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Micromechanical model for asphalt mixture coupling inter-particle effect and imperfect interface

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HIGHLIGHTS

- The linear spring model is adopted to simulate the asphalt mixture imperfect interface.
- The imperfect interfacial bonding weakens the overall property of asphalt mixture.
- The weaken effect of imperfect interface increase with inter-particle effect.

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ABSTRACT

Inter-particle effect and imperfect interface are the two major challenges during the micromechanical modeling of asphalt mixture due to its complex heterogeneity. This paper presents the development and validation of a micromechanical model regarding this concern. The linear spring model is adopted to simulate the imperfect interface between asphalt mortar and aggregates, and the replacement procedure is established to incorporate the imperfect interface effect into the Ju-Chen (J-C) model to coupling inter-particle effect and imperfect interface. The proposed model is used to predict the dynamic modulus of asphalt mixture and analyze the influence of inter-particle effect and imperfect interface. The results show that the predictions decrease with the interface parameter m_r/m_0 but increase with parameter $Y(g)$. The imperfect interfacial bonding weakens the overall property of asphalt mixture and the weaken effect for composites with stronger inter-particle effect is more significant.

1. Introduction

On the mesoscopic scale, asphalt mixture is a random heterogeneous material, which is composed of asphalt binder, mineral aggregates with different sizes, and air voids. The overall performance of asphalt mixture is dependent on its internal compositions including the properties, proportions and distributions of the ingredients [1]. Last decades, the micromechanics has been applied to build the multiscale models of asphalt mastics and mixtures, which link the microstructural characteristics to macro mechanical properties [2–5]. The theoretical assignments have been successfully set up to describe the quantitative relation of various macro performance and microstructure [6], and provide the essential basis for the numerical simulation, such as finite element method (FEM) simulations [7–9], discrete element method (DEM) simulations [10,11]. However, some special challenges have been confronted due to the complex heterogeneity of asphalt mixture. One major challenge is the inter-particle effect among aggregates with high volume fraction in asphalt mixture, and the other is the imperfect interface between asphalt binder and mineral aggregate.

For the inter-particle effect, the aggregates account for more than 90% in mass percentage and 80% in volume fraction of the commonly used asphalt mixtures, which are much higher than that of other particle reinforced composites. The reinforcement mechanism of particle inclusion on composite consists of three parts which are the volume filling, physiochemical interaction and inter-particle effect [12]. At low volume fraction, the inter-particle effect is weak and it contributes little to the whole stiffening effect. But for moderate and high volume fraction situations, the inter-particle effect increases and even dominates the stiffening effect. As the single inclusion based micromechanical models (e.g. self-consistent model, M-T model, general self-consistent

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model) fails to deal with the inter-particle effect mechanism, they are inapplicable for high volume fraction composites [13–15]. Theoretically, several micromechanical methods have been established for considering the inter-particle effect [16–19]. In the micromechanical framework developed by Ju and Chen [16,17], the authors firstly proposed an approximate treatment for the interaction problem of two identical elastic spherical particles were embedded in the elastic matrix. Then, based on the probabilistic pairwise particle interaction mechanism, the localization relation was established and a new model, called J-C model, was presented for two-phase composites containing randomly located spherical particles. Pei et al. [20] extended the J-C model to viscoelastic situation and introduced this model in the effective dynamic shear modulus prediction of asphalt mastics with different filler concentrations. Hence, the J-C model is also suitable for asphalt mixture to deal with the inter-particle effect problem.

On the other hand, the imperfect interfacial bonding inherently exists in asphalt mixture [21–24]. As a controlling factor, the imperfect interfacial bonding conditions have great impact on the overall properties of asphalt mixture. Therefore, the assumption of perfect bonding is inappropriate for the description of the physical nature and mechanical behavior of the interface region [25]. By replacing the particles/fibers together with the interface by equivalent homogeneous inclusions, Duan et al. [26,27] proposed a unified micromechanical scheme to predict the effective modulus of multiphase composites with three typical interface effects, including the linear spring model, interface stress model and interphase model. Underwood and Kim [28] proposed a four phase micromechanical model for asphalt mastic to consider the asphalt/aggregate physico-chemical interaction. Zhu et al. [23] introduced the Kelvin–Voigt viscoelastic interface to simulate the imperfect bonding between asphalt mastic and aggregates, and applied the Mori-Tanaka method to develop the micromechanical creep model.

Research efforts have been devoted to the inter-particle effect and imperfect interface of asphalt mixture respectively. However, none of the existing works involves the coupling of these two effects, which is more valuable and practicable. The aim of this paper is to propose a micromechanical model for asphalt mixture coupling inter-particle effect and imperfect interface. The linear spring model is selected to simulate the imperfect interface between asphalt mortar and aggregates, and the replacement procedure is adopted to incorporate the imperfect interface effect into the J-C model to develop the micromechanical model coupling inter-particle effect and imperfect interface. The dynamic modulus experiments of asphalt mortar and mixture are conducted to validate the proposed model.

2. Micromechanical model coupling inter-particle effect and imperfect interface

2.1. Microstructural idealization

The microstructure idealization process of this research is schematically presented in Fig. 1. The aggregates in asphalt mixture are usually classified into coarse aggregates, fine aggregates and mineral fillers according to the particle sizes, and the aggregates with different sizes paly different roles in the microstructure composition of asphalt mixture [1]. Some researchers believed that the asphalt mastic (the mix of asphalt binder and mineral fillers) is the actual binder, instead of the pure asphalt cement [29], which is to say the coarse and fine aggregates are actually coated by asphalt mastic. Shu and Huang [30], and Zhu et al. [23] adopted this assumption and predict the overall property of asphalt mixture from the known mastic and aggregates properties. The others proposed that the asphalt mortar (the mix of asphalt binder, mineral fillers and fine aggregates) acts as the matrix phase in asphalt mixture composite and the coarse aggregates can be regarded as dispersed in the mortar [4,9,31–33], and the overall property of asphalt mixture could be predicted according the asphalt motor and coarse aggregates properties. Considering the small proportion of asphalt mastic in mixture, it is not enough volumetrically to prevent the aggregates from contacting each other [4]. Thus, this research selected the second assumption and the idealized microstructure of asphalt mixture composite is shown in Fig. 1(a).

All coarse aggregates are assumed to be identical spherical particles and its equivalent radius can be determined according to the specific surface area equivalent principle, which ensures that the total interface surface area remains unchanged after microstructure idealization. The interface bonding condition also remains the same and the idealized asphalt mixture microstructure is shown in Fig. 1(b).

Due to the existence of imperfect interface, the prediction of the effective modulus of the spherical particle reinforced composite in Fig. 1(b) is more complicated. In the previous studies, two kinds of methods are generally used to deal with the imperfect interface effect. The first method can be referred as direct computation method in which the Eshelby tensor is modified and resolved from the modified Eshelby inclusion problem [24,25,34–36]. The second is the replacement method which replaces the inclusions together with the interface by equivalent homogeneous inclusions [26,27,37–40]. In the second method, the elastic constants of the equivalent homogeneous inclusions are calculated according to the energy equivalent principle or composite sphere model. Then, the equivalent homogeneous inclusions are back embedded and perfectly bonded with the matrix, as shown in Fig. 1(c). The

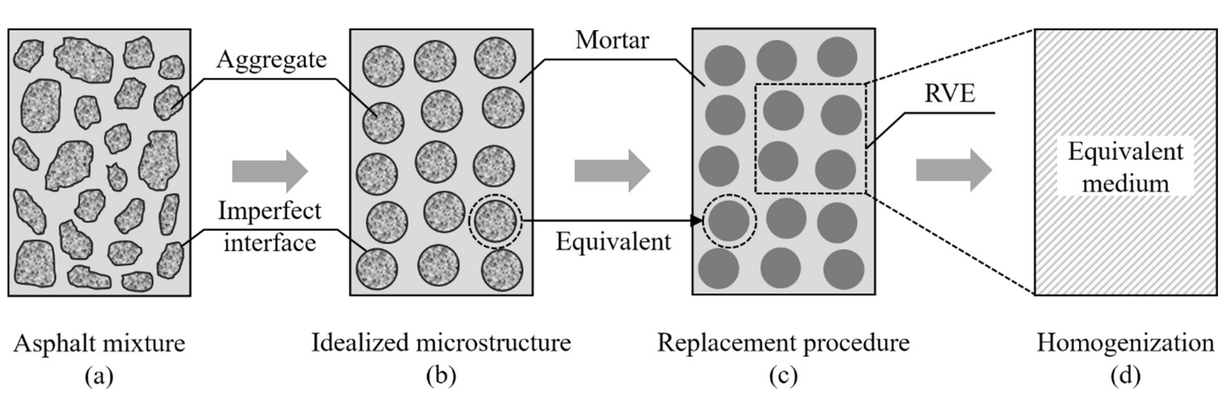

Fig. 1. Schematic representation of microstructure idealization process.