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# Micromechanical creep models for asphalt-based multi-phase particle-reinforced composites with viscoelastic imperfect interface

Xing-yi Zhu [a,b], Xinfei Wang [c], Ying Yu [d,*]

[a] Key Laboratory of Road and Traffic Engineering of Ministry of Education, Tongji University, Shanghai 200092, PR China
[b] Shanghai Institute of Applied Mathematics and Mechanics, Shanghai University, Shanghai 200072, PR China
[c] Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA
[d] Department of Civil Engineering, Shantou University, Shantou 515063, PR China

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ABSTRACT

A methodology to account for the interface effect on the viscoelastic behavior of asphalt-based multi-phase particle-reinforced composites is presented. A Kelvin–Voigt type viscoelastic interface is introduced first to simulate the imperfect interface between asphalt mastic and particles. The concept of “effective” particle properties is used to take into account the viscoelastic characteristic of the interface in an averaged manner. Then, the micromechanical creep model is developed based on the Mori–Tanaka method, and further solved analytically by incorporating the elastic–viscoelastic correspondence principle. Tests are conducted on the three types of asphalt concrete with different microstructures, and then compared with the predicted results. The results indicate that the developed micromechanical model has the capability to predict the creep behavior observed from the asphalt concrete. Finally, the effects of particle size, viscoelastic characteristic of asphalt mastic, the different rheological models for simulating asphalt mastic, elastic properties of particles, volume fraction of particles, and particularly interface imperfection on the creep behavior of asphalt concrete are further investigated.



## 1. Introduction

Asphalt is a sticky and thermoplastic material, which is readily adhesive, waterproof, durable, and presents small elastic recovery capabilities. Asphalt itself has poor mechanical performance, however, when it is used as the glue or binder and reinforced by aggregates, fillers, rubber-like polymers, and other functional materials, its mechanical properties will be greatly improved, and presents apparent viscoelastic behavior (Liu, Wu, Ye, Qiu, & Li, 2008; Palade, Attane, & Camaro, 2000). The primary use of asphalt is in road construction, bridge deck, and water-proofing coatings. Now, through embedded with graphite particles, it also can be used as an electrical conductive material, which exhibits self-sensing ability to strain, defects, and temperature (Wu, Liu, Ye, & LI, 2006).

Asphalt-based particle-reinforced composites generally exhibit extremely complicated mechanical behavior, particularly present apparent time-dependent viscoelastic behavior. To fully understand each constituent’s contribution to the global mechanical performance, a suitable micromechanical-based method should be established. Based on the percolation-like model and the frequency-composition temperature correspondence principle, Blanco, Rodricuez, Carcia-Carduno, and

* Corresponding author.
*E-mail address:* yuying@stu.edu.cn (Y. Yu).

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Castano (1996) investigated the rheological behavior of an asphalt-based composite within a wide range of compositions. The discrete-element viscoelastic geometric and mechanical models of asphalt-based materials were developed by Liu and You (2011) according to the frequency–temperature superposition principle. Zhou, Wang, and Zhou (2012) presented a new differential effective medium formula to predict the thermal conductivity modification in asphalt-based materials with graphite and cenosphere powders modification. Masad, Tashman, Little, and Zbib (2005) utilized an anisotropic non-associated flow rule based on the Drucker–Prager yield surface to study the effects of anisotropy, damage, and aggregate characteristic on the viscoelastic behavior of asphalt mixes. Shashidhar and Shenoy (2002) gave the complex sets of equations based on the generalized self-consistent scheme to describe dynamic mechanical behavior of asphalt mastic. They also investigated the effect of volume fractions, particle gradation, particle shape, degree of dispersion, and average particle size on the global creep behavior. Shu and Huang (2008) proposed a 3D built-in micromechanical model by embedding the asphalt mastic-coated aggregates in the equivalent hot-mix asphalt (HMA) medium, which was used to predict the effective relaxation modulus of HMA.

Above developed micromechanical models can account for the effect of the phase properties and phase geometries. However, one important factor, the interfacial bonding strength between particles and asphalt binder has been ignored by most of researchers. Actually, an imperfect interface always exists in the particle-reinforced composites due to the processing conditions and physico-chemical reactions (Wei & Huang, 2004). And this interface imperfection will significantly influence the mechanical properties and failure mechanisms as well as the strength of the composites.

Matzenmiller and Gerlach (2004) adopted a generalized method of cells to study the influence of compliant fiber–matrix bonds on the overall behavior of polymeric fiber composites. The fiber–matrix bond was simulated as an interphase with a finite thickness. Huang, Shu, Li, and Chen (2007) presented a three-layered HMA model, in which the elastic interfacial zone was characterized by an asphalt film with a specified thickness. Sevostianov and Kachanov (2007) developed explicit expressions to study the effect of interphase layers on the overall elastic/conductive properties of matrix composites. In their developed method, they proposed the concept of equivalent homogeneous inclusion, which has the radius of the core inclusion plus the interphase thickness and produces the same effect on the overall mechanical property of the composite. Furthermore, Sevostianov (2007) used above similar concept of effective particle properties and the incremental homogenization scheme to investigate the effect of interphase layers on the thermal pressure coefficient of a composite. Tan, Huang, and Liu (2008) studied the effect of particle/mastic interface debonding on the composites consisting of elastic particles and viscoelastic mastic. In their study, the interface debonding was represented by a nonlinear cohesive law. Papanicolaou, Xepapadaki, Drakopoulos, Papaefthymiou, and Portan (2012) studied the interfacial viscoelastic behavior of CNT reinforced nanocomposites by using a newly developed hybrid viscoelastic interphase model. In their model, the viscoelastic interphase thickness has not a constant value, but is dependent on the creep time. An effective medium theory was presented by Pan, Wenga, Meguid, Bao, and Zhu (2013) to study the effect of interfacial sliding on the effectiveness of CNT reinforcement. They concluded that the viscoelastic characteristics of a CNT nanocomposite were very sensitive to the interface condition. Recently, Zhu and Chen (2012) utilized a spring-layer model to simulate the interfacial strength, and a closed-form micromechanic-based analytical method and a numerical method based on the fast multipole boundary element method were developed to consider the effect of interfacial strength on the elastic behavior of asphalt concrete.

To the best of our knowledge, no one has investigated the effect of a viscoelastic interface on the macro-mechanical behavior of asphalt-based multi-phase particle-reinforced composites. The objective of this paper is to give a simpler and more efficient micromechanical formulation for researching the effect of interfacial bonding on the linear viscoelastic (LVE) behavior of asphalt-based multi-phase particle-reinforced composites. In this paper, a Kelvin–Voigt type viscoelastic interface is first introduced to simulate the imperfect interface between asphalt mastic and particles. Then, a similar concept of "effective" particle properties used by Sevostianov and Kachanov is adopted to take into account the viscoelastic characteristic of the interface. Based on the Mori–Tanaka method, the micromechanical creep formula is developed by incorporating the elastic–viscoelastic correspondence principle. Tests on the typical asphalt-based particulate composites, namely, asphalt concrete (AC), are conducted to verify the developed method. To investigate the effect of particle size and gradation on the global creep behavior of AC, three different microstructures of AC are prepared. The derived method not only has a good agreement with the experimental results, but also can explore the effects of particle gradation, viscoelastic characteristic of asphalt mastic, the different rheological models for simulating asphalt mastic, elastic properties of particles, volume fraction of particles, and interfacial strength on the viscoelastic properties of asphalt-based materials.

## 2. Micromechanical modeling of multi-phase LVE materials with imperfect interface

### 2.1. Model establishment

To investigate the viscoelastic behavior of the composites with interfacial imperfection, we establish the micromechanical model, which can be described as a viscoelastic domain embedded with $N$ randomly distributed elastic spherical-shaped particles with different sizes, see Fig. 1. For an elastic problem, we can simulate the interface by the spring layer model of vanishing thickness (Achenbach & Zhu, 1989; Hashin, 1991; Jasiuk & Tong, 1989; Lane & Leguillon, 1982) or consider a third material with a specified thickness existing between the asphalt mastic and particles (Achenbach & Zhu, 1990; Broutman & Agarwal, 1974; Zhu & Achenbach, 1991). However, for LVE materials, the interface will present apparent viscoelastic