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Effect of low VMA in hot mix asphalt on load-related cracking resistance

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HIGHLIGHTS

- Load-related cracking resistance was evaluated for HMA mixes with low VMA.
- Three approaches were used: DCSE, |E*|sin φ, and M-E PDG cracking models.
- Results indicated that reduction in VMA leads to increase in cracking potential.
- Low VMA asphalt mixes can be utilized in pavements with low traffic volumes.

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ABSTRACT

Voids in mineral aggregate (VMA) is an important parameter in hot mix asphalt (HMA) mix design. It is believed that a minimum VMA requirement is necessary to ensure adequate binder content and durability for HMA. This paper investigates the effect of lower than typically acceptable VMA on the load-related cracking resistance of four dense-graded asphalt mixes. The mixes were prepared with three aggregate types: limestone, sandstone, and granite. Three different approaches were used to evaluate the cracking resistance of the mixes: the dissipated creep strain energy (DCSE), the fatigue parameter (|E*|sin φ), and the mechanistic-empirical pavement design guide (M-E PDG) cracking models. The indirect resilient modulus (M_r), indirect tensile strength (ITS), and dynamic modulus (E*) tests were performed on the mixes. Finite element analysis was used together with the M-E PDG cracking models to predict the expected longitudinal and alligator cracking performance of the mixes when used in a typical pavement structure. Both DCSE and (|E*| sin φ) results showed that lower VMA decreases the cracking resistance of the mixes. DCSE parameter decreased by 50%, while |E*| sin φ increased by 12%, for a 3.8% reduction in VMA. The analysis results of M-E PDG cracking models were consistent with the experimental findings. The predicted longitudinal cracking increased by 73%, while the alligator cracking increased by 24% for the same reduction in VMA.

1. Introduction

Hot mix asphalt (HMA) is considered a key road paving material worldwide. The mix design process for HMA aims at striking a balance between constituent materials in the mix that will result in a satisfactory mix performance. Many highway agencies developed specific requirements that need to be met for the mixes to be acceptable. The voids in the mineral aggregate (VMA) is one example of such requirements. VMA is defined as the intergranular void space in a compacted asphalt mix. It is the volume of air voids and the volume of effective asphalt. A durable mix requires an adequate film thickness. VMA, when combined with the air voids, provides an indirect way to specify the asphalt film thickness, which is related to mix durability. In general, the volumetric criteria used to assess the quality of asphalt mixes such as VMA are a result of accumulated experience with the performance of certain type of mixes, or in some cases are set with the aid of some laboratory-based research studies. The decision whether to accept or reject a mix is generally made based on those criteria without a further validation of their expected performance using fundamental testing. Such practice could lead to rejecting potentially good mixes only because they do not meet the minimum VMA requirement.

The difficulty in satisfying the VMA requirement has been a topic of discussion by many researchers [1–3]. Anderson and Bahia [3] concluded that coarse-graded asphalt mixes with high VMA could actually have poor performance. On the other hand, fine asphalt mixes are less sensitive to the variation in VMA levels. Another subject of debate related to VMA parameter is the fact that

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some specifications relate the VMA minimum requirement to the nominal maximum aggregate size (NMAS) of the mix. An example of such specifications is the Superpave mix design method. Studies [4,5] showed that VMA requirement based on nominal maximum aggregate size (NMAS), as in the Superpave mix design method, does not take into account the overall gradation of the mix, the effect of asphalt film thickness and therefore, could prove inadequate for distinguishing mixes in terms of performance. Therefore, higher VMA mixes cannot guarantee better mixes that are durable, fatigue and rut resistant compared with the ones with lower VMA.

Roque et al. [6] criticized the Superpave level I mix design specification of VMA as a function of NMAS. They emphasized that mixture volumetric properties are related to the gradation of aggregates in the mix. A coarse mix must have different volumetric criteria than a fine mix as well as dense and gap-graded mixes of the same NMAS. This is due to the fact that the density and consequently the air voids in the same mass of mix for different gradations will be different. Therefore, air voids available for asphalt binder will also differ from mix to mix which leads to the variation of VMA and other volumetric properties. They concluded that using the same VMA criteria for all mixes with the same NMAS is probably inappropriate.

Nukunya et al. [7] studied fine and coarse-graded mixtures that were produced at multiple VMA levels by varying the gradations and proportions for a common set of aggregates and asphalt cement. Some mixtures were purposely designed to not meet the VMA requirements, while meeting all other Superpave requirements. Binder was extracted and recovered for testing. Several mechanical tests were performed on the designed mixtures such as resilient modulus, creep compliance and m-value, and tensile strength tests (strength, failure strain, and fracture energy density) after short and long-term oven aging, to evaluate the durability and fracture resistance of the mixtures. The research reported that the rate of binder hardening was not related to VMA, and that low VMA did not result in durability or cracking problems in fine-graded mixtures. Low VMA was not related to fracture resistance or rutting for coarse-graded mixtures. Therefore, the relevance of Superpave VMA criterion must be seriously questioned in their opinion. The researchers, however, emphasized that although the study provided some insight into the effects of changes in volumetrics on specific mix properties, much work remains to be done in this area.

The dissipated creep strain energy (DCSE) is estimated from the resilient modulus (M_r) and the indirect tensile strength (ITS) tests. This parameter represents the maximum energy the mix can sustain before fracturing. An asphalt mix with higher DCSE value should have a better cracking resistance than a mix with lower DCSE value under similar loading and environmental conditions. Roque et al. [8] examined a number of asphalt mixes from actual pavement sections that have been in service for more than 10 years in Florida. They found that thick pavement structures had a top-down cracking problem when the DCSE of the surface course mix was below approximately 0.75 kJ/m^3 at 10 °C. Wang et al. [9] presented the implementation of the Florida top-down (longitudinal) cracking model into the M-E PDG flexible pavement design framework. The work of the model was based on energy ratio which is a function of the DCSE.

The dynamic modulus $|E^*|$ of HMA is a key input parameter in the Mechanistic Empirical Pavement Design Guide (M-E PDG), developed under NCHRP Project 1-37A [10] and published by AASHTO [11]. One of the parameters that is calculated from the dynamic modulus test that is correlated with the cracking resistance of asphalt mixes is the fatigue parameter $|E^*|\sin\phi$. The lower this parameter is, the better the obtained fatigue resistance [12]. M-E PDG developed models to predict the load associated cracking (alligator cracking and longitudinal cracking) using the dynamic modulus $|E^*|$ of HMA.

The main objective of this study was to evaluate the effect of low VMA in dense HMA mixes on the relative resistance to load-associated cracking. Four asphalt concrete mixes with three types of aggregates were examined. Indirect resilient modulus, indirect tensile strength, and dynamic modulus ($|E^*|$) tests were used to characterize the mixes. Three different methods were used to evaluate the fatigue resistance of the mixes: the dissipated creep strain energy (DCSE), the fatigue parameter ($|E^*|\sin\ \varphi$), and the mechanistic-empirical pavement design guide (M-E PDG) cracking models.

2. Materials

Limestone, Granite, and sandstone aggregates were used in this study. All the individual stockpiles used in the study for the different types of aggregate met the Superpave consensus properties requirement for design equivalent single axle load (ESALs) ≥ 30 millions. For the coarse aggregate, the fractured faces according to ASTM D5821 [13] were 100%, for one and two or more fractured faces, with no flat and elongated particles according to ASTM D4791 [14]. The fine aggregate angularity (AASHTO T 304 [15]) ranged from 45.1% to 47.8%, while the sand equivalent (AASHTO T176 [16]) value ranged from 51.6% to 100%. Styrene-butadiene (SB) polymer-modified asphalt binders for high-volume traffic mixtures (ESALs ⩾ 30 millions) meeting the requirements of PG 76-22 according to AASHTO M320 [17] was used. Table 1 shows the binder properties.

3. Asphalt concrete mix design

Four mixes having an aggregate NMAS of 12.5 mm were designed according to Supeprave mix design method. Two of the four mixes used limestone with fine and coarse gradations. Fig. 1

Table 1
Performance graded binder properties.

Parameter	Requirement	Test Results
Rotational viscosity 135 °C, Pa s	3.0 max	1.68
Dynamic shear, 10 rad/s $G^*/\sin\delta$, kPa	1.00 min	1.29 at 76 °C
Flash point °C	232 min	305
Solubility %	99.0 min	99.5
Force ductility ratio (F2/F1), 4 °C, 5 cm/min, F2 @ 30 cm elongation	0.30 min	0.49
Short Term Aged Binder (RTFO)		
Mass loss%	1.00 max	0.08
Dynamic shear, 10 rad/s $G^*/\sin\delta$, kPa	2.20 min	2.84 @76 °C
Elastic recovery, 25 °C, 10 cm elongation %	60 min	70
Long Term Aged Binder (PAV)		
Dynamic shear, 10 rad/s, $G^*\sin\delta$, kPa	5000 max	2297 at 25 °C
Bending beam creep stiffness, S, MPa	300 max	195 at −12 °C
Bending beam creep slope, m-value at 60 s	0.300 min	0.327 at −12 °C