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Modelling for the electrical conductivity of graphite-modified asphalt concrete based on micromechanics

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Research Paper

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Modelling for the electrical conductivity of graphite-modified asphalt concrete based on micromechanics

This paper proposes a novel micromechanics theory to model the electrical conductivity of graphite-modified asphalt concrete. The constraint range of electrical conductivity was derived according to the Hashin–Shtrikman (H–S) method. Based on the self-consistent (SC) method and percolation theory, a modified self-consistent (MCS) method was used to develop the electrical conductivity model. The results predicted by the MSC model were compared with the test data by adjusting the aspect ratio and percolation exponent. We highlight this new theory and its application to graphite-modified asphalt concrete, and demonstrate that the predicted values are in close agreement with the test data.

Key words:
asphalt concrete, graphite, electrical conductivity, micromechanics, modified self-consistent (MSC) method

Prethodno priopćenje

Yi Yang, Canlong Wu

Modeliranje električne vodljivosti grafitom modificiranog asfaltbetona na temelju mikromehanike

U ovom je radu predložena nova teorija mikromehanike za modeliranje električne vodljivosti grafitom modificiranog asfaltnog betona. Ograničenje raspona električne vodljivosti izvedeno je prema Hashin–Shtrikmanovoj (H–S) metodi. Na temelju konzistentne metode (SC) i teorije perkolacije, izmijenjena samokonzistentna metoda (MSC) primijenjena je za razvoj modela električne vodljivosti. Rezultati predviđeni MSC modelom uspoređeni su s ispitnim podacima prilagođavanjem razmjera proporcija i potencije perkolacije. O ovoj novoj teoriji i njezinoj primjeni na grafitom modificiranom asfaltnbetonu raspravlja se u ovom radu, a dokazano je da se pretpostavljene vrijednosti uvelike slažu s podacima ispitivanja.

Ključne riječi:
asfaltbeton, grafit, električna vodljivost, mikromehanika, izmijenjena samokonzistentna metoda (MSC)

1. Introduction

Asphalt concrete is a good insulation material. Carbon fillers, such as graphite particles, mixed with asphalt concrete can significantly improve the electrical conductivity of asphalt concrete. The addition of fillers changes the conventional pavement performance of asphalt concrete and improves its electrical properties. Graphite-modified asphalt concrete can be used to melt ice on pavements and bridge decks, preventing the harmful effects of ice and improving traffic safety and security. Graphite particles, as conductive fillers, can significantly enhance the conductivity of asphalt concrete. When the number of conducting particles in the composite increases to a certain extent, the particles come into contact with each other to form a conductive network, resulting in conductive behaviour [1]. Graphite, a common inorganic material, exhibits a good conductive performance. It is also used as an antifriction agent and a lubricating material. Owing to these characteristics, graphite can be used as a conductive filler for composites.

Using graphite and carbon fibre as conductive materials, Wu et al. [2] presented an SEM image of graphite-modified asphalt concrete. Pan et al. [3] prepared conductive asphalt concrete and investigated the properties of graphite as the primary conductive material. Liu et al. [4] analysed the fractal dimensions of conductive asphalt concrete. They found that the conductive path of the conductive asphalt concrete exhibited remarkable fractal characteristics. The variation trends of the fractal dimension and resistivity were similar to those of the graphite content. However, this application was based on the premise of fully understanding the conduction mechanism. Wang et al. [5] studied the preparation and conductivity of conductive asphalt concrete containing graphene and carbon fibres. Graphene and carbon fibre were added to asphalt concrete to achieve electrical and thermal conductivity. Graphene played a complementary role throughout the conduction process. Ren et al. [6] investigated the effects of chemical alkali excitation, ultrasonic vibration, and combined activation on a conductive cementitious composite composed of copper slag and nano graphite. Çetin [7, 8] studied porous asphalt mixtures containing waste Ethylene Propylene Diene Monomer (EPDM) rubber and the effects of fly ashes and hydrated lime on moisture damage of SMA mixtures. Oner et al. [9] investigated stone mastic asphalt (SMA) mixtures containing textile waste which can be used instead of traditional fibres. Gáspár et al. [10] studied the key factors contributing to good durability and quality of road pavements.

Although current studies measuring the electrical conductivity of graphite-modified asphalt concrete have been conducted using experimental data, a thorough conductive mechanism to explain the intrinsic conductive behaviour does not exist to date. There are several representative conductive theories, such as the effective medium theory, percolation theory, and tunnel effect theory. However, the complex conductive behaviour of graphite-modified asphalt concrete cannot be explained using these different conductive methods. Pal [11] introduced the effective-medium theory to predict the conductivity of particle composites. In theoretical physics, the self-consistent (SC) method simplifies a multiparticle problem to a single-particle problem, which can be solved more accurately [12-14]. Based on the micromechanics method of ellipsoid inclusions in composite materials, the contact surface of the inclusion matrix, random distribution direction of the particles, and particle-size distribution can be further considered. The Mori–Tanaka method can be adapted to predict the overall conductivity of particles or fibre-reinforced composites of non-uniform sizes [15]. Further, micromechanical models have been developed to study the formation of conductive networks and the effects of electronic jumping on the conductive properties of nanocomposites [16, 17]. The continuum theory was proposed to establish a conductive model of carbon nanotube composites and graphene nanocomposites, considering the self-consistent theory of an ideal interface, a thin interface with interface conductivity, and the interface conductivity statistical function due to an increase in the electronic tunnelling effect [18-21]. Jang et al. [22] proposed a comprehensive model based on micromechanics to consider the effects of various material compositions on the conductivity of water-bearing carbon nanotubes and cement composites. Haghgooa et al. [23] analysed the effect of fillers on the electrical conductivity and electrical resistivity of carbon black/carbon fibre-reinforced polymer nanocomposites using a percolating electrical network model and a two-step analytical Mori–Tanaka micro-mechanical model. Kil et al. [24] determined the electrical conductivity of composites containing carbon nanotubes and carbon fibres based on a micromechanics model, and applied a genetic algorithm to determine the optimised model parameters. The results showed that the combination of the model and genetic algorithm resulted in a better simulation. The effects of fibre orientation, electrical conductivity, and aspect ratio on the electrical conductivity of multiscale nanocomposites were further investigated. Yang et al. [25] analysed the influence of graphite particle shape on the conductivity of graphite composites in the two-dimensional system using the Eshelby solution of polygonal inclusion. Owing to the complexity involved in solving the three-dimensional polygonal inclusion Eshelby tensor, a simpler oblate spheroid inclusion was considered to establish a conductive model for graphite-modified asphalt concrete in a three-dimensional system.

In this study, the micromechanical theory of graphite-modified asphalt concrete is investigated. The Hashin–Shtrikman method provides a wide range of electrical conductivity boundaries. The modified self-consistent (MSC) method combines the percolation theory and the self-consistent (SC) method; thus, it is more suitable for predicting the electrical conductivity of graphite-modified asphalt concrete. A modified self-consistent (MSC) method was adopted to predict the electrical conductivity and analyse the influencing factors of the proposed method. This method provides support for thoroughly exploring the conductive mechanism of particle composites in the future. The influence of the percolation exponent t on the predictive value of the electrical conductivity is important; this parameter is related to the system dimensions. In a three-dimensional system, the theoretical value of t lies in the range 1.65–2.0. Owing to the influence of the shape of the graphite particles, the true value of t typically exceeds the aforementioned range. Carmona et al. [26] proposed that the t value could reach 3.1 for a graphite polymer composite. Quivy et al. [27] suggested that the t value could even reach 6.27. For this study, the t values were selected as 1.65, 2.0, 3.1, and 6.27 for the MSC model.

Most of the electrical conductivity of graphite-modified asphalt concrete has been analysed through tests, and there is no in-depth theoretical and mechanistic research by relevant scholars. In this paper,a micromechanics method is presented to theoretically study the percolation threshold and graphite size effects on the electrical conductivity of graphite-modified asphalt concrete. First, the constraint range of electrical conductivity was derived by exploring the Hashin–Shtrikman (H–S) method. Considering a graphite particle as an oblate spheroid inclusion is more realistic than considering it as a spherical inclusion. The Eshelby tensor and percolation theories were used to modify the self-consistent (SC) method. Subsequently, we incorporated a modified self-consistent (MSC) method to develop an electrical conductivity model. Finally, the results predicted by the MSC model were compared with those obtained from the test data by adjusting the aspect ratio and percolation exponent.

2. Micromechanics theory

Before introducing micromechanics theory, we made the following assumptions: we assumed that a heterogeneous material consists of a matrix phase and ellipsoidal inhomogeneities. For the graphite-modified asphalt concrete, graphite was used as the inclusion phase and asphalt concrete was used as the matrix phase. According to Ohm's law, the following expression can be obtained:

$$\mathbf{J} = \bar{\boldsymbol{\sigma}}\mathbf{E} \tag{1}$$

where $\mathbf{J}$ is the total electric flux vector, $\mathbf{E}$ is the total electric field vector, and $\bar{\boldsymbol{\sigma}}$ is the electrical conductivity of the graphite-modified asphalt concrete. For an isotropic medium, the electrical conductivity is a scalar; for an anisotropic medium, the electrical conductivity is a tensor.

Graphite-modified asphalt concrete is composed of the high conductive phase-graphite (conductivity is $\boldsymbol{\sigma}_1$) and the low conductive matrix (conductivity is $\boldsymbol{\sigma}_0$).

When ellipsoidal inclusions (graphite particles) were present in the matrix (asphalt concrete), a perturbed electrical flux vector was induced, denoted as $\mathbf{J}_1$. The total electrical flux vector is the sum of the two electrical flux vectors, that is, $\mathbf{J}_0 + \mathbf{J}_1$.

By applying the Ohm's law in Ω and D–Ω fields, we obtain:

$$\mathbf{J} = \mathbf{J}_0 + \mathbf{J}_1 = \boldsymbol{\sigma}_1(\mathbf{E}_0 + \mathbf{E}_1^{pt}) \quad \text{in} \quad \Omega \tag{2}$$

$$\mathbf{J} = \mathbf{J}_0 + \mathbf{J}_1 = \boldsymbol{\sigma}_0(\mathbf{E}_0 + \mathbf{E}_1^{pt}) \quad \text{in} \quad \text{D-}\Omega \tag{3}$$

where D, Ω, and D–Ω are the domains of graphite-modified asphalt concrete, graphite particles, and asphalt concrete, respectively. The perturbed electric field vector is denoted as $\mathbf{E}_1^{pt}$. Next, a homogeneous body D (graphite-modified asphalt concrete) was considered, containing an inclusion Ω (graphite particles) with $\mathbf{E}_1^*$. $\mathbf{E}_1^*$ was introduced to simulate inhomogeneity. In other words, an inclusion problem was created which, by properly adjusting the value of $\mathbf{E}_1^*$, has the same electric field as the inhomogeneity problem [28]. For the inclusion problem, Ohm's law gives

$$\mathbf{J} = \mathbf{J}_0 + \mathbf{J}_1 = \boldsymbol{\sigma}_0(\mathbf{E}_0 + \mathbf{E}_1^{pt} - \mathbf{E}_1^*) \quad \text{for} \quad \Omega \tag{4}$$

$$\mathbf{J} = \mathbf{J}_0 + \mathbf{J}_1 = \boldsymbol{\sigma}_0(\mathbf{E}_0 + \mathbf{E}_1^{pt}) \quad \text{for} \quad \text{D-}\Omega \tag{5}$$

Combining Eq. (2) and Eq. (4),

$$\boldsymbol{\sigma}_1(\mathbf{E}_0 + \mathbf{E}_1^{pt}) = \boldsymbol{\sigma}_0(\mathbf{E}_0 + \mathbf{E}_1^{pt} - \mathbf{E}_1^*) \tag{6}$$

where $\mathbf{E}_1^*$ is the Eshelby equivalent transformation electric-field vector. The perturbed electric field vector $\mathbf{E}_1^{pt}$ is related to $\mathbf{E}_1^*$ as follows:

$$\mathbf{E}_1^{pt} = \mathbf{S}_1\mathbf{E}_1^* \tag{7}$$

Where $\mathbf{S}_1$ denotes the Eshelby tensor.

Substituting Eq. (7) in Eq. (6)

$$\mathbf{E}_1^* = -[\mathbf{S}_1 + (\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_0)^{-1}\boldsymbol{\sigma}_0]^{-1}\mathbf{E}_0 \tag{8}$$

The total electric field vector in the inclusions can be expressed as:

$$\mathbf{E}_1 = \mathbf{E}_0 + \mathbf{E}_1^{pt} = \mathbf{E}_0 + \mathbf{S}_1\mathbf{E}_1^* = \mathbf{T}_1\mathbf{E}_0 \tag{9}$$

where:

$$\mathbf{T}_1 = [\mathbf{I} + \mathbf{S}_1\boldsymbol{\sigma}_0^{-1}(\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_0)]^{-1} \tag{10}$$

$\mathbf{T}_1$ is defined as the concentration factor and $\mathbf{I}$ is the unit tensor.

2.1. Hashin–Shtrikman method

The H–S method places the upper and lower bounds, which are derived using variational theorems. These bounds can be achieved using the volume fractions and electrical conductivities of the inclusions. These bounds were regarded as narrow constraints on the electrical conductivity of the composite. According to Hashin et al. [29], the upper and lower bounds of the electrical conductivity for graphite-modified asphalt concrete, $\bar{\boldsymbol{\sigma}}_-$ and $\bar{\boldsymbol{\sigma}}_+$, can be expressed as follows:

$$\bar{\boldsymbol{\sigma}}_- = \boldsymbol{\sigma}_0\left[1 - \frac{3\phi(\boldsymbol{\sigma}_0 - \boldsymbol{\sigma}_1)}{3\boldsymbol{\sigma}_0 - (1-\phi)(\boldsymbol{\sigma}_0 - \boldsymbol{\sigma}_1)}\right] \tag{11}$$

$$\bar{\boldsymbol{\sigma}}_{+}=\boldsymbol{\sigma}_1\left[1+\frac{3(1-\phi)(\boldsymbol{\sigma}_0-\boldsymbol{\sigma}_1)}{3\boldsymbol{\sigma}_1+\phi(\boldsymbol{\sigma}_0-\boldsymbol{\sigma}_1)}\right] \quad (12)$$

where ϕ is the volume fraction of the graphite particles.

2.2. Self-consistent method

The essence of a self-consistent model is that it considers the interactions between inclusions, assuming that the inclusions exist only in a certain equivalent medium. To a certain extent, this is equivalent to the assumption that the inclusions interact with the matrix, which includes several other inclusions. The SC theory assumes that the conductive behaviour of graphite-modified asphalt concrete is associated with conductive particles (graphite particles) and the matrix (asphalt concrete). The morphology of the graphite particles and the distribution of factors affect the performance of graphite-modified asphalt concrete. When the volume fraction of the conductive phase is very low, the conductive particles (graphite particles) are well separated by the matrix which is suitable for the SC method. Because it is a mean-field theory, the predictive values of the critical volume fraction are always higher than the experimental values of the critical volume fraction.

Our primary assumption was that the graphite-modified asphalt concrete can be treated as a uniform medium. Thus, the graphite particles were treated as a single inclusion phase with electrical conductivity ($\boldsymbol{\sigma}_1$) in an infinitely uniform medium of electrical conductivity ($\bar{\boldsymbol{\sigma}}$). The concentration factor can be expressed using Eq. (10):

$$\bar{\mathbf{T}}_1=[\mathbf{I}+\bar{\mathbf{S}}_1\bar{\boldsymbol{\sigma}}(\boldsymbol{\sigma}_1-\bar{\boldsymbol{\sigma}})]^{-1} \quad (13)$$

where $\bar{\mathbf{T}}_1$ is the concentration factor in a uniform medium and $\bar{\mathbf{S}}_1$ is the Eshelby tensor in a uniform medium.

According to the SC method, we obtain:

$$\bar{\boldsymbol{\sigma}}=\boldsymbol{\sigma}_0+\phi(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_0)\bar{\mathbf{T}}_1 \quad (14)$$

Substituting Eq. (13) in Eq. (14),

$$\bar{\boldsymbol{\sigma}}=\boldsymbol{\sigma}_0+\phi\bar{\boldsymbol{\sigma}}(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_0)\left[\bar{\boldsymbol{\sigma}}+\bar{\mathbf{S}}_1(\boldsymbol{\sigma}_1-\bar{\boldsymbol{\sigma}})\right]^{-1} \quad (15)$$

According to Quang et al. [30], for spherical inclusions, $\bar{\mathbf{S}}_1$ = 1/3. Therefore,

$$\bar{\mathbf{T}}_1=\frac{3\bar{\boldsymbol{\sigma}}}{2\bar{\boldsymbol{\sigma}}+\boldsymbol{\sigma}_1} \quad (16)$$

$$\bar{\boldsymbol{\sigma}}=\boldsymbol{\sigma}_0+\frac{3\phi\bar{\boldsymbol{\sigma}}(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_0)}{2\bar{\boldsymbol{\sigma}}+\boldsymbol{\sigma}_1} \quad (17)$$

2.3. Modified self-consistent method

Based on the SC method, a modified self-consistent (MSC) method was introduced. The Eshelby tensor is related to the shape of the inclusion. Furthermore, actual graphite particles are not spherical. In this study, flaky graphite particles were assumed to be oblate spheroid inclusions. According to Hiroshi et al. [31], for an oblate spheroid, $a_1 = a_2 > a_3$. The components of the Eshelby tensor can be written as follows:

$$S_{11}=S_{22}=\frac{a_1^2a_3}{2(a_1^2-a_3^2)^{3/2}}\left\{\cos^{-1}\frac{a_3}{a_1}-\frac{a_3}{a_1}(1-\frac{a_3^2}{a_1^2})^{1/2}\right\} \quad (18)$$

$$S_{33} = 1\text{-}2S_{22} \quad (19)$$

The Eshelby tensor can be used to establish an electrical conductivity model for the graphite-modified asphalt concrete. This can be simplified into a two-dimensional system. The Eshelby tensor can then be expressed as :

$$\bar{\mathbf{S}}=\begin{bmatrix} S_{11} & 0 \\ 0 & S_{33} \end{bmatrix} \quad (20)$$

Randomly distributed oblate spheroid inclusions can be considered using the transform matrix in a two-dimensional system, where a is the orientation angle of the inclusion phase.

$$\mathbf{K}=\begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \quad (21)$$

In a two-dimensional system, the electrical conductivity of the graphite-modified asphalt concrete can be expressed as follows:

$$\bar{\boldsymbol{\sigma}}=\boldsymbol{\sigma}_0+\frac{1}{2\pi}\phi\bar{\boldsymbol{\sigma}}(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_0)\int_0^{2\pi}[\bar{\boldsymbol{\sigma}}+\mathbf{K}^T\cdot\bar{\mathbf{S}}_1\cdot\mathbf{K}\cdot(\boldsymbol{\sigma}_1-\bar{\boldsymbol{\sigma}})]^{-1}d\alpha \quad (22)$$

Based on the percolation theory,

$$\bar{\sigma}^{1/t}=\sigma_1^{1/t}\left(\phi-\phi_c\right) \quad (23)$$

where ϕ_c is the percolation threshold and t is the percolation exponent.

Parameter t is the percolation exponent, which depends on the dimensions of the system. From Eq. (22) and Eq. (23), the MSC model is obtained as

$$\bar{\boldsymbol{\sigma}}^{1/t}=\boldsymbol{\sigma}_0^{1/t}+\frac{1}{2\pi}\phi\bar{\boldsymbol{\sigma}}^{1/t}(\boldsymbol{\sigma}_1^{1/t}-\boldsymbol{\sigma}_0^{1/t})\int_0^{2\pi}[\bar{\boldsymbol{\sigma}}^{1/t}+\mathbf{K}^T\cdot\bar{\mathbf{S}}_1\cdot\mathbf{K}\cdot(\boldsymbol{\sigma}_1^{1/t}-\bar{\boldsymbol{\sigma}}^{1/t})]^{-1}d\alpha \quad (24)$$

3. Materials and methods

3.1. Materials

Asphalt is a viscoelastic material whose performance is mainly affected by temperature, load, and bearing rate. The asphalt binder used in this study was of the heavy-duty type (AH-70), with a penetration of 65.9 (0.1 mm at 25 °C,100 g, and 5 s), softening point of 49.5 °C, and ductility of 167.3 cm (at 15 °C). As a pavement material, the aggregate should be clean, dry, pure, and have a certain strength and wear resistance.

Table 1. Parameters of graphite performance

Project	**Density** [g/cm^3]	**Particle size** [μm]	**Carbon content** [%]	**Conductivity** [S/m]	**Ash content** [%]	**Iron content** [%]
Indicators	2.1 – 2.3	150	98.9	10^5	0.2	0.03

The aggregate adopted was a basalt mineral with a density of 2.98 g/cm^3 and maximal size of 16 mm. Superpave 12.5 gradation was used in the aggregate mix design.

Graphite exhibits good electrical conductivity and is an ideal conductive filler. The lamellar shape of graphite provides a lubricating effect, allowing it to be uniformly dispersed in asphalt concrete. Flaky (crystalline) graphite exhibits excellent electrical conductivity, heat conductivity, lubrication, and oxidation resistance. Flaky graphite was used as the conductive phase. The graphite performance parameters are listed in Table 1.

Asphalt acts as a binder and an insulating material in graphite-modified asphalt concrete. An asphalt mixture requires sufficient asphalt coating to provide good bonding strength. Conductive-phase materials cannot improve the conductivity of asphalt concrete because the asphalt film acts as a barrier between the conductive particles to form conductive paths. A reasonable amount of asphalt is required to not only ensure that the volume performance of asphalt concrete meets technical requirements but also to obtain good electrical performance. Microscopically, flaky graphite is a hexagonal crystal system containing densely packed carbon atoms. The binding force between the atoms is very strong, but that between the layers is very weak. Aggregates not only have individual characteristics but also combined characteristics, that is, aggregates undergo gradation according to different particle sizes. From a macroscopic perspective, aggregates of different particle sizes combine with different skeleton structures of graphite-modified asphalt concrete, resulting in the formation of different conductive networks. Therefore, the distribution of conductive networks is related to the filling of conductive asphalt mortar, which in turn is related to the skeleton structure of the graphite-modified asphalt concrete.

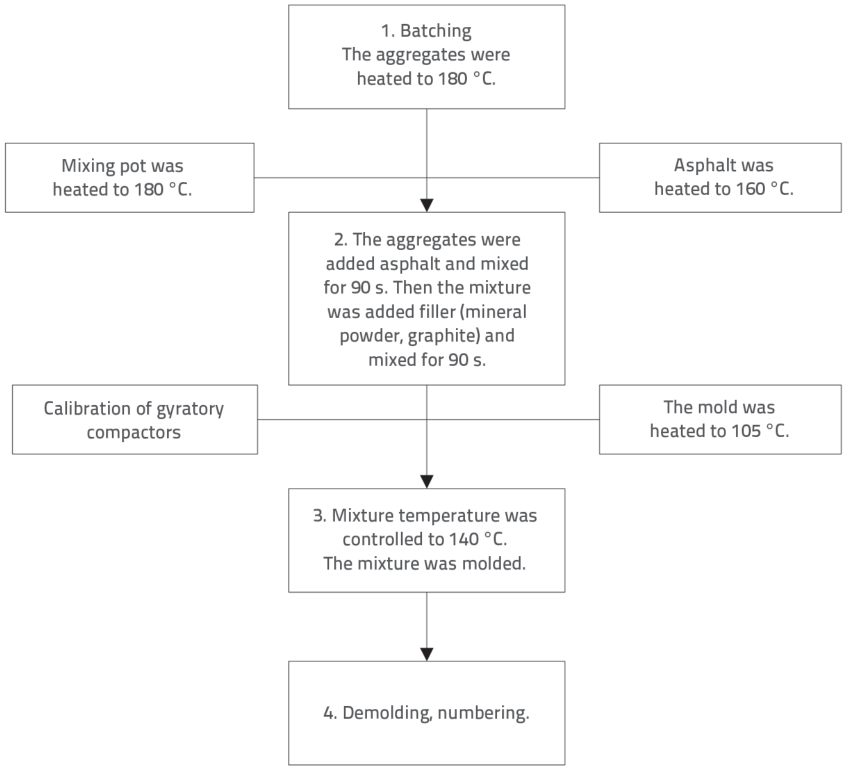

Figure 1. Specific mixing and moulding processes for graphite-modified asphalt concrete

3.2. Methods

In this study, a Superpave 12.5 asphalt mixture was prepared for the electrical conductivity measurements. Marshall samples were used to measure the conductivity of graphite-modified asphalt concrete. Graphite-modified asphalt concrete requires adjustments to the mixing process owing to the incorporation of conductive-phase materials. Graphite must be mixed with mineral powder for 90 s after the addition of asphalt owing to its oil-absorbing properties. The asphalt mixtures were compacted with a Superpave gyratory compactor (SGC) to realistically compact the mixtures to the densities attained under actual pavement climatic and loading conditions. The density of the sample can be estimated from the mass of the material in the mould, inner diameter of the mould, and height of the specimen during compaction. The specific mixing and moulding processes are shown in Figure 1.

The electrical conductivity was measured using the two-probe method at an indoor temperature of 25 °C. A data acquisition instrument was used to measure the electrical conductivity of the graphite-modified asphalt concrete. Because graphite-modified asphalt concrete exhibits a poor conductive performance, a test method for measuring the insulation resistance of the material was adopted. The graphite-modified asphalt concrete had a rough surface, and there was a large contact resistance between the contact points of the electrode and the sample in the test method. If close contact is not achieved, the contact resistance will exceed the resistance of the sample itself, and the test result will inevitably be greater than the true resistivity of the sample.

Table 2. Resistivity test values of the graphite-modified asphalt concrete

Samples \ **Graphite content** [vol %]	**Resistivity** [Ωm]						
	5.0	7.8	9.5	12.7	18.9	22.6	30
Sample 1	1.2×10^{11}	7.8×10^{9}	7.9×10^{8}	3.9×10^{3}	76.9	31.3	2.4
Sample 2	1.5×10^{11}	1.0×10^{10}	1.1×10^{9}	4.3×10^{3}	90.9	35.7	2.8
Sample 3	1.9×10^{11}	1.3×10^{10}	1.2×10^{9}	5.1×10^{3}	120.0	43.5	3.6
Sample 4	2.5×10^{11}	1.5×10^{10}	1.4×10^{9}	6.2×10^{3}	128.9	52.6	3.8

To achieve a tight contact, the surface of the sample was carefully cleaned and polished. Based on the operational methods and costs, dry graphite powders smaller than 0.075 mm in dispersion form were used to fill the gap between the electrodes and samples to ensure perfect contact and minimise measurement error. The electrodes were fabricated from stainless steel. The electrical resistance was measured using a Keithley 6517 high-resistance meter (USA). The resistivity can be derived from the measured resistance. The resistivity obtained from the test was the average of the resistivity values of the four samples. Because the resistivity and conductivity are reciprocal, the conductivity of the graphite-modified asphalt concrete was obtained. The resistivity test values of the graphite-modified asphalt concrete are listed in Table 2.

4. Results and discussion

Previous studies have only predicted the conductivity of composite materials using theoretical formulae, and only a few have confirmed the results using test data. In our study, the H–S, SC, and MSC methods were used to compare the results with the test data. The H–S method confirmed that the bounds were normal and could be applied to all macroscopically isotropic composites. Therefore, the electrical conductivity of graphite-modified asphalt concrete should be within the H–S bounds. The bounds can act as theoretical limits, because any predicted value outside the H–S bounds is regarded as invalid. The graphite particles were considered to be spherical inclusions in the SC method, which deviates from the real shape of the graphite particles. The MSC method is based on the SC method and percolation theory, which considers the influence of the shape of graphite particles according to the Eshelby tensor.

The predicted values of the H–S bounds can be calculated using Eq. (11) and (12). Figure 2 shows the predicted values of the H–S bounds and the test data. The blue solid line represents the calculated values of the H–S upper bound and the red dashed line represents the calculated values of the H–S lower bound. As shown in Figure 1, all test data lie within the bounds. However, the range of H–S bounds is very large; thus, the electrical conductivity of graphite-modified asphalt concrete is difficult to predict. The H–S bounds can only provide a wide range of boundaries which cannot precisely predict the electrical conductivity.

Eq. (17) was used to predict conductivity based on the self-consistency method. Figure 3 shows the electrical conductivity curves of the SC model (spherical inclusion) and the test data. The solid black curve represents the values calculated using the SC model. As shown in Figure 3, the test data and the predicted values of the SC model differed. The graphite volume fraction break of the SC model was approximately 34 %, whereas the volume fraction break obtained experimentally was always between 9 % and 12 %. Therefore, the results obtained from the SC model were inconsistent with those obtained from the test. The SC model presumes that the conductive particles are spherical inclusions. However, real graphite particles were flaky in our tests. Therefore, it is not reasonable to consider graphite particles as spherical inclusions. Therefore, another method must be adopted to establish an electrical conductivity model for graphite-modified asphalt concrete.

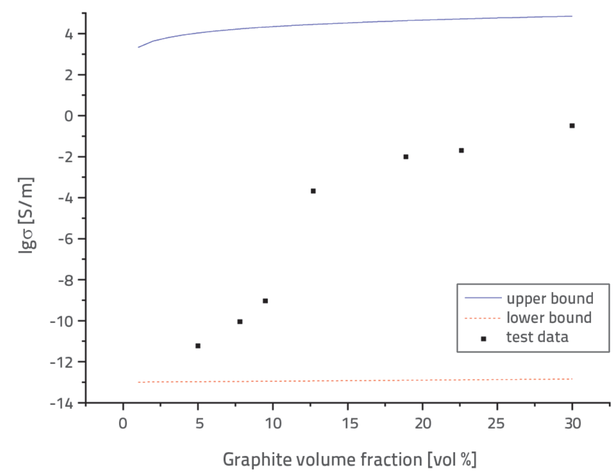

Figure 2. Electrical conductivity bounds of the H–S method

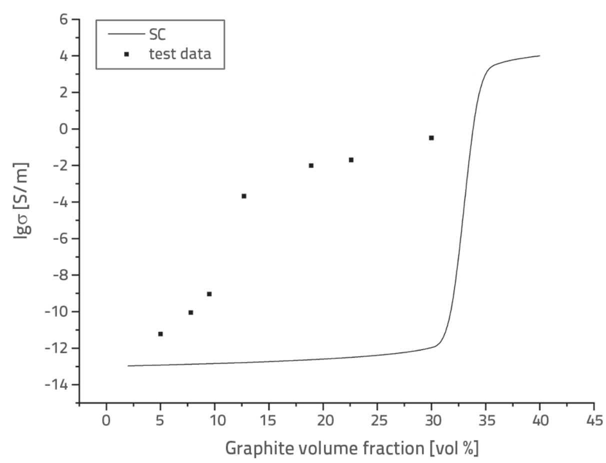

Figure 3. Electrical conductivity curve of the SC method

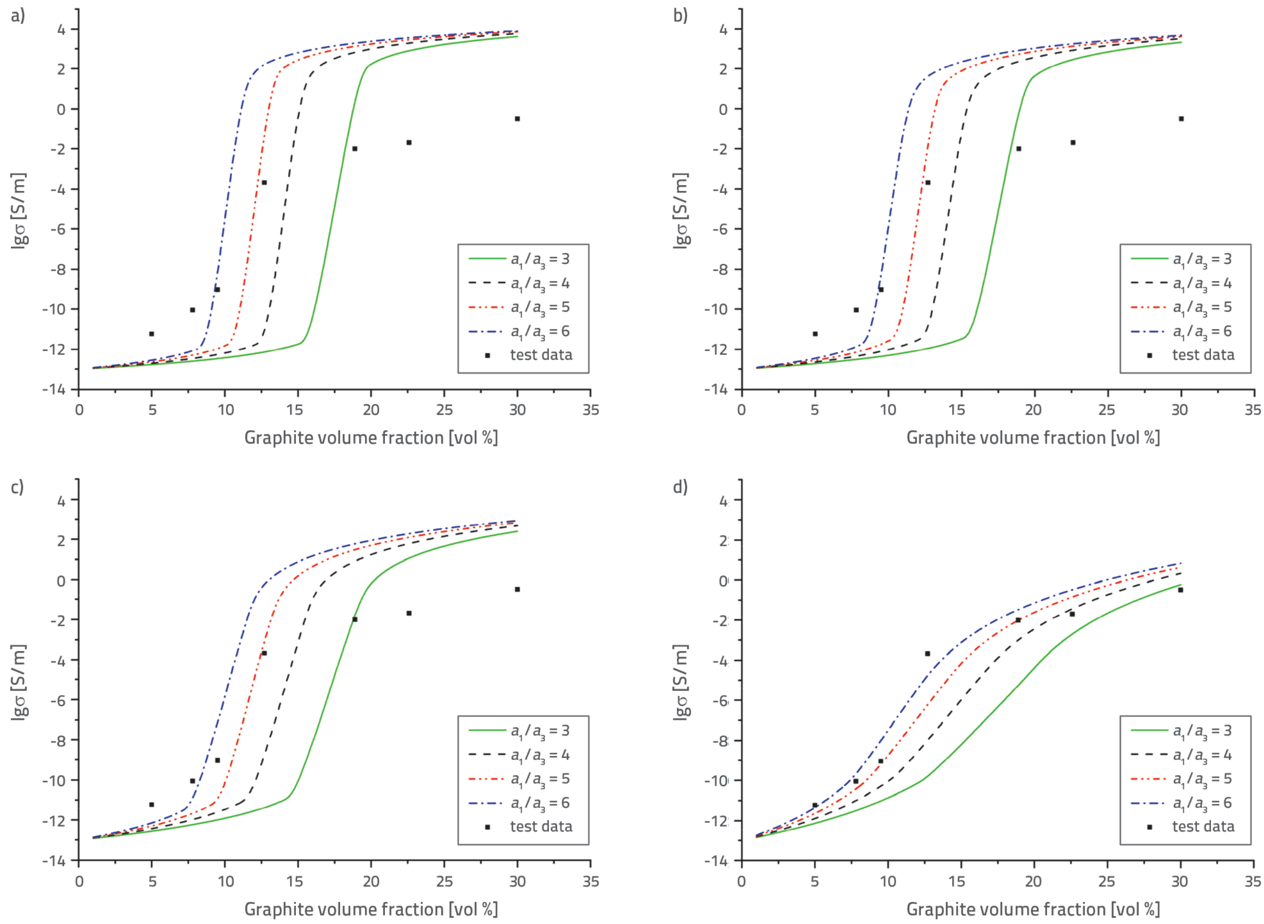

Figure 4. Electrical conductivity curves of the MSC method depending on the weight coefficient or percolation potency: a) t = 1.65; b) t = 2; c) t = 3.1; d) t = 6.27. The green solid, black dash, red dash dotted, and blue dash dotted curves represent the calculated values with different aspect ratios of graphite particle, respectively. The black squares represent the test data

Considering the shape of the inclusion, the Eshelby tensor can be calculated using Eq. (18)–(20). Learning from the percolation theory and the SC method, the predicted values of electrical conductivity can be obtained using Eq. (24) with different percolation exponents. In a previous study, the percolation exponents were selected as 1.65, 2.0, 3.1, and 6.27 in the MSC model. Figure 4 shows the electrical conductivity curves of the MSC method for different percolation exponents. As shown in Figure 4, the shapes of the curves are similar for different aspect ratios when the percolation exponent *t* is constant. However, the point at which the electrical conductivity breaks off in each of these curves is evident when the *t* value is small. With increasing aspect ratio (a_1/a_3), the percolation threshold gradually decreases. The results showed that the aspect ratio of the graphite particles directly affected the percolation threshold. Therefore, the shape of the conductive phase must be considered when predicting the electrical conductivity of graphite-modified asphalt concrete.

Subsequently, the predicted values and test data were compared for different aspect ratios. Figure 5 shows the electrical conductivity curves obtained using the MSC method for different aspect ratios. As shown in these figures, when the graphite volume fraction approached the percolation threshold, the predictive value of the electrical conductivity increased abruptly. Subsequently, with a further increase in the volume fraction, the predicted value of the electrical conductivity increased slowly. When the aspect ratio is constant, different *t* values have a major impact on the prediction of electrical conductivity. The predicted value of the degree of sensitivity of the percolation exponent, *t*, was greater than that of the graphite particle aspect ratio.

In Figure 4 and 5, the curves qualitatively describe the variation in the conductivity behaviour near the percolation threshold. A comparison of the theoretical calculation and test data shows that the changing trend of the theoretical calculation data is similar to that of the test data. When the percolation exponent *t* of the MSC model had values of 1.65, 2.0, and 3.1, the theoretical calculation data and test data tended to exhibit a similar change trend; however, the numerical difference was still large. When *t* was 6.27, the tendencies were similar; however, the predicted values were closer to the test values. Based on the theoretical calculations and test data, the graphite particle aspect ratio was

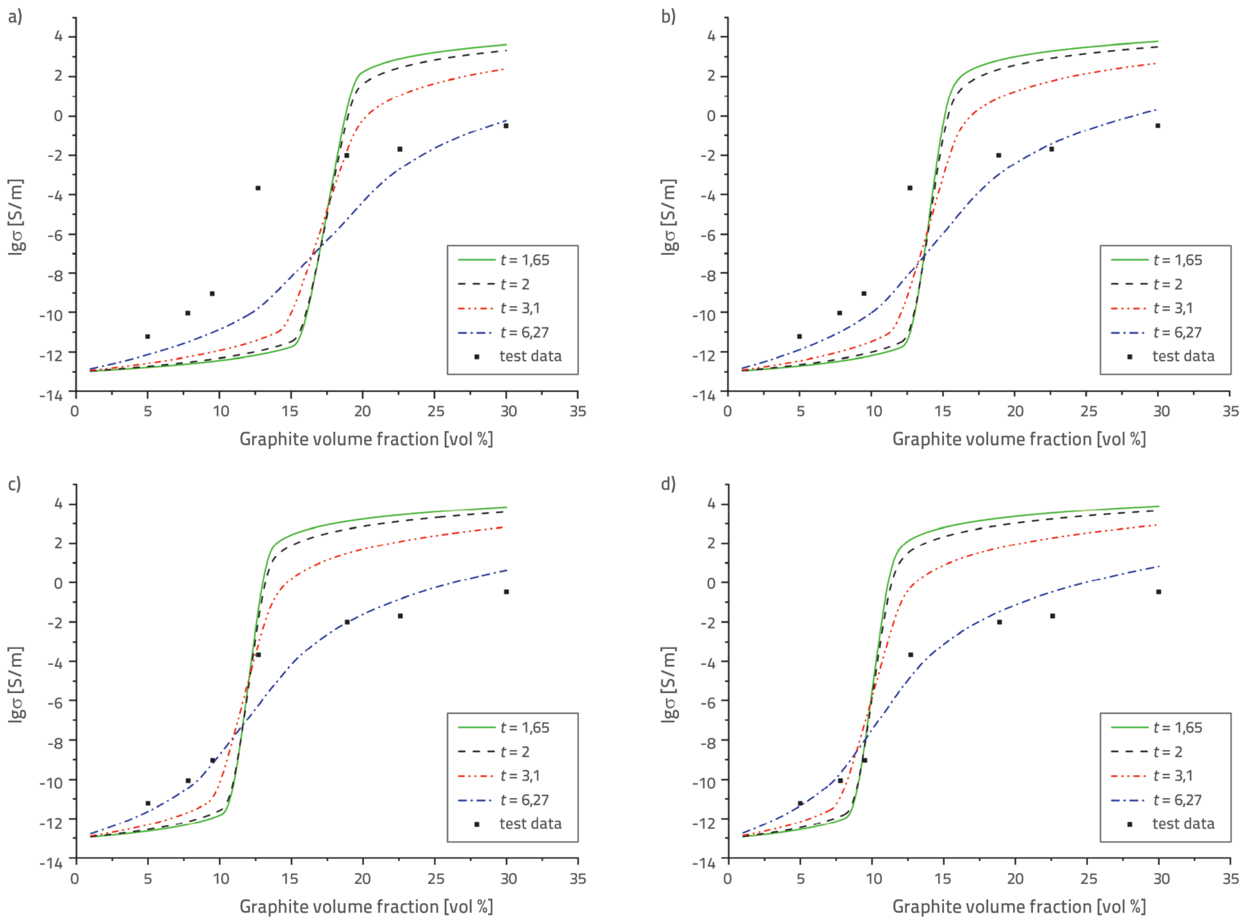

Figure 5. Electrical conductivity curves of the MSC method depending on the scale of the proportion of graphite particles: a) a_1/a_3 =3; b) a_1/a_3 =4; c) a_1/a_3 =5; d) a_1/a_3 =6. The green solid, black dash, red dash dotted, and blue dash dotted curves represent the calculated values with different percolation exponents, respectively. The black squares represent the test data.

selected as a_1/a_3 = 5. The percolation exponent *t* was selected as 6.27. The percolation exponent depends on the characteristic coefficient of dispersion. This coefficient depends on the shape of the particle and orientation or randomness of the dispersion. Different conductive phases can also affect percolation exponents. Currently, in most cases, the percolation exponent is determined experimentally.

5. Conclusion

The electrical conductivity of graphite-modified asphalt concrete is related to several factors: (i) the properties of asphalt concrete; (ii) the conductivity, shape, and aspect ratio of graphite particles; and (iii) the methods and technologies adopted during the preparation of graphite-modified asphalt concrete (which also has a certain amount of influence on the electrical conductivity). In this study, a Superpave 12.5 asphalt mixture was prepared for the electrical conductivity testing. The conductive phase consists of flaky graphite. The flaky graphite particle aspect ratio was selected as a_1/a_3 = 5. The percolation exponent *t* was selected as 6.27.

The conductive mechanisms of the graphite-modified asphalt concrete were tested using the H–S, SC, and MSC methods. The H–S method can only be used to forecast the approximate scope of the electrical conductivity. The values predicted using the SC method deviated significantly from the test data. The MSC method is based on the SC method and the percolation theory. By selecting different values for the aspect ratio of the graphite particles and the percolation exponent, we modified the SC method. Hence, only the MSC method can be used to establish a reliable conductivity model for graphite-modified asphalt concrete. The selection of the percolation exponent was based on previous studies. Actual graphite particles are three-dimensional systems, but they are simplified to a two-dimensional system based on the MSC method. For these reasons, there is some deviation between the predicted and test values at some points. Therefore, further research is needed to further strengthen the use of the MSC method for modelling electrical conductivity.

In summary, this study provides a comprehensive theoretical analysis (MSC method) of the electrical conductivity of graphite-modified asphalt concrete and has implications for snow melting and de-icing studies on pavements. It is important that future research investigates the percolation exponent through numerous tests and intrinsic mechanisms. The prediction of the effective conductivity of conductive asphalt concrete currently considers only the conductivity prediction of graphite-modified asphalt concrete. The prediction of electrical conductivity when graphite, carbon fibre, and other conductive fillers are added simultaneously is currently not considered. In practical engineering, multiplex conductive asphalt concrete is often chosen to better understand the conductive properties of conductive asphalt concrete used in pavement snow and ice melting. Therefore, the prediction of the effective conductivity of multiplex conductive asphalt concrete based on micromechanics will be further studied in the future.

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REFERENCES

[1] Liu, X.M., Wu, S.P.: Study on the graphite and carbon fiber modified asphalt concrete, Construction and Building Materials, 25 (2011) 4, pp. 1807-1811, https://doi.org/10.1016/j.conbuildmat.2010.11.082

[2] Wu, S.P., Mo, L.T., Shui, Z.H., Chen, Z.: Investigation of the conductivity of asphalt concrete containing conductive fillers, Carbon, 43 (2005), pp. 1358-1363, https://doi.org/10.1016/j.carbon.2004.12.033

[3] Pan, P., Wu, S.P., Chen, M., Tang, N.: A method for improvement of the heating efficiency of conductive asphalt pavement, Journal of Testing and Evaluation, 42 (2014) 5, pp. 1141-1147, https://doi.org/10.1520/jte20130173

[4] Liu, X.M., Wang, C., Deng, Y.D., Cao, F. Computation of fractal dimension on conductive path of conductive asphalt concrete. Construction and Building Materials, 11 (2016) 5, pp. 699-704, https://doi.org/10.1016/j.conbuildmat.2016.04.051

[5] Wang, Y.Y., Tan, Y.Q., Liu, K, Xu, H.N. Preparation and electrical properties of conductive asphalt concretes containing graphene and carbon fibres Construction and Building Materials, 318 (2022), 125875, https://doi.org/10.1016/j.conbuildmat.2021.125875

[6] Ren, Z.H., Sun, J.B., Zeng, X.T., Chen, X., Wang, Y.F., Tang, W.C., Wang, X.Y.: Research on the electrical conductivity and mechanical properties of copper slag multiphase nano-modified electrically conductive cementitious composite, Construction and Building Materials, 339 (2022), 127650, https://doi.org/10.1016/j.conbuildmat.2022.127650

[7] Çetin, A.: The effect of filler additives on moisture damage in stone mastic asphalt (SMA) mixtures, GRAĐEVINAR, 73 (2021) 12, pp. 1209-1221, https://doi.org/10.14256/JCE.3321.2021

[8] Çetin, A.: Laboratory performance of porous asphalt mixtures containing Ethylene Propylene Diene Monomer - EPDM, GRAĐEVINAR, 74 (2022) 1, pp. 1-8, https://doi.org/10.14256/JCE.3309.2021

[9] Oner, J., Ozdas, F.: Investigation of textile waste usage in stone mastic asphalt (SMA) mixtures, GRAĐEVINAR, 73 (2021) 5, pp. 469-481, https://doi.org/10.14256/JCE.3135.2020

[10] Gáspár, L., Bencze, Z.: Increasing the life expectancy of road pavements, GRAĐEVINAR, 72 (2020) 6, pp. 515-522, https://doi.org/10.14256/JCE.2644.2019

[11] Pal, R.: On the electrical conductivity of particulate composites, Journal of Composite Materials, 41 (2007) 20, pp. 2499-2511, https://doi.org/10.1177/0021998307076489

[12] Hori, M., Yonesawa, F.: Statistical theory of effective electrical, thermal, and magnetic properties of random heterogeneous materials. Journal of Mathematical Physics, 16 (1975) 2, pp. 352-364, https://doi.org/10.1063/1,1666347

[13] Yonesawa, F., Cohen, M.: Granular effective medium approximation Journal of Applied Physics, 54 (1983) 6, pp. 2895-2899, https://doi.org/10.1063/1.332490

[14] Moctesuma, B.A., Visice, A., Adler, P.M.: Macroscopic conductivity of vulgular porous media, Transport in Porous Media, 49 (2002), pp. 313-332, https://doi.org/10.1023/A:1016297220013

[15] Helmut, J.B., Sergio, N.: Mori-Tanaka models for the thermal conductivity of composites with interfacial resistance and particle size distributions, Composites Science and Technology, 68 (2008) 5, pp. 1181-1187, https://doi.org/10.1016/j.compscitech.2007.06.009

[16] Yu, J., Jr, T.E.L., Toghiani, H.: Micromechanically based effective thermal conductivity estimates for polymer nanocomposites, Composites Part B: Engineering, 53 (2013), pp. 267-273, https://doi.org/10.1016/j.compositesb.2013.04.055

[17] Xiang, R., Gary, D.S.: Computational micromechanics modelling of inherent piezoresistivity in carbon nanotube- polymer nanocomposites, Journal of Intelligent Material Systems and Structures, 24 (2013) 12, pp. 1459-1483, https://doi.org/10.1177/1045389X12471442

[18] Wang, Y., Weng, G.J., Meguid, S.A., Hamouda, A.M.: A continuum model with a percolation threshold and tunneling-assisted interfacial conductivity for carbon nanotube-based nanocomposites, Journal of Applied Physics, 115 (2014) 19, https://doi.org/193706, 10.1063/1,4878195

[19] Wang, Y., Shan, J.W., Weng, G.J.: Percolation threshold and electrical conductivity of graphene-based nanocomposites with filler agglomeration and interfacial tunneling, Journal of Applied Physics, 118 (2015) 6, 065101, https://doi.org/10.1063/1,4928293

[20] Xia, X.D., Wang, Y., Zhong, Z., Weng, G.J.: A theory of electrical conductivity, dielectric constant, and electromagnetic interference shielding for lightweight graphene composite foams, Journal of Applied Physics, 120 (2016) 8, 085102, https://doi.org/10.1063/1,4961401

[21] Su, Y., Li, J.J., Weng, G.J.: Theory of thermal conductivity of graphene-polymer nanocomposites with interfacial Kapitza resistance and graphene-graphene contact resistance, Carbon, 137(2018), pp. 222-233, https://doi.org/10.1016/j.carbon.2018.05.033

[22] Jang, S.H., Hochstein, D.P., Kawashima, S.: Experiments and micromechanical modelling of electrical conductivity of carbon nanotube/cement composites with moisture, Cement and Concrete Composites, 77 (2017), pp. 49-59, https://doi.org/10.1016/j.cemconcomp.2016.12.003

[23] Haghgooa, M., Ansari, R., Hassanzadeh-Aghdam M.K.: The effect of nanoparticle conglomeration on the overall conductivity of nanocomposites, International Journal of Engineering Science, 157 (2020), 103392, https://doi.org/10.1016/j.ijengsci.2020.103392

[24] Kil, T., Jin, D.W., Yang, B., Lee, H.K.: A comprehensive micromechanical and experimental study of the electrical conductivity of polymeric composites incorporating carbon nanotube and carbon fiber, Composite Structures 268 (2021), 114002, https://doi.org/10.1016/j.compstruct.2021.114002

[25] Yang, Y., Song, G.Q., Chen, Y.G.: Modified self-consistent model for the effective electrical conductivity of polygonal graphite composites. Journal of Reinforced Plastics and Composites 34 (2015) 4, pp. 307-314, https://doi.org/10.1177/0731684415571190

[26] Carmona, F., Canet, R., Delhaes, P.: Piezoresistivity of heterogeneous solids, Journal of Applied Physics, 61 (1987) 7, pp. 2550-2557, https://doi.org/10.1063/1,337932

[27] Quivy, A., Deltour, R., Jansen, A.G.M., Transport phenomena in polymer-graphite composite materials, Physical Review B, 39 (1989) 2, pp. 1026-1030, https://doi.org/10.1103/PhysRevB.39.1026

[28] Qu, J.M., Cherkaoui, M.: Fundamentals of micromechanics of solids, John Wiley & Sons, Inc., 2006.

[29] Hashin, Z., Shtrikman, S.: A variational approach to the theory of the effective magnetic permeability of multiphase materials, Journal of Applied Physics, 33 (1962) 10, pp. 3125-3130, https://doi.org/10.1063/1,1728579

[30] Quang, H.L., He, Q.C., Zheng, Q.S: Some general properties of Eshelby's tensor fields in transport phenomena and anti-plane elasticity, International Journal of Solids and Structures, 45 (2008) 13, pp. 3845-3857, https://doi.org/10.1016/j.ijsolstr.2007.10.030

[31] Hiroshi, H., Minoru, T.: Effective thermal conductivity of a misoriented short fiber composite, Journal of Applied Physics, 58 (1985) 7, pp. 2478-2486, https://doi.org/10.1063/1,335924