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Elastic-adhesive interface effect on effective elastic moduli of particulate-reinforced asphalt concrete with large deformation

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A B S T R A C T

A methodology is developed to account for the elastic-adhesive interface effect on the effective elastic moduli of particulate-reinforced asphalt concrete. The nonlinear factor related with the second-order term of strain is introduced to consider the large deformation of asphalt mastic. The elastic and adhesive coefficients of interface are used to describe the imperfect interface, and the closed-form for the elastic moduli of asphalt concrete reinforced by isotropic particles is derived. Through some numerical examples, it is found that the effective elastic moduli show significant variation with the interfacial microstructure in asphalt concrete, especially with small radius of particles. The interface effect with large deformation of asphalt concrete is also examined in detail.

1. Introduction

To enhance the mechanical performance of asphalt concrete (AC), the aggregates, polymers and other functional reinforcements are often added into AC. As a typical multi-phase composite, the characters of each constituents, interfaces and their interactions contribute to the overall performance of AC. The evaluation of mechanical properties of AC is an important issue in designing the road pavement.

In the past decades, the macro-mechanical behavior of AC was mainly studied by the micromechanical method (Zhu, Wang, & Yu, 2014; Shu & Huang, 2008). Cao et al. have applied this method to predict the elastic and viscoelastic properties of AC (Cao, Jin, & Feng, 2016). A fast multi-pole boundary element method was introduced to simulate the real structure of complex microstructure of materials, and the roles of constituent materials were discussed (Zhu & Chen, 2012). Based on the Burgers model, Feng et al. studied the visco-elastic behavior of asphalt mixtures by using the three-dimensional discrete element method, and the frequency-temperature superposition principle was adopted (Feng, Pettinari, & Hofko, 2015). Wang et al. established the Abaqus finite element model of two-dimensional cohesion zone of AC specimen to analyze the variation of displacements and stresses during loading (Wang, Ren, & Xing, 2017). The micromechanics and microstructure of asphalt mixture interface were characterized by nanometer scale measurement such as nano-indentation, field emission scanning electron microscope, and energy dispersive X-ray spectrometer (Zhu, Yuan, & Li, 2017). The mechanical behavior of particle-reinforced asphalt concrete is usually extremely complicated. Xiao et al. showed that adding nano-particles to bitumen binders can increase their destruction temperature, complex modulus, and modulus of elasticity (Xiao, Amirkhanian, & Amirkhanian, 2011). Nano-Al_2O_3 can also significantly improve the elastic modulus of particle-reinforced asphalt concrete (Zhang, Zhu, & Yu, 2015).

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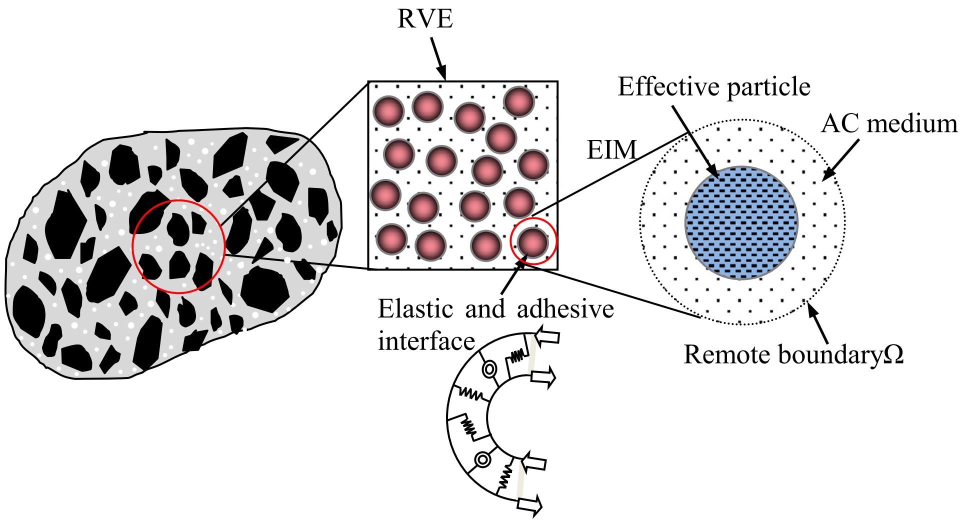

Fig. 1. The RVE and interface model of AC.

In fact, due to the processing conditions and physicochemical reactions, there are always imperfect interfaces in particle-reinforced bituminous concrete. In general, the perfect bonding between the asphalt mastic and the aggregates is a simplified boundary condition (Wei & Huang, 2004). In recent years, people are gradually beginning to pay attention to the effect of imperfect interface on the overall performance of AC. In recent years, a spring layer model was used to discuss the imperfect interface effect between coarse aggregate and asphalt mastic on the overall mechanical properties of AC (Zhu, Yang, Guo, & Chen, 2011). Li et al. developed an aggregate slip shear device to evaluate the slip shear resistance of asphalt mixture, and the effects of loading rate, test temperature and asphalt content on the shear resistance of asphalt mixture were discussed (Li, Ding, & Zhang, 2014). Gao et al. studied the interface effect on the visco-elastic properties of AC by using the linear spring layer model (Gao, Dong, Li, Wang, & Sun, 2015). In Ref. Zhu, Wang, and Yu (2014), the Kelvin–Voigt viscoelastic interface model was used to the creep behavior of particle-reinforced asphalt concrete, and only the circumferential body force was considered. For convenience, the small strains and linear elastic materials were assumed.

In order to fully understand the complex mechanical properties of particle-reinforced asphalt concrete, an elastic-adhesive interface is developed in this paper. To consider the large deformation of AC, a nonlinear factor of strain is proposed. The Generalized Self-consistent Method (GSM) and Effective Inclusion Method (EIM) are used to obtain the analytical solution. The elastic and adhesive coefficients are introduced to describe the imperfect interface between the particles and asphalt mastic. The effects of interface properties on the effective elastic moduli are analyzed in numerical examples.

2. Micromechanical modeling of AC with interface effect

An infinite AC with randomly distributed particles is described in Fig. 1(a). Let Ω be the three dimensional domain occupied by a representative volume element (RVE), as shown in Fig. 1(b). This is the smallest portion of AC, and has the same interfacial properties, elastic constants, and specified particle volume fraction of the whole AC. The volume fraction of particles is ϕ. It is assumed that the phases (asphalt mastic and particles) and the interface are all isotropic. At the macroscopic scale, the AC under consideration is assumed to be isotropic.

Due to the adhesive property of asphalt mastic and the imperfect interfacial bonding between the aggregate and asphalt mastic, the elastic and adhesive interface model is established, as depicted in Fig. 1(b). In the interface model, a rather thin interface zone of unspecified thickness is proposed. The asphalt mastic and particles are connected by a system with elastic and adhesive coefficients. The continuity of traction from one phase to the other is still maintained. However, the displacement jump has to be taken. By introducing Effective Inclusion Method (EIM), the RVE is reduced to the AC medium containing an equivalent particle of radius R, as shown in Fig 1(c).

The constitutive relations of the isotropic aggregate and asphalt mastic are defined as

$$\boldsymbol{\varepsilon}^{(i)} = \frac{1}{2}\left[\nabla \boldsymbol{u}^{(i)} + \left(\nabla \boldsymbol{u}^{(i)}\right)^T\right], \tag{1}$$

$$\boldsymbol{\sigma}^{(i)} = D_1^{(i)}\boldsymbol{\varepsilon}^{(i)} + D_2^{(i)}\left(\boldsymbol{\varepsilon}^{(i)}\right)^2 \tag{2}$$

$$D_p^{(i)} = 3k_p^{(i)}\left(\frac{1}{3}\boldsymbol{I}\otimes\boldsymbol{I}\right) + 2\mu_p^{(i)}\left(\prod - \frac{1}{3}\boldsymbol{I}\otimes\boldsymbol{I}\right), \tag{3}$$