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Determination of voids in the mineral aggregate and aggregate skeleton characteristics of asphalt mixtures using a linear-mixture packing model

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HIGHLIGHTS

- A modified linear-mixture packing model to estimate VMA was proposed.
- A high correlation between estimated and laboratory VMA was found.
- A new aggregate structure definition was introduced.
- Rutting in asphalt mixtures was correlated to the proposed aggregate structure.

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ABSTRACT

Voids in the mineral aggregate (VMA), as a main design parameter in the Superpave mixture design method, is an important factor to ensure asphalt mixture durability and rutting performance. Moreover, an asphalt mixture's aggregate skeleton, related to VMA, is another important factor that affects critical asphalt mixture properties such as durability, workability, permeability, rutting, and cracking resistance. The main objectives of this research are to propose an analytical approach for estimating changes in VMA due to gradation variation and determining the relevant aggregate skeleton characteristics of asphalt mixtures using the linear-mixture packing model, an analytical packing model that considers the mechanisms of particle packing, filling and occupation. Application of the linear-mixture packing model to estimate the VMA of asphalt mixtures shows there is a high correlation between laboratory measured and model estimated values. Additionally, the model defines a new variable, the central particle size of asphalt mixtures that characterizes an asphalt mixture's aggregate skeleton. Finally, the proposed analytical model shows a significant potential to be used in the early stages of asphalt mixture design to determine the effect of aggregate gradation changes on VMA and to predict mixture rutting performance.

1. Introduction

Asphalt mixtures are typically thought to be heterogeneous materials consisting of aggregates, asphalt binder, and air voids. The majority of a dense-graded asphalt mixture is the aggregates (approximately 85% by volume) and as such, the load bearing capacity of an asphalt mixture is strongly related to its aggregate skeleton. Besides the physical and mechanical properties of the asphalt binder, the aggregate related parameters such as shape, texture, chemical properties, and gradation affect the volumetric properties and subsequently, the performance of asphalt mixtures. At high pavement temperatures, the role of the aggregate skeleton on rutting performance can be even more prominent, since at such temperatures the asphalt binder becomes less viscous. Therefore, designing asphalt mixtures with effective aggregate skeletons is especially crucial to rutting performance at high mixture temperatures.

Over the years, much research has been conducted on the effect of aggregate skeleton on asphalt mixture performance [3,13,5,2]. In [22] showed the significant role of aggregate in an asphalt mixture, pointing out that aggregate structure and aggregate characteristics, such as gradation, shape, and coarse aggregate surface texture are main factors influencing the development of the aggregate skeleton. Dukatz [9] concluded that asphalt mixture rutting resistance is highly dependent on aggregate gradation and that mixtures produced with the best possible materials can show poor rutting resistance without an appropriate aggregate gradation. The effect of aggregate gradation on the asphalt mixture properties was also evaluated by Elliott et al. [10] who concluded that changing the

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List of Acronyms

Acronym	Description
CCPS	Coarse controlling particle size, mm
CN	Coordination number
CPD	Coarse packing density
CPS	Controlling particle size
CUW	Chosen unit weight, kg/m^3
DF	Disruptive factor
FCPS	Fine controlling particle size, mm
FPD	Fine packing density
LUMR	Large un-mixing range
LUW	Loose unit weight, kg/m^3
MPSR	Main particle size range
NMAS	Nominal maximum aggregate size
PCS	Primary control sieve
RRSB	Rosin-Raimmer-Sperling-Bennett function
RSCH	Repeated shear constant height
RUW	Rodded unit weight, kg/m^3
SGC	Superpave gyratory compactor
SUMR	Small un-mixing range
VMA	Void in mineral aggregate

gradation curve shape has a substantial effect on the mechanical and volumetric properties of asphalt mixtures.

Haddock et al. [16] also evaluated the impact of aggregate gradation on asphalt mixture performance. They used two mixture types having nominal maximum aggregate sizes (NMAS) of 9.5 and 19.0 mm to evaluate the sensitivity of asphalt mixture performance to gradation changes. For each mixture type, three aggregate gradations (above, through, and below the Superpave restricted zone) were designed. Triaxial tests, accelerated pavement tests, and laboratory wheel tracking tests were used to gauge mixture response. Results of the study indicated that mixtures with gradations above the restricted zone (fine-graded) had the best rutting resistance in both the accelerated pavement tests and the laboratory wheel tests. Additionally, the fine-graded mixtures displayed higher strength, based on the triaxial compression testing results.

In addition to experimental approaches, the effect of particle size distribution on the packing behavior of mixtures has been studied by two other approaches, numerical and analytical analyses [4,17]. Discrete element modeling (DEM) is perhaps the best-known numerical approach [17,28,25,24]. However, this method has some limitations. First, the full range of particles cannot be considered, especially when there is a large difference between the maximum and minimum particle sizes [6]. Secondly, DEM requires large amounts of computational time, and the time requirement increases with increasing number of particle sizes. Alternatively, the analytical approaches are able to cover the full range of particle sizes with negligible computational time, though they are usually based on basic packing concepts and need to be calibrated by experimental works. Due to the ability to cover the full particle size distribution and the need for less computer time, the analytical approach was chosen for this study.

A conceptual and analytical approach to the effects of asphalt mixture gradation on asphalt mixture performance has also been studied by Roque et al. [27] who proposed an analytical model to evaluate the coarse aggregate structure of asphalt mixtures based on the basic principles of particle packing. Their work determined the main aggregate size range of the aggregate structure in an asphalt mixture and related the quality of this structure to asphalt mixture performance. The researchers named the main aggregate size range the dominant aggregate size range (DASR) and suggested that to keep the DASR particles in contact with each other, the DASR porosity should not exceed 48 percent. Evaluation of their proposed model using an extensive range of asphalt mixtures indicated the model could identify asphalt mixture gradations that resulted in asphalt mixtures with poor rutting performance.

Guarin et al. [15] used the concept of DASR to evaluate the effects of binder content changes, aggregate smaller than the DASR, and air voids content on asphalt mixture performance, both (rutting and cracking). In the study, aggregates smaller than the DASR were referred to as the interstitial component (IC) and a new parameter, the disruption factor, was introduced to measure the disruptive effect of the IC particles on the DASR particle structure. Additionally, in Lira et al. [21] presented a framework to recognize the range of aggregate sizes which form the load carrying structure in asphalt mixtures and determine its quality. The porosity and coordination number were considered as two parameters to evaluate the quality of the load carrying structure and relate it to mixture rutting resistance. In this framework, the gradations were considered as discrete particle sizes having a size ratio of 2 to 1 between contiguous sieve sizes. Results of this study were fairly consistent with experimental rutting performance data.

Voids in mineral aggregate (VMA) is an important volumetric parameter in asphalt mixture design that, when used properly, can reduce the risk of designing poorly-performing mixtures. A great deal of research has shown that asphalt mixture gradation and properties such as the NMAS, aggregate surface texture, and aggregate shape are factors that significantly influence asphalt mixture VMA [23,8,1,26,7]. Like many asphalt mixture design methods, the Superpave mixture design methods recommends a minimum VMA requirement dependent on the size of the aggregate particles used in the mixture. The importance of VMA to asphalt mixture performance means that asphalt mixture designers expend a great deal of time and effort to select the best aggregate gradation that meets the target mixture VMA. Currently, the common approach to do so is a trial and error procedure, sometimes based on empirical predictive equations, but almost always requiring a good deal of experimental testing. Although some experimental methods, such as the Bailey method, can reduce the experimental testing necessary to determine the proper aggregate gradation for an asphalt mixture, development of an analytical procedure to predict asphalt mixture VMA based on the mixture gradation would allow asphalt mixture designers to more quickly and accurately design mixtures that meet their respective VMA requirements.

1.1. Objectives

Existing analytical models to evaluate the impact of gradation change on VMA and rutting performance of asphalt mixtures can help mixture designers better predict the optimum asphalt mixture gradation in the early stage of mixture design and thereby reduce the cost and time of completing a mixture design. The objectives of this investigation were to propose and develop an analytical framework for estimating VMA and determining the aggregate skeleton characteristics of asphalt mixtures using a linear-mixture packing model. The proposed model uses aggregate gradation characteristics as input and relates the aggregate skeleton characteristics to asphalt mixture rutting performance. While many factors can affect asphalt mixture VMA and rutting