Construction and Building Materials 166 (2018) 324–333

Contents lists available at ScienceDirect

Construction and Building Materials

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

Modeling asphalt mastic modulus considering substrate–mastic interaction and adhesion

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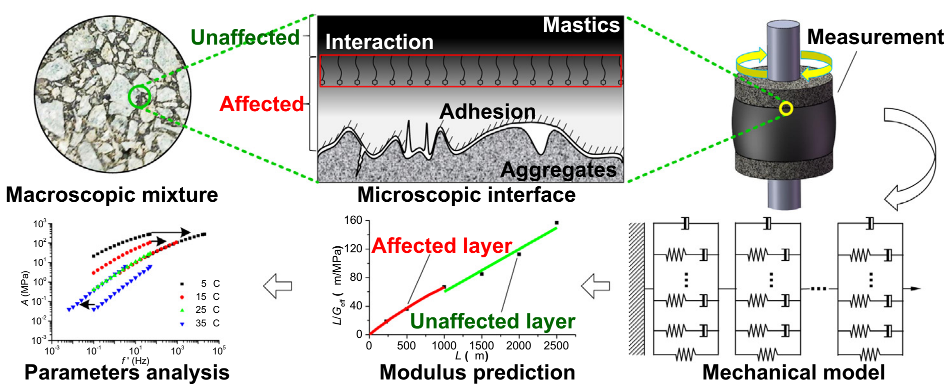
HIGHLIGHTS

- The effect of interaction and adhesion was considered as four mechanical parameters.
- A mechanical model was proposed to formulate the mastic modulus on substrate.
- The time-temperature superposition of parameters characterizes the viscoelasticity.
- The measured modulus underestimates the real modulus of bulk mastic.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 October 2017
Received in revised form 14 January 2018
Accepted 24 January 2018

Keywords:
Mechanical model
Substrate–mastic interaction
Adhesion
Shear modulus
Asphalt mastic

ABSTRACT

Microscopic aggregate–mastic interaction and adhesion lead to macroscopic modulus nonuniformity of asphalt mastic on aggregate surface. This nonuniformity is ignored in multiscale models of mixture and causes prediction errors. This study aimed to establish a macromechanical model considering microscopic aggregate–mastic interaction and adhesion to characterize the mastic modulus in contact with aggregate substrates. Frequency sweep tests were conducted to measure the modulus of mastic with different thicknesses, and the measured mastic was simplified as a mechanical model comprising viscoelastic elements series. By introducing a piecewise function of thickness, the measured modulus was deduced as an expression containing the contribution of the affected layer and bulk phase. Four model parameters described the microscopic interaction, adhesion, affected range, and modulus of bulk mastic, respectively. The model was applied to the mastic modulus on different substrates, and results effectively demonstrated the applicability. The temperature and frequency dependence and time–temperature superposition of interface mastic modulus and bulk mastic modulus were observed, and it demonstrated the model's ability to characterize mastic viscoelasticity. Moreover, evaluation of the gap between the measured and real moduli on a substrate showed the necessity of considering interaction and adhesion.

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https://doi.org/10.1016/j.conbuildmat.2018.01.140
0950-0618/

1. Introduction

Asphalt mixture is a multiphase composite that consists of graded mineral aggregates bound to a cementitious phase. Due to its heterogeneity, anisotropy, viscoelasticity, and damage growth in multiple forms, its mechanical behaviors at different scales exhibit distinct characteristics. The small-scale constituents and their mechanical behavior significantly affect the large-scale mechanical properties and responses of asphalt mixture. The relationship of the mechanical characteristics at multiscale needs to be established, and the overall constitutive relationship needs to be accurately formulated. Such information is important to promote the development of material design, performance evaluation, and prediction, and thus an excellent performing and long-lasting asphalt mixture can be produced [1]. Many multiscale approaches were employed to study the mechanical response and damage of an overall multicomponent asphalt mixture [2–7]. In these studies, the asphalt mastic is regarded as a homogeneous cementitious phase whose modulus and tackiness greatly influences the overall mechanical performance of the mixture [8–14]. A measured uniform modulus is generally utilized in multiscale mechanical models to predict the overall mechanical response of the mixture. However, the assumption of homogeneity becomes invalid for the mastic coating the aggregate surface in real mixtures because the microscopic components of mastic are reorganized by the physicochemical interaction between aggregates and mastic at microscale. Such reorganization leads to macroscopic modulus nonuniformity within a certain thickness on the aggregate surface. Once the nonuniform modulus of mastic induced by the microscopic interaction is modeled and further introduced into the present multiscale approaches, the overall mechanical behavior of asphalt mixture can be more accurately predicted.

The mastic within a certain thickness on an aggregate surface is a complicated region that simultaneously is affected by the physicochemical natures of mastic and aggregates and aggregate–mastic microinteractions, as seen in Fig. 1. The physiochemical interaction between the polar components in mastic and the active sites in aggregates promotes the binding of mastic to the aggregates. Nevertheless, the formed interface adhesion inevitably produces some microscopic adhesive defects induced by the microcracks, micropores, and residual stress of the surface. The mechanical property of mastic at the surface is enhanced by the physicochemical interaction and weakened by the adhesive defects. Therefore, the complicated microscopic interaction and adhesion are two essential aspects in modeling the mastic modulus. Generally, the microscopic interaction decays as the distance from the aggregates increases. Thus, the mastic modulus where the effect remains significant varies as the distance from the aggregates increases, whereas the mastic modulus where the effect is negligible stabilizes to a certain value. The region from the aggregate substrate surface to the boundary where interaction is negligible is defined as the affected layer. The steady mastic modulus outside the affected layer is the real modulus of bulk mastic. Accordingly, the thickness of the affected layer and mastic modulus outside the affected range are another two important parameters. In summary, a valid modulus model of mastic coating the aggregate surface must consider the interaction, adhesion, thickness of the affected layer, and modulus of bulk mastic. An important task in this study was to propose macroscopic mechanical parameters to characterize the influence of microscopic interaction and adhesion.

Considerable research has been conducted on microscopic interaction and adhesive bonding by using nanoscale metrology techniques and molecular dynamics simulation [15–19]. These microscopic studies effectively promote the understanding of physicochemical adhesive bonding and interaction. However, the complex components, surface texture, and adhesive defects are hardly considered. The microscopic methods seem difficult to propose valid macroscopic parameters characterizing microscopic interaction and adhesion. On the other hand, macroscopic mastic modulus is generally measured with a 2000 μm thickness on aluminum substrate by using a dynamic shear rheometer. An implicit hypothesis in the test is that mastic on substrate is homogeneous and has uniform shear modulus. However, the microscopic interaction and adhesion lead to the mastic modulus nonuniformity within the affected layer. This interaction is also observed in the reported rheological studies of asphalt binder and mastic [20–24]. The results strongly showed that the thin asphalt films on mineral substrates exhibit substantially changing rheological properties that depend on the film thickness and the rheological properties have evident susceptibility to aggregate types, asphalt

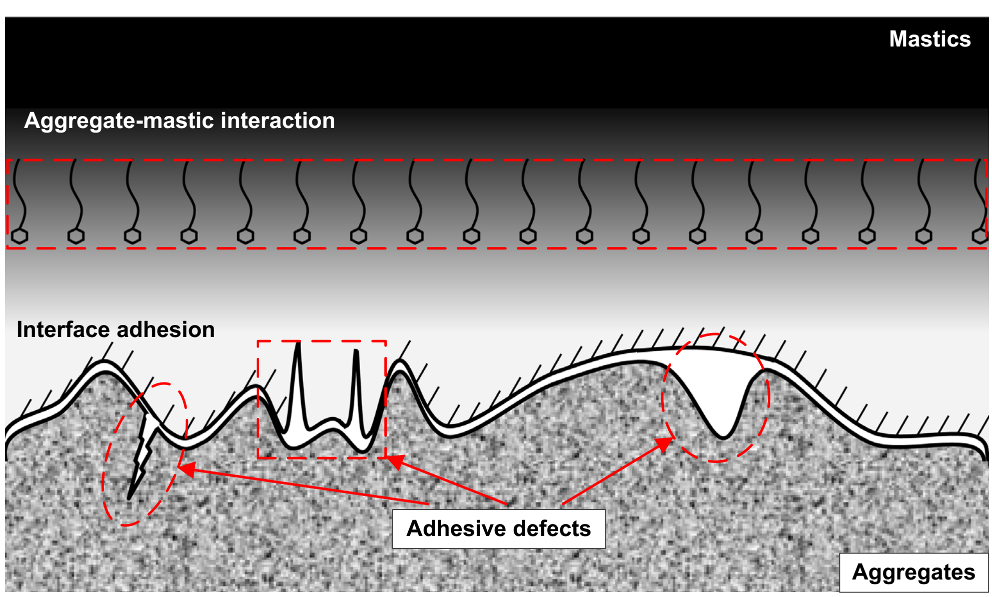

Fig. 1. Diagram of the mastic in an affected layer with the effect of aggregates.