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Micromechanics prediction of effective modulus for asphalt mastic considering inter-particle interaction

Jianzhong Pei, Zepeng Fan, Pengzhi Wang, Jiupeng Zhang *, Bin Xue, Rui Li

School of Highway, Chang'an University, Xi'an, Shaanxi 710064, China

HIGHLIGHTS

- The J–C model is applied to illustrate the reinforcement mechanisms of mastic.
- A simplified parameter ς is proposed to reflect the inter-particle interaction.
- The inter-particle interaction increases with filler concentration and decreases with test frequency.
- New method shows well applicability up to a filler volume fraction of 50%.

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ABSTRACT

This paper presents the development and validation of a new micromechanical model, Ju–Chen (J–C) model, to predict the effective viscoelastic modulus of asphalt mastic by considering the inter-particle interaction. Based on the approximate solutions for two-particle interaction problem, the radial distribution function is integrated into the ensemble-volume averaged eigenstrain tensor so as to consider the inter-particle interaction, and the solution could be extended and simplified to predict the effective complex modulus of asphalt mastic with different filler volume fractions. It is found that the inter-particle interaction increases with the filler volume fraction and decreases with the test frequency, and the predictions agree well with the experiment data at low and moderate filler volume fractions, not exceeding 50%. Compared with two commonly used micromechanical models (M–T model and DSEM model), the J–C model relatively gives the best estimation of the effective modulus of mastics, and the applicability of J–C model could be further improved.

1. Introduction

Asphalt mastic could be considered as a kind of heterogeneous two-phase composite material, consisting of asphalt binder and fillers smaller than 75 μm. The mechanical behavior of asphalt mastic significantly affects all the aspects of asphalt mixture, such as design, construction and performance [1–3]. The overall mechanical properties of asphalt mastic are closely related to the complicate microstructure, which is depended on the various raw materials' properties, shapes, sizes and proportions. Micromechanics could bridge the overall properties of heterogeneous materials from microstructural parameters and have long been successfully applied to predict the effective modulus from mechanical properties and volume fractions of individual constituents for composite materials such as metal and polymer matrix composites [4–8].

Since Lytton [9] attempted to utilize the micromechanics in modeling the behavior of asphalt mixtures, the concept of micromechanical modeling has been widely used to predict the effective modulus of asphalt materials [10–25]. By dividing the reinforcement mechanisms associated with the presence of fillers in asphalt mastics into volume-filling reinforcement, physiochemical reinforcement and particle-interaction reinforcement, Buttlar et al. [3] proposed that the micromechanical model can be "a powerful tool for separating various reinforcement mechanisms in the mastic". Shashidhar and Shenoy [12] evaluated the applicability of the generalized self-consistent (GSC) model in describing the dynamic mechanical behavior of mastics with particle volume fractions up to 31% and found that this model trends to underestimate the effective modulus. The deviations were attributed to the failure to capture all effects involved in the increase of reinforcement. Kim and Litter [15] selected two models to investigate the effect of fillers on mastic and found that the traditional mechanical models showed well agreement with testing data at low filler volume

* Corresponding author.
E-mail address: zhjiupeng@163.com (J. Zhang).

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fractions but diverged at high fractions. The divergent indicates the presence of significant particle interactions and potential physic-chemical reinforcement between asphalt binder and fillers. Yin et al. [20] formulated four micromechanical models to predict the viscoelastic properties of mastics based on the elastic-viscoelastic correspondence principle, and simplifications and limitations of these four models were analyzed. More recently, Underwood and Kim [25] evaluated 12 existing dilute suspension and micromechanical models under a wide range of temperatures and frequencies for mastics with varying filler volume fractions up to 60%, and a new physico-chemical interaction based micromechanical model was proposed to overcome the inability of existing models. Comparison results show that the new model could consider the interphase effect, and it is capable to match test data of asphalt mastic with no more than 40% filler.

Even though the considerable research efforts have been done to illustrate the reinforcement mechanisms of filler on mastic, few of them involve the inter-particle interaction. Actually, the particle-interaction reinforcement contributes little at low filler concentration, but more within the moderate and high concentrations, that's why the precision of prediction become larger as the filler concentration increases. In order to consider the inter-particle interactions, several approximate solutions for two-particle interaction problem have been established for other composite materials [26–30], which could be applied for asphalt mastic.

In this paper, the approximate solutions for two-particle interaction problem proposed by Ju and Chen [26,27] are briefly introduced firstly, and then the solutions were applied to establish a new micromechanical formulation considering the inter-particle interactions. The new model is used to predict the effective viscoelastic modulus of asphalt mastic, and the predictions were compared with the experiment results of mastics with different particle volume fractions to validate its applicability. In additions, the prediction precise of the new model is compared with two single-inclusion based models (M–T model [6] and DSEM model [23]).

2. Development of micromechanical model considering inter-particle interactions

2.1. Reviewing on the approximate solutions for two-particle interaction problem

According to the micromechanical framework of Ju and Chen [26,27], the derivation starts with an approximate treatment for

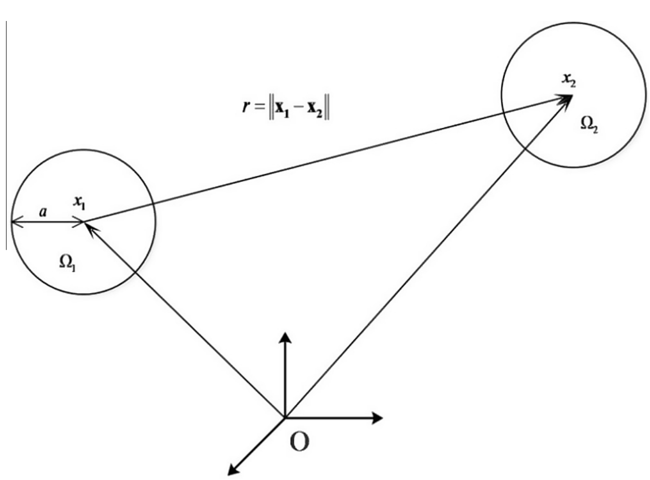

Fig. 1. Schematic diagram for two-particle interaction problem.

the interaction problem of two elastic spherical particles which were embedded in the elastic matrix. Then, based on the probabilistic pairwise particle interaction mechanism, the localization relation is established and thus the effective elastic modulus of two-phase composites containing randomly located spherical particles is presented. Moreover, as asphalt mastic is a kind of viscoelastic material, the model is extended to be capable of predicting the effective complex modulus by virtue of the elastic-viscoelastic corresponding principle. More details is given in the following.

In these solutions, two identical spherical particles (phase 1) are embedded into a homogeneous matrix (phase 0), as shown in Fig. 1. The radius of the particle is a and both of the two phases are assumed to be linearly isotropic elastic. The stiffness tensors of the two phases are denoted as $\mathbf{C}_i$ $(i = 0,\ 1)$, and k_i, u_i $(i = 0, 1)$ represent the bulk modulus and shear modulus of different phases respectively.

Subjected to a remote uniform strain $\boldsymbol{\varepsilon}^0$, the approximate solution for the two-particle interaction problem can be expressed in Eq. (1) [27]

$$\bar{\mathbf{d}}^* = -[\mathbf{K}^{-1}\cdot(\rho^3\mathbf{H_1} + 2\rho^5\mathbf{H_2})] : \boldsymbol{\varepsilon}^{*0} - \rho^6[\mathbf{L}\cdot\mathbf{H_1}] : \boldsymbol{\varepsilon}^{*0} + O(\rho^8) \tag{1}$$

where

$$\bar{\mathbf{d}}^* = \frac{1}{\Omega}\int_\Omega(\boldsymbol{\varepsilon}^*(\mathbf{x}) - \boldsymbol{\varepsilon}^{*0})d\mathbf{x} \tag{2}$$

$$\mathbf{K}_{ijkl} = \mathbf{F}_{ijkl}(0,0,0,0,\alpha,\beta) \tag{3}$$

$$\mathbf{L}_{ijkl} = \frac{5}{4\beta^2}\mathbf{F}_{ijkl} \times\left(-15, 3\upsilon_0, \frac{6\alpha(1-2\upsilon_0)}{3\alpha+2\beta}, \frac{6\alpha(1+\upsilon_0)}{3\alpha+2\beta}, \frac{2\alpha(2-\upsilon_0)}{3\alpha+2\beta}, 1-2\upsilon_0\right) \tag{4}$$

$$\mathbf{H_1}(\mathbf{x_1}-\mathbf{x_2}) = 5\mathbf{F}(-15, 3\upsilon_0, 3, 3-6\upsilon_0, -1+2\upsilon_0, 1-2\upsilon_0) \tag{5}$$

$$\mathbf{H}_2(\mathbf{x_1}-\mathbf{x_2}) = 3\mathbf{F}(35, -5_0, -5, -5, 1, 1) \tag{6}$$

where $\rho = a/r$, $r = \|\mathbf{x}-\mathbf{x}'\|$, $\boldsymbol{\varepsilon}^{*0}$ is the "noninteracting" solution for eigenstrain, υ_0 is the Poisson's ratio of the matrix, and

$$\alpha = 2(5\upsilon_0 - 1) + 10(1-\upsilon_0)\cdot\left(\frac{k_0}{k_1-k_0} - \frac{u_0}{u_1-u_0}\right) \tag{7}$$

$$\beta = 2(4-5\upsilon_0) + 15(1-\upsilon_0)\cdot\frac{u_0}{u_1-u_0} \tag{8}$$

The component of the fourth-rank tensor $\mathbf{F}$, which depends on its arguments, are defined by m, equaling 1–6, as shown in Eq. (9)

$$\begin{aligned}\mathbf{F}_{ijkl}(B_m) = {} & B_1 n'_i n'_j n'_k n'_l + B_2(\delta_{ik}n'_j n'_l + \delta_{il}n'_j n'_k + \delta_{jk}n'_i n'_l + \delta_{jl}n'_i n'_k) \\ & + B_3\delta_{ij}n'_k n'_l + B_4\delta_{kl}n'_i n'_j + B_5\delta_{ij}\delta_{kl} + B_6(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk})\end{aligned} \tag{9}$$

where the normal vector $\mathbf{n}' = \mathbf{r}/r$, δ_{ij} is the Kronecker delta.

2.2. Ensemble-volume averaged eigenstrains

Based on the approximate solution for two-particle interaction problem, the ensemble-average solution can be obtained by integrating $\bar{\mathbf{d}}^*$ over all possible positions of particle $\mathbf{x_2}$ when the location of particle $\mathbf{x_1}$ is fixed. It can be expressed in Eq. (10) [27]

$$\langle\bar{\mathbf{d}}^*\rangle(\mathbf{x_1}) = \int_{V-\Omega_1}\bar{\mathbf{d}}^*(\mathbf{x_1}-\mathbf{x}_2)P(\mathbf{x}_2|\mathbf{x_1})d\mathbf{x}_2 \tag{10}$$

where $\langle\bar{\mathbf{d}}^*\rangle$ is the ensemble-average solution and angled bracket represent the ensemble-average. $P(\mathbf{x_2}|\mathbf{x_1})$ is the conditional proba-