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A new simplified micromechanical model for asphalt mastic behavior

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HIGHLIGHTS

- A new micromechanical model was developed to predict the asphalt mastic behavior.
- A power model was found to fit the rheological data of the mastic the best.
- The model had a high degree of confidence and high coefficient of determination.
- The new model showed improved predictions compared with available models.
- The stiffening ratio increased with the increase in temperature and decrease in frequency.

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ABSTRACT

This study presented a new simplified micromechanical model that describes the asphalt mastic behavior at intermediate and high temperatures. Asphalt mastics were prepared using four fillers: glass, limestone, stone sawdust, and medical ash and one asphalt binder with a penetration grade of 60/70 (PG 64-10). The mastics were prepared at four volume concentrations: 0.05, 0.10, 0.20, and 0.30. The Dynamic Shear Rheometer (DSR) frequency sweep tests were conducted at a wide range of temperatures and loading frequencies. A new model was developed for the mastic complex shear modulus value with a simplified form $G_m = AG_b^B$, such that A is a quadratic polynomial function of the volume concentration. The model had a high adjusted coefficient of determination (R^2). It was validated using external measured data, and showed improved predictions of the mastic behavior. Findings also showed that the stone sawdust asphalt mastic had the highest complex shear modulus value at volume concentrations 0.05 and 0.10; whereas, at higher volume concentrations (0.20 and 0.30), the medical ash asphalt mastic and the glass asphalt mastic had the highest values, respectively. The stiffening effect of the asphalt mastics increased with the increase in temperature and the decrease in loading frequency.

1. Introduction

A relatively considerable research has been done to: (1) understand the behavior of filler-asphalt mastic, (2) investigate the factors including filler type that affect the properties of the asphalt mastic or/and the mixture, (3) develop models which correlate the properties of the fresh asphalt binder and the mastic. In the next paragraphs, findings of previous recent studies are presented.

Mineral filler (the material passing No. 200 (0.075 mm) sieve) is used as part of the aggregate portion in asphalt mixture design at specific percentages to ensure good workability and stability of the mixture. In Superpave, the dust proportion (DP), defined as the filler material passing No. 200 sieve divided by the effective asphalt binder (percentage by total weight of the mixture), was introduced to control this important portion in the mixture design at optimum values. The acceptable range of the DP in Superpave is 0.6–1.2 [1].

The filler-asphalt mastic has a higher stiffness or viscosity than the original asphalt binder. The mastic in asphalt mixtures is known to affect the performance of these mixtures [2]. In addition, the stiffness of the mastic in field impacts the ability of the mixture to resist permanent deformation (rutting) at higher temperatures, influences stress development and fatigue resistance at intermediate temperatures, and affects stress development and fracture resistance at low temperatures [3].

Tuncan et al. [4] investigated the effect of fillers including fly ash on properties of asphalt mixture. They concluded that marble

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powder and fly ash could be used as filler materials instead of stone powder in the asphalt pavement specimens. In addition, Yi-qiu et al. [5] studied the high- and low-temperature properties of asphalt-mineral filler mastic. They found that the optimal range for filler/asphalt (F/A) ratio was 0.9–1.4 to balance the high-temperature and low-temperature properties.

Chen [6] presented a mathematical model to predict the properties of asphalt mastics depending on time-temperature parameters. Two types of filler at several volume concentrations were used in the study. The Bending Beam Rheometer (BBR) and the Dynamic Shear Rheometer (DSR) were utilized to measure the rheological properties of asphalt mastics. The findings of the study showed that the stiffening effect of fillers is relatively small at shorter loading times and low temperatures, but higher at longer loading times and higher temperatures.

Delaporte et al. [7] used a specifically developed experimental device (Annular Shear Rheometer) to perform an experimental work on asphalt mastics. The goal of their study was to measure the linear viscoelastic behavior of mastics at low strain levels. The effects of asphalt binder aging and filler factors including: type, size, gradation, and concentration were investigated. The complex shear modulus (G^*) value of mastics was obtained at a wide range of temperatures: −25 to 80 °C and loading frequencies: 0.03–10 Hz. A significant change in behavior between binder and mastics with high filler volume concentration (>40%) was observed and quantified. The new aging complex coefficient, R_A^* (the ratio between the complex shear modulus of aged binder to shear modulus of unaged binder at same loading frequency) was useful to show that at high temperatures and/or low frequencies, the filler effect was significant. The effect of filler gradation and size on the viscoelastic behavior of mastics was minimal. It was also found that the effect of binder aging quantified by the aging complex coefficient on the mastic behavior was influenced by the filler type and gradation.

Delaporte et al. [8] used the same Annular Shear Rheometer (ASR) in Delaporte et al. [7] to conduct an experimental work on asphalt mastics and mixtures produced using ultrafine particles (silica fumes). The goal was to compare the effect of the ultrafine particles to that of the traditional particles. The linear viscoelastic properties of mastics were measured using the ASR including the complex shear modulus (G^*). The results showed that the ultrafine particles significantly increased the complex modulus value of mastics at high temperatures compared to the traditional fillers. At low temperatures, the complex modulus was little affected by the filler characteristics.

Buttlar et al. [9] used micromechanics to assess the mechanical properties of mastics produced using hydrated lime and three baghouse fines (distinguished by three different gradations). Mastics were produced using four volume concentrations: 0.05, 0.15, 0.25, and 0.40. The DSR was used to measure the rheological properties of the asphalt mastics. They concluded that a rigid layer adsorbed to the filler explained the ability of the filler to result in stiffening ratios that are greater than would be predicted based on volumetric concentrations alone. Specifically, physicochemical reinforcement effects played a considerable role throughout the range of filler-to-asphalt ratios encountered in practice based on the equivalent rigid-layer concept. The hydrated lime showed much higher level of physicochemical reinforcement than the baghouse fillers.

Buttlar and Roque [10,11] extended the concepts of micromechanical modeling from polymer composites to asphalt mixtures and mastics. While none of the available models was found suitable for predicting asphalt mixture properties, it was concluded that micromechanical models had a potential use in predicting asphalt mastic properties.

Hopman et al. [12] compared the effects of hydrated lime with limestone of identical size and gradation. Rheological measurements were obtained before and after aging of mastics. It was found that the hydrated lime reduced temperature susceptibility of the mastic; in other words, mastics with hydrated lime were significantly stiffer at higher temperatures than the mastics with identically-sized limestone filler; whereas, minimum stiffness difference existed between the two at lower temperatures. They reported an increase of approximately 50 percent in stiffness modulus at 60 °C. The findings of the study also showed that the increase in stiffness modulus after aging is significantly smaller for the mastics with hydrated lime than for those with the limestone filler. And hence, the effects of hydrated lime would be important for wearing courses and porous asphalt mixtures where aging is one of the main causes of road deterioration.

Muniandy et al. [13] conducted a study to take the advantage of the empty fruit bunch (EFB) of date and oil palm trees (which are considered as waste) to produce cellulose fiber to be used as additives in the asphalt binder. A total of 11 mastic blends were prepared: 5 blends with date palm fiber, 5 blends with oil palm fiber, and one control sample that contained no fibers. The samples were evaluated using the DSR following the Superpave standards. The phase angle, shear strain, and complex shear modulus were measured for the unaged (neat) samples, Rolling Thin Film Oven (RTFO)-aged samples, and Pressure Aging Vessel (PAV)-aged samples. The results indicated that the fibers improved the rheological performance of Bio Mastic Asphalt (BMA) blends. The control sample, which was categorized as PG58, was enhanced to PG76 with 0.375% date palm fiber. The oil palm also improved the performance grade of the blend to PG70 with 0.3% oil palm fiber.

Despite that the asphalt binder composes approximately 5 percent of the asphalt mixture, the mechanical properties of the binder significantly contribute to the mechanical behavior of the mixture. In the asphalt mixture volumetric phasing system, the asphalt binder coats the aggregate particles filling part of the total voids between the particles and creates an important phase called voids filled with asphalt (VFA). The voids filled with asphalt and the effective asphalt binder are alternatively used to represent the same volumetric phase, which is accountable for the durability of the mixture. Fine and coarse aggregate particles in the mixture are unquestionably covered with asphalt binder, which is known as asphalt film. Nevertheless, the fine aggregate particles are part of the asphalt film coating the coarse (large) aggregate particles in the mixture. Due to the fact that this asphalt film is the phase that is responsible for the durability of the mixture, the mechanical properties and behavior of this asphalt blend are essential. The blend of the filler material and the asphalt binder is what so called filler-asphalt mastic in the mixture.

Several types of mineral fillers are commonly used to produce the filler-asphalt mastic. The properties of the produced mastic correlate with the behavior of the original asphalt binder through models. The role of modeling has been always vital. With accurate predictive models, the need to conduct experimental work is minimized; and hence, time and cost can be reduced. In asphalt technology, micromechanical modeling is one approach to develop models that are capable of predicting the behavior of asphalt mastic from the behavior of asphalt binder or further (if possible) the behavior of asphalt mixture from asphalt binder or/and mastic.

Asphalt technologists and researchers devoted a good pioneering effort to study the behavior of asphalt mastic from that of binder trying to finally predict the properties of asphalt mixture. Although predicting the asphalt mixture mechanical properties from asphalt binder properties or mastic properties has failed, attempts to predict the mastic behavior have succeeded.