Construction and Building Materials 96 (2015) 591–598

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Interface effects on the creep characteristics of asphalt concrete

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HIGHLIGHTS

- A micromechanical model is developed to predict the creep behavior of AC.
- The prediction is compared with available experimental data to verify the method.
- Interface effects on the creep characteristics of AC are explored using the model.

ARTICLE INFO

Article history:
Received 24 April 2015
Received in revised form 27 July 2015
Accepted 9 August 2015

Keywords:
Asphalt concrete
Imperfect interface
Micromechanics
Rheological properties

ABSTRACT

A micromechanical creep model is presented to predict the creep behavior of asphalt concrete (AC) and investigate the effect of imperfect interface between asphalt mastic and aggregates on the viscoelastic properties of AC. The linear spring layer model is introduced to characterize the interface imperfection. Based on the modified Mori–Tanaka method, the micromechanical model is developed. To describe the viscoelastic properties of AC with imperfect interface, micromechanical creep compliance formulation is obtained by incorporating the elastic–viscoelastic correspondence principle. The present prediction is compared with available experimental data in the literature to verify the proposed method. It is found that the micromechanical creep model has the capability to predict the creep behavior of AC. Interface effects on the creep behavior of AC are explored using the developed model. It is concluded that the imperfect interface between asphalt mastic and aggregates has a significant influence on the overall mechanical behavior of AC, and that the interfacial damage should be controlled within a certain extent.
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1. Introduction

Due to permanent deformation caused by repeated traffic loads, rutting is one of the main failure modes in asphalt concrete (AC) pavements. For making a desirable design, it is extremely important to improve the resistance of AC to permanent deformation. The laboratory wheel tracking test is the most direct method to investigate the rutting resistance, but it is difficult to make a deep understanding of the road material properties. It has been well known that AC is a time-dependent material which presents noticeable viscoelastic characteristics. These properties can be reflected by creep. When AC is subjected to a constant load, deformation occurs and develops slowly with time. Therefore, the creep behavior of AC should be first concerned to investigate the rutting resistance.

AC is a typical asphalt-based particle-reinforced viscoelastic composite, whose constituents include asphalt mastic and coarse aggregates. AC generally exhibits extremely complicated mechanical behavior, particularly presents apparent time-dependent viscoelastic behavior. Micromechanical method is an effective approach to fully understand each constituent's contribution to the overall mechanical performance of AC. Recently, research efforts have been made to apply this method to predict the mechanical properties of asphalt mastics and mixtures [1–6].

In the above proposed micromechanical models, aggregate particles are assumed to be perfectly bonded to asphalt mastic. However, the imperfect interfaces always exist in the particle-reinforced composites due to surface chemical reactions and the processing conditions [7]. The interface imperfection will have a significantly influence on the failure mechanisms and mechanical properties of the composites. Therefore, the assumption of perfect interface is inadequate for the description of the mechanical behavior and physical nature of the interface region [8].

Research efforts have been made to investigate the influence of interfacial bonding condition on the mechanical properties of particle-reinforced composites. The mechanical models which account for the influence of imperfect interfaces can be divided into two major categories. The first kind of models postulates that the displacement or traction field across the interfaces are both

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http://dx.doi.org/10.1016/j.conbuildmat.2015.08.075
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discontinuous, and is usually referred to as interface models. The second kind describes the interface region as a layer with a certain thickness, called an interphase, between the matrix and inhomogeneity, and is usually referred to as interphase models. The properties of the interphase are different from those of either the inhomogeneity or matrix, and can be uniform or variable. The inhomogeneity and matrix are both generally assumed to be perfectly bonded to the interphase.

Researchers have extensively studied the interface models. Ghahremani [9], Mura and Furuhashi [10], and Jasiuk et al. [11] adopted the free sliding model to analyze the local elastic fields and mechanical properties of composite materials. The free sliding model allows only relative slip along tangential direction at the interface, while a displacement jump along the normal direction is not permitted. Benveniste [12] formulated the mathematical framework of linear spring interfaces. The linear spring model assumes that only the traction across the interface is continuous but that the displacement field is discontinuous [13–15]. The linear spring model has been used to study the mechanical properties of composites [16–21]. Recently, Tan et al. [22–24] proposed a three-stage nonlinear interfacial cohesive law to simulate the interface debonding in high explosives. Other works can be seen from Achenbach and Zhu [25], Pagano and Tandon [26], and Hashin [27].

Interphase models have also been extensively studied and applied to conventional particle and fiber reinforced composites. The studies on elastic interphases [28–30] and those on viscoelastic interphases [31–33,7,34] are included in representative works. Hashin [13,35] has presented that the spring constants in interface models can be evaluated in terms of interphase elastic properties and thickness in interphase models. It should be noted that the interphase and interface models are not completely independent of each other. In addition to, Duan et al. [36] have proposed a unified theoretical framework to replace either interfaces or interphases by equivalent particles or fibers based upon energy equivalency.

For AC, good bonding between asphalt mastic and aggregate particles remain challenging tasks. Poor bonding often have a significant influence on the effectiveness of particle reinforcement. A few literatures have investigated the interface effect on the mechanical properties of AC. Zhu et al. established a micromechanical model [37] and a numerical method [38] to predict the elastic modulus of AC and found that the imperfect interface has a significant influence on the elastic properties of AC. Recently, Zhu et al. [39] also presented a methodology to research the influence of interface imperfection on the viscoelastic characteristics of asphalt-based multi-phase particle-reinforced composites, and the results indicated that the interface is a crucial factor affecting the overall viscoelastic properties of composites.

The primary objective of this paper is to develop a micromechanical model to describe the creep behavior of AC and investigate the effect of imperfect interface between asphalt mastic and aggregates on the viscoelastic properties of AC. A linear spring layer model is first introduced to characterize the interface imperfection. Based on the modified Mori–Tanaka method, a creep compliance formula is then established by incorporating the elastic–viscoelastic correspondence principle, and is called the micromechanical creep model in this paper. The present prediction is compared with available experimental data in the literature to verify the proposed method. Interface effects on the creep behavior of AC are discussed using the micromechanical creep model.

2. Imperfect interface modeling

Consider an elastic inhomogeneity Ω embedded in a different elastic domain D. Let S denote the interface between the inhomogeneity and the matrix. For perfect interface, the displacement and traction fields are both continuous across this interface, and the continuity of displacement and traction can be written as

$$\Delta u_i \equiv u_i(S^+) - u_i(S^-) = 0, \tag{1}$$

$$\Delta \sigma_{ij} n_j \equiv \left[\sigma_{ij}(S^+) - \sigma_{ij}(S^-)\right] n_j = 0, \tag{2}$$

where n_j is the unit outward normal vector of the interface S, and $u_i(S^+)$ and $\sigma_{ij}(S^+)$ are the values evaluated at the positive side of S, while $u_i(S^-)$ and $\sigma_{ij}(S^-)$ are the values evaluated at the negative side of S. It is assumed that the positive side of S is the side to which n_j points.

However, an imperfect interface could undergo a displacement jump. The present study will follow the linear spring layer model proposed by Benveniste [12], Hashin [13], and Qu [14,15]. In this model, the interfacial traction continuity is be maintained, but displacement discontinuity may occur at the interface. The displacement jump at the interface is related to the interfacial traction, and the interface conditions can be written as

$$\Delta \sigma_{ij} n_j \equiv \left[\sigma_{ij}(S^+) - \sigma_{ij}(S^-)\right] n_j = 0, \tag{3}$$

$$\Delta u_i \equiv u_i(S^+) - u_i(S^-) = \eta_{ij} \sigma_{jk} n_k, \tag{4}$$

where η_{ij} is a second-rank tensor representing the spring compliance of the interface. For simplicity, it is assumed that η_{ij} is symmetric and positive definite. It is clear from Eq. (4) that $\eta_{ij} = 0$ corresponds to the perfect interface, while $\eta_{ij} \to \infty$ represents complete debonded. The physical significance of η_{ij} can be given by adopting the following form

$$\eta_{ij} = \alpha \delta_{ij} + (\beta - \alpha) n_i n_j, \tag{5}$$

where δ_{ij} is the Kronecker delta, and α and β represent the tangential and normal compliance of the interfaces, respectively, i.e.,

$$\Delta u_i (\delta_{ik} - n_i n_k) = \alpha \sigma_{ij} n_j (\delta_{ik} - n_i n_k), \tag{6}$$

$$\Delta u_i n_i = \beta \sigma_{ij} n_j n_i. \tag{7}$$

When $\alpha \neq 0$ and $\beta = 0$, such constitutive characterization of the interfaces allows for tangential sliding between the two surfaces, but not normal separation or interpenetration. This condition will be assumed in this paper. Therefore, the influence of α on the overall viscoelastic properties of the composite is concerned. It is clear that $\alpha = 0$ stands for perfectly bonded interface and $\alpha \to \infty$ completely debonded interface.

3. Micromechanics approach of particle-reinforced composites

Consider an elastic ellipsoidal inhomogeneity Ω with stiffness tensor L^1_{ijkl} embedded in a different elastic infinite medium D with stiffness tensor L^0_{ijkl}. Suppose the eigenstrain ε^*_{ij} is prescribed in the inhomogeneity Ω and the interface between the inhomogeneity and the matrix is perfect, Eshelby [40] found that the perturbed strain field ε_{ij} in the ellipsoidal inhomogeneity Ω is uniform if the eigenstrain distribution ε^*_{ij} is uniform and is given by

$$\varepsilon_{ij} = S_{ijkl} \varepsilon^*_{kl}, \tag{8}$$

where S_{ijkl} is a uniform fourth-rank tensor, which is traditionally called Eshelby tensor. In case of an imperfect interface S and the displacement jump across the interface governed by Eqs. (6) and (7), Qu [14,15] has derived a modified Eshelby tensor S^M_{ijkl}. However, the perturbed strain field in the ellipsoidal inhomogeneity is no longer uniform but position dependent, namely,

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