ARTICLE IN PRESS

Materials Today Communications xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Materials Today Communications

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

Mixture-property-independent asphalt film thickness model

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ARTICLE INFO

Keywords:
Asphalt film thickness
Asphalt film thickness models
VMA criteria
Superpave
Gradation
HMA
Mix design
Aggregate
Asphalt

ABSTRACT

The durability of asphalt mixtures and hence the service life of asphalt pavement surface layers depends to a large extent on the asphalt film thickness. The current Superpave Voids in Mineral Aggregate (VMA) criterion relates mixture durability with VMA. The need to modify the Superpave criterion was supported by a previous study [1]. As the Superpave VMA criterion is based on the minimum asphalt content in the asphalt mixture and not on the asphaltfilm thickness, this minimum requirement does not ensure mixture durability in many cases. Additionally, coarse asphalt mixtures that tend to have enough asphalt film thicknesses normally have difficulty fulfilling the Superpave minimum VMA criteria. From this contention, the need for simple and reasonably accurate models to estimate the asphalt binder film thicknesses in asphalt mixtures becomes essential.

In this study, a model for estimating the asphalt film thickness (FT_b) has been developed using only parameters/properties of the two mixture constituents (aggregate and asphalt binder) and without the inclusion of any mixture property. The derivation of the model is based on physics, and the determined model coefficients (constants) have been obtained through statistical regression analysis. Superpave aggregate gradations of three nominal maximum aggregate sizes (NMAS), 9.5, 12.5, and 19.0 mm with aggregate gradations passing above, below, crossover, hump through, and pass through restricted zone were used. Superpave Gyratory Compactor (SGC) test data of 100 compacted asphalt mixtures were used in developing the model, and SGC data of 31 mixtures were used for verification of the model. MS Excel program solver was used for regression analysis. The final outcome is a physics-based statistical regression model, with a high enough coefficient of determination (R^2) value of 0.9 for FT_b, which is easy to use and likely to predict the film thickness with a reasonable degree of accuracy.

1. Background

The conventional method used by most highway agencies to compute the asphalt film thickness in asphalt mixtures was developed about 50 years ago and needs to be updated. There are very limited studies in the literature that have focused on this topic to come up or develop new models or formulas to estimate the asphalt film thickness as can be seen from the scanty available information reviewed below.

Attia et al. [2] evaluated the voids in mineral aggregate (VMA) and the asphalt film thickness (AFT) as mixture design parameters through field performance of Superpave mixtures. Film thickness was estimated by different formulas using calculated aggregate surface area. Pavement sections with early flushing and rutting problems were considered in the study to correlate the AFT with the development of pavement distresses. The findings of their study showed that the AFT capability to explain specific field performance distresses such as rutting and bleeding is dependent on the calculation method.

Heitzman, [3] developed new models for asphalt film thickness based on random spatial distribution of particles in asphalt mixtures. The models were applied to Iowa State Department of Transportation (DOT) hot-mix asphalt (HMA). The results indicated that the proposed models accounted for the individual aggregate source gradations, specific gravities, and particle shape that comprise the HMA blend, and might give a better measure of mixture durability.

Radovskiy, [4] developed analytical formulas for asphalt film thickness in compacted asphalt mixtures to determine the film thickness for any volume fraction of aggregates and any volume fraction of effective asphalt. The formulas were developed using a model of asphalt concrete in which the aggregates are spherical with arbitrary size distribution. Details of the calculations were summarized and examples were provided.

Li et al. [5] in their study proposed a computation approach that was believed to improve the current conventional method for asphalt film thickness calculation by considering shape factors and flat surface

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https://doi.org/10.1016/j.mtcomm.2017.11.007
Received 9 November 2017; Accepted 13 November 2017

Please cite this article as: Al-Khateeb, G.G., Materials Today Communications (2017), https://doi.org/10.1016/j.mtcomm.2017.11.007

factors for all sieves. In their approach, two methods for calculating the aggregate surface areas were discussed: the surface area factor and the surface area index. The analytical results of their study showed that the fine aggregate particles and aggregate shapes significantly affect the computation of surface area. The results of both field performance data from Minnesota Road (MnROAD) Test Track and rutting data from laboratory fabricated mixtures (with coarse and fine gradations) showed that the asphalt film thickness is a significant factor affecting the rutting performance for asphalt mixtures.

Panda et al. [6] presented a mathematical model to estimate the surface area of aggregate blends of Hot-Mix Asphalt (HMA) from physical properties of aggregate evaluated using simple laboratory equipment. The motivation behind their study was the presumption that the conventional method that is currently used for calculating the asphalt film thickness is purely manual, labor intensive, and prone to human errors, and the imaging techniques still have limited use due to capital intensiveness requirement of well-established laboratories and qualified technicians. The developed empirical method was compared with the existing established methods of calculations and it was concluded that this method has the potential to be used as one of the tools for proper design of HMA.

Wang [7] studied the effect of the asphalt film thickness on aggregate contact behavior. To understand the micromechanical behavior of asphalt mixture, contact modeling of asphalt mixture was reviewed and numerical tools were introduced. The displacement and resistant force of a system of particles bonded by a thin asphalt binder layer were measured using x-ray tomography system. These measurements were compared with the theoretical solutions of a normal compliance model for a similar system. It was shown from the study that a reasonable agreement between experimental results and model-predicted results was obtained.

Durability is considered a crucial property for asphalt mixtures, which has been shown in the literature to be directly related to the performance of mixture. Serval researchers investigated the effect of asphalt film thickness on the performance and behavior of asphalt mixtures. Kandhal and Chakraborty, [8] studied the effect of film thickness on short- and long-term aging of asphalt mixtures. It was found that at an asphalt film thickness of less than 9–10 μm when the air voids are 8 percent for compacted asphalt mixtures, a significant and fast aging occurs. Kandhal et al. [9] in the review they conducted about the Superpave VMA requirement indicated that the film thickness approach represents a proper method to ensure asphalt mix durability. Sebaaly et al. [10] compared performance results of asphalt mixtures with gradation ARZ, BRZ, and TRZ and used field test sections, which were monitored for 5 years after construction. They found in their study that TRZ mixtures performed better than coarse-graded mixtures (generally BRZ) and that TRZ mixtures experienced higher stiffness than BRZ mixtures. Attia et al. [2] also evaluated the asphalt film thickness and VMA as mixture design parameters through field performance of Superpave mixtures. It was found in the study that the method used to calculate the film thickness plays a role in explaining specific field performance distresses such as rutting and bleeding. Sengoz and Topal [11] reported that the optimum film thickness is 9-10 μm based on the relationship between the film thickness and some performance indicators such as resilient modulus and indirect tensile strength of short- and long-term aged mixtures.

Studies such as Al-Khateeb [1] that investigated the (VMA) criteria used in the Superpave, have concluded that the criteria are inadequate and emphasized the need to revise the criteria. The criteria do not ensure enough asphalt film thickness in the mixture for some mixtures passing the criteria and on other hand, show adequate film thickness for other mixtures, particularly for coarse mixtures, failing the criteria.

Hence, the measurement and/or estimation of the asphalt film thickness in asphalt mixtures is a topic of importance that needs attention. In this study, an asphalt film thickness model is developed and presented based on key parameters of aggregate gradations and asphalt binder content, and without the use of any mixture-related property.

2. Objective

The main objective of this study is to develop a mixture-property-independent model for asphalt film thickness based on aggregate gradation parameters and asphalt binder content through physics-based statistical regression analysis using data collected on the asphalt film thickness for a variety of asphalt mixtures.

3. Theoretical basis for the development of asphalt film thickness model

The essence of the development of the asphalt film thickness model is dependent on understanding the physics of what is involved and this is outlined below. The effective asphalt binder is defined as that part of asphalt filling the voids between the aggregate particles in the asphalt mixture. It is composed of the asphalt film coating the aggregate particles in the compacted asphalt mixture. It is considered a critical volume phase in the asphalt mixture that (if adequate) ensures durability and impacts aging.

The asphalt film thickness (FT_b) is defined simply as the volume of the effective asphalt binder phase (V_{be}) divided by the total surface area of the aggregate (SA_{Total}) that is coated by asphalt. Thus,

$$FT_b = \frac{V_{be}}{SA_{Total}} \tag{1}$$

The total surface area of the aggregate in the mixture is calculated as:

$$SA_{Total} = 10 \times SA \times W_s \tag{2}$$

where SA_{Total} is total surface area of aggregate (cm^2), 10 is conversion factor that converts m^2/kg into cm^2/g, W_s is weight of aggregate (g), and SA is the surface area factor (m^2/kg) defined as:

$$SA = \frac{1}{100}\sum SAF_i \times P_i \tag{3}$$

where SAF_i is surface area factor on sieve i, and P_i is percentage of aggregate passing sieve i. Thus,

$$SA_{Total} = \frac{1}{10}W_s\sum SAF_i \times P_i \tag{4}$$

The volume of the effective binder phase can be written as

$$V_{be} = \frac{P_{be}W_T}{G_b\gamma_w} \tag{5}$$

where P_{be} is the effective asphalt binder content, W_T is total weight of mixture, G_b is the specific gravity of the binder, γ_w is the density of water.

Using Eq. (4) and (5) and knowing that $\gamma_w = 1\ \text{g/cm}^3$, the asphalt film thickness (FT_b), equation (1) is formulated as shown below after rearrangement:

$$FT_b = \frac{\left(\frac{P_{be}}{G_b}\right)}{\frac{1}{10}\left(\frac{W_s}{W_T}\right)\sum SAF_i \times P_i} \tag{6}$$

The model so far has been derived fundamentally, purely on the basis of the physics. A few approximations and regression coefficients are now introduced to make it amenable for developing a material-property-independent model.

Using the fact that $\frac{W_s}{W_T} = \frac{P_s}{100} \approx \frac{100 - P_b}{100}$, and introducing regression coefficients to adjust for G_b and ΣSAF_i the above Eq. (6) is rewritten as

Mixture-Property-Dependent Model: