fibers results in higher rates of reduction in the electrical resistivity. Furthermore, the electrical resistivity is dropped sharper for shorter fibers with the same aspect ratio.
Figure 5. Electrical conductivity lines in the simulated model.

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Table 3. Regression results for surface electrical resistivity.

| Model  | Exponential Rate of Decline | Coefficient of Determination |
|--------|-----------------------------|------------------------------|
| F1-1   | -0.701                      | 0.6932                       |
| F1-2   | -0.366                      | 0.6919                       |
| F2-1   | -0.327                      | 0.8771                       |
| F2-2   | -0.149                      | 0.8226                       |

Figure 6. The electrical resistance for different percentages of fiber content.
Table 3. Regression results for surface electrical resistivity.

| Model | Exponential Rate of Decline | Coefficient of Determination |
|-------|----------------------------|-----------------------------|
| F1-1  | −0.701                     | 0.6932                      |
| F1-2  | −0.366                     | 0.6919                      |
| F2-1  | −0.327                     | 0.8771                      |
| F2-2  | −0.149                     | 0.8226                      |

4. Discussion

Statistical evaluation of numerical results indicate the best fitting model to follow Equation (3), which is comparable with the outcome of part 1 of this paper for cementitious composites (Figure 7):

\[ R_{\text{FRAC}} = R_{\text{PAC}} e^{(pv \ell + q)}, \]

where \( R_{\text{FRAC}} \) and \( R_{\text{PAC}} \) are the measured electrical resistivity (\( \Omega \cdot \text{m} \)) of fiber-reinforced and plain asphalt concrete, respectively; \( \ell \) is the fiber length (mm); \( d \) is the fiber diameter (mm); \( v \) is the volumetric fiber content (%); and \( p \) and \( q \) are regression constants. The surface electrical resistivity of the investigated plain asphalt concrete model, \( R_{\text{PAC}} \), is \( 4.5 \times 10^{11} \Omega \cdot \text{m} \), and associated regression parameters \( p \) and \( q \) are \( -0.0287 \pm 8.56 \times 10^{-2} \) and \( -0.00228 \pm 7.08 \times 10^{-4} \) for 95% confidence bounds, respectively. Figure 8 shows that the effect of fiber reinforcement on surface electrical resistivity is negligible for low fiber aspect ratios, say 20. Similarly, the effect of aspect ratio is not significant when the fiber content is lower than 0.5% by volume. Figure 9 exhibits a residuals plot for the proposed model revealing dispersion of results for a few prototypes with the same aspect ratio but different length and diameter values, which are greater than those observed in part 1 of the paper. Furthermore, surface electrical resistance reduction trends with fiber content are similar to experimental cases, validating the proposed methodology (Figure 10, Table 4).

![Figure 7. The electrical resistance for different percentages of fiber content.](image-url)
Figure 8. The surface electrical resistance (Ω·m) contour map for the proposed fit.

Figure 9. The residuals plot of surface electrical resistance (Ω·m) for the proposed fit.
5. Conclusions

Fiber reinforcement in bituminous asphalt typically involves shorter and thinner fibers than cementitious concrete. The difference in size implies that the number of fibers in asphalt is more significant than concrete fibers for the same fiber content volume. In addition, the practical content of fiber by volume in asphalt is more than that in concrete. Regardless, the presence of steel fibers reduces the electrical resistivity of the asphalt-like concrete.
Numerical studies indicated that the reduction rate in surface electrical resistivity in asphalt follows the same model as concrete and varies according to fiber content and aspect ratio. Regression parameters of asphalt are close to those observed for concrete; however, the goodness of fit for asphalt shows less fidelity due to the more significant dispersion of results. Hence, further studies are required to broaden the range of parameters and provide empirical verifications.

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