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A four phase micro-mechanical model for asphalt mastic modulus

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ABSTRACT

In this paper, existing formulations for predicting the stiffening effects of graded aggregate particles at moderate and high concentrations in a viscoelastic matrix (asphalt) are evaluated. These functions encompass dilute, micro-mechanical, and phenomenological solutions, but each is found to produce qualitatively and quantitatively unsatisfactory results at all particle concentrations. These shortcomings are hypothesized result from the inability of these models to consider a third phase of the composite, a physico-chemically influenced layer at the aggregate surface. A model to account for this layer is developed and applied to predict the stiffening of asphalt mastics across a range of volumetric concentrations. The model is found to predict the stiffening responses at moderate concentrations well, but under predicts the responses at the highest concentrations. At these concentrations, particulate contact and internal structure development occurs and provides an additional stiffening mechanism that the four phase model does not account for. The under predictions at these higher concentrations are thus expected and rational.

1. Introduction

Asphalt mastic is a composite material consisting of an asphalt cement binder and well graded aggregate particles smaller than 75 μm (e.g., aggregate filler). It is a commonly encountered version of the class of materials consisting of soft viscoelastic binding medium and relatively rigid, irregularly shaped and well-graded inclusions. Such a material is similar to particulate filled polymer matrix composites, which have wide ranging engineering applications (Rothon, 2003). Asphalt mastics are generally found in roofing and pavement applications, but may also be used as waterproofing and tank/pipe lining due to their voidless, impermeable, and solid to semi-solid nature. In dense graded asphalt concrete the mastic binds larger aggregate particles into a material capable of supporting vehicular traffic under widely ranging environmental conditions. In this application the mastic generally contains 20% to 40% filler by volume. The thermo-mechanical properties of the mastic have been known to strongly influence the properties of the asphalt concrete composite since at least the 1930s (Traxler and Miller, 1936). However, misunderstanding of the complex linkages between the constituent materials properties and the composite mastic behaviors and then between the mastic and mixture has resulted in empirically driven evaluations.

A fundamental problem in the area of asphalt mastics in particular and in particulate filled composites in general, is the prediction of the composite modulus from the known moduli values and blend percentages of the constituent phases. Such predictions enable many useful engineering tasks: more appropriate selection of source materials; enhanced material development to ensure that desirable mechanical properties are achieved; and improved design of multi-phase composite materials within the context of

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multiscale approaches (Pindera et al., 2009). Classically, upscaling of the composite properties from known constituent properties (examples exist in filled polymer composites, asphalt concrete, solid composites with reinforced matrices, and portland cement concrete) has been accomplished using dilute suspension or micro-mechanical models (Benveniste, 1987; Budiansky, 1965; Christensen and Lo, 1979; Einstein, 1956; Halpin and Kardos, 1976; Hashin, 1962; Hill, 1965; Kataoka et al., 1978; McLaughlin, 1977; Pindera et al., 2009; Yin et al., 2008). These models typically idealize the microstructure using regular particle geometries and simplified compositional consideration. They also treat the matrix as an inert, elastic medium. However, many times these materials contain well-graded and irregularly shaped particles and a binding matrix that is an organic, physico-chemically active, viscoelastic material with source and distillation dependent properties.

Despite these differences, some moderately successful applications to predict the modulus of the asphalt concrete (Aigner et al., 2009; Buttlar and Roque, 1996; Kim and Buttlar, 2011; Pichler et al., 2012; Shu and Huang, 2008, 2009) and the asphalt mastic (Abbas et al., 2005; Buttlar et al., 1999; Faheem and Bahia, 2009; Heukelom, 1965; Kim, 2003; Rigden, 1947; Shashidhar and Shenoy, 2002; Yin et al., 2008) have been reported in the literature. The conclusions from studies with asphalt concrete are scattered with some research showing good predictions at lower temperatures (Buttlar and Roque, 1996; Kim and Buttlar, 2011). Generally though it is found that these models under predict the composite modulus. Similar conclusions are drawn with regards to mastic predictions. Shashidhar and Shenoy (2002) evaluated the generalized self-consistent model for asphalt mastics at multiple volumetric concentrations up to 31% and found that the method under predicted the observed behaviors substantially. The authors proposed a percolation mechanism and formulate a model that better matches the measured behaviors. Kim (2003) experimented with four different materials at particle concentrations of 5%, 10%, and 25%, and compared the measured data with predictions from the composite sphere model (Hashin, 1962) and two generalized self-consistent models (Christensen and Lo, 1979; Lewis and Nielsen, 1970). The results varied, but overall better predictions were found in the lower particle concentrations than with the predictions at 25% particle concentration. Abbas et al. (2005) performed a similar analysis as Kim with different mastics and reached the same conclusions. Yin et al. (2008) applied the elastic–viscoelastic correspondence principle to several micro-mechanical models, and then evaluated their accuracy for the prediction of mastic moduli. Two data sets were included in this comparison: (i) a single mastic at 32% filler particle concentration by volume with moduli measured at various frequencies and at temperatures between −20° and 0 °C and (ii) mastic at various volumetric compositions tested at only 25 °C and 10 Hz. The authors found that the generalized self-consistent and Mori–Tanaka schemes consistently underestimate the measured modulus and conclude that the self-consistent model formulation best matches the measured data.

It is believed that some of the above observations from the literature occur because the models do not consider physico-chemical interactions between asphalt binder and aggregates, which may be significant in asphalt mastic due to the relatively large specific surface area of filler sized particles. It is widely reported that the physico-chemical process of selective adsorption of the asphalt binder compounds by the aggregate particles occur in asphaltic composites, see (Anderson et al., 1992; Clopotel et al., 2012; Huang et al., 2005; Ishai et al., 1980; Kim, 2003; Warden et al., 1959) and the references cited therein. Direct evidence of such a phenomenon is found in the work of Clopotel (2012) and Craus et al. (1978). Buttlar et al. (1999) attempted to incorporate these effects into the generalized self-consistent scheme by modifying the effective volume of the aggregate particles, e.g., a rigid particle approximation. Favorable comparisons between measured and predicted stiffening at a temperature of 25 °C and 10 Hz were shown. Yin et al. (2008) also evaluate this potential, but assume that the adsorbed layer effectively reduces the modulus of the aggregate particles.

Overall, these dilute suspension and micro-mechanical methods have been evaluated for only a relatively narrow range of temperatures, frequencies, and particle concentrations. In practice, asphalt mastics are subjected to a wide range of temperatures and loading frequencies, and so a more thorough investigation of the model predictions is needed. The two objectives of the work presented here are;

(1) To show the shortcomings of existing dilute suspension and micro-mechanical models by evaluating their predictions across a range of conditions that are commensurate with the application conditions for asphalt mastic and
(2) Propose a micro-mechanical formulation that accounts for physico-chemical interactions within the asphalt mastic that can more accurately predict the effect of particle concentration on the composite modulus of asphalt mastic

The primary differentiation of this work from the work presented elsewhere and discussed above is the breadth of conditions considered. In this work, the measured and predicted moduli are compared for 64 different combinations of temperature and frequency ranging from 10 °C and 14 Hz to 54 °C and 0.1 Hz and across volumetric particle concentrations ranging from 10% up to 60%. This extensive number of conditions provides an opportunity to more comprehensively evaluate the existing models and to develop a more robust alternative formulation.

2. Materials and methods

2.1. Materials

Asphalt mastics from two different aggregate and asphalt binder sources have been used in this study. The first group (designated as MS95-XX, where the XX will differentiate between the different volumetric concentrations