



Principle analysis of mix design and performance evaluation on Superpave mixture modified with Buton rock asphalt

Shutang Liu^a, Weidong Cao^{a,*}, Xiaojun Li^b, Zhuozhi Li^a, Chunyang Sun^a

^a School of Civil Engineering, Shandong University, No. 17923 Jingshi Road, Jinan, Shandong Province 250061, PR China

^b Dept. of Civil & Geomatics Engineering, California State University, Fresno, 2320 E. San Ramon Ave., M/S EE94, Fresno, CA 93740-8030, United States

HIGHLIGHTS

- Two equations of Superpave system were analyzed and new equations were established.
- Gradation of Superpave mixture modified with BRA was analyzed and designed.
- Performances of Superpave mixture modified with BRA were evaluated.

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ABSTRACT

The main objectives of this study are to conduct principle analysis of mix design and evaluate the performance of the Buton rock asphalt (BRA) modified Superpave mixture through wheel tracking test, freeze-thaw indirect tensile strength ratio test, bending beam test, dynamic modulus test, and flow number (FN) test. The results prove that the voids in mineral aggregate (VMA) and the initial asphalt content calculated using the new equations proposed by this study based on theoretical analysis are more accurate than those of the traditional Superpave's empirical equations. The high temperature performance and the moisture damage resistance of the Superpave mixture modified with BRA were improved, but the low temperature performance was slightly declined comparing with the control mixture. The values of $E^*/\sin\phi$ from dynamic modulus test of the BRA modified Superpave mixture were larger than those of the control mixture at various test temperatures and loading frequencies. In conclusion, the Superpave mixture modified by BRA has excellent high temperature performance.

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1. Introduction

The design of aggregate gradation and the determination of optimum asphalt content are the two core elements in the mix design of hot mix asphalt mixture (HMA). The mix proportion design, especially the gradation design, has been studied for a long time. The grain size distribution or gradation has been identified as one of the main factors that influence the accumulation of permanent strain and deformation [1]. Amir Gholipour et al. [2] reported that the aggregate gradation has a critical role in the rutting resistance due to the fact that aggregate structure is the main load carrying component of mixtures. Dukatz [3] also concluded that the rut resistance is “highly dependent upon aggregate grading” and that mixes made with the best possible materials will fail without a proper gradation. The test results from Xiao [4] indicated that

aggregate gradation affected the moisture susceptibility and rutting resistance of open graded friction course (OGFC) mixtures. Other studies [5–7] indicated that the performance of HMA mixture and eventually the HMA layer in asphalt pavement are directly affected by aggregate characteristics, particularly, aggregate gradation, shape, angularity, and surface texture. Shen et al. [8] indicated that aggregate gradation and properties had great impact on the strength, stability, and fatigue performance of the HMA mixtures. In order to improve the performance, durability, safety, and efficiency of asphalt mixtures, the Strategic Highway Research Program (SHRP), established in 1987, proposed the Superpave system in 1993. The Superpave system made significant advancements in the asphalt binder classification and asphalt mixture design [9] and was adopted worldwide. According to China's asphalt pavement specification, Marshall experiment design method, which was impacted by Superpave system, is currently used in China. Regardless of the Marshall Method or the Superpave system, the mix design is mainly based on the analysis of volumetric indexes including V_a (the volume of air voids) and VMA (voids

* Corresponding author.

E-mail address: cwd2001@sdu.edu.cn (W. Cao).

in the mineral aggregate). The two volumetric indexes play a critical role in the design process of aggregate gradation. In the Superpave system, the aggregate gradation is determined based on the value of VMA with 4% V_a in total mix at the design number of gyrations (N_{design}), and the volumetric properties at the initial and maximum number of gyrations (N_{ini} and N_{max}). However, the initial asphalt content and the adjusted VMA at 4% V_a are determined by empirical equations in Superpave mix design procedure.

Buton rock asphalt (BRA) is a type of natural asphalt found in Buton Island of the South Pacific Indonesia. After a long-term environmental action, the components and material properties of BRA are relatively stable [10]. BRA has gained a wide attention due to its high asphalt binder content, low cost, and convenience of use in practice [11]. Previous studies have shown the field performance of asphalt mixtures modified by BRA and its mechanism. Based on experimental study of asphalt mixtures modified by BRA, Liu et al. [12] showed that the asphalt in BRA could dramatically improve the high temperature performance of the mixtures, while the low temperature performance was reduced. Asphalt mixture modified with BRA was reported to have better fatigue resistance than SBS modified asphalt mixture by Li et al. [13,14]. They explained that the chemical structure of BRA is similar to that of asphalt binder and therefore the compatibility of asphalt binder and BRA is better than that of asphalt binder and SBS. Suaryana [15] investigated the performance of stone matrix asphalt (SMA) using BRA as stabilizer. The results indicated that BRA could prevent asphalt draindown as well as increase the proportion of mineral filler. The addition of BRA could also improve the performance of the SMA, indicated by increased dynamic stability. Although studies showed promising results on the performance of asphalt mixtures with BRA modification, there are few researches regarding its effects on the performance of Superpave mixture. The main objectives of this study are to conduct principle analysis of mix design and evaluate the performance of Superpave mixture modified with BRA.

2. Design principle analysis of Superpave mix

The design principle and method of Superpave system have been widely accepted. In Superpave system, Eqs. (1) and (2) are used to calculate the asphalt content and the VMA corresponding to 4% V_a [16].

$$P_{\text{pre}} = P_b - 0.4 * (4 - V_a) \quad (1)$$

where P_b is initial asphalt content; V_a is air voids of the compacted asphalt mixture at P_b ; P_{pre} is the predicted asphalt content when V_a is 4%.

$$VMA_{\text{pre}} = VMA_{\text{ini}} + C * (4 - V_a) \quad (2)$$

where VMA_{ini} is VMA of compacted asphalt mixture at the initial asphalt content; $C = 0.1$, when $V_a < 4\%$; $C = 0.2$, when $V_a > 4\%$; VMA_{pre} is the predicted VMA when V_a is 4%.

There are four steps to determine the initial asphalt content: 1) the determination of the effective relative density of mineral aggregate; 2) the estimation of asphalt volume absorbed by aggregates; 3) the calculation of effective asphalt volume; and 4) the calculation of initial asphalt content. The first three steps are based on empirical equations. To solve the obvious empirical problems of determining the initial asphalt content, a new Eq. (3) by mathematical deduction was established according to the calculation equations for V_a and VMA, which could be used to determine the initial asphalt content for a given aggregate gradation [17]. As a consequence, the characteristics of Eq. (3) are more theoretical and less empirical.

$$P_a = \left(\frac{100 - V_a}{100 - VMA} \cdot \frac{1}{\gamma_{\text{sb}}} - \frac{1}{\gamma_{\text{se}}} \right) \cdot \gamma_a \times 100 \quad (3)$$

where P_a is the asphalt-aggregate ratio, %; V_a is the air void (%); VMA is the voids in mineral aggregate (%); γ_{se} is the effective specific gravity of aggregate; γ_{sb} is the bulk specific gravity of aggregate; γ_a is the specific gravity of asphalt binder.

Eq. (3) reveals the precise physical relationship among P_a , V_a , VMA, specific gravities of aggregate (γ_{se} and γ_{sb}), and specific gravity of asphalt binder (γ_a) for a given aggregate gradation.

Eqs. (1) and (2) are two critical empirical equations in Superpave system, which can be employed to predict the asphalt content and VMA at V_a of 4%. Therefore, it is of importance to evaluate the reliability and accuracy of Eqs. (1) and (2). Based on other study of the authors [17], Eq. (1) has reasonable reliability and accuracy. But Eq. (2) is redundant and can be replaced by Eq. (4), which is actually obtained from the transformation of Eq. (3) [17].

$$VMA = 100 - \frac{100 - V_a}{\gamma_{\text{sb}} \left(\frac{1}{\gamma_{\text{se}}} + \frac{P_a}{\gamma_a} \right)} \quad (4)$$

Eq. (4) reveals the physical relationship among the P_a , V_a , and VMA for a given compacted asphalt mixture specimen. If any two of these variables are known, the third variable can be calculated through Eq. (4). Notice that when V_a is 4%, the asphalt content (which may be converted into asphalt-aggregate ratio) can be determined according to Eq. (1). Therefore, the VMA value at V_a of 4% could be calculated solely by Eq. (4).

Eqs. (3) and (4) are different expressions of the same equation established by mathematical derivation of the general calculation equations of V_a and VMA, which are applicable for all asphalt mixtures. However, when Eqs. (3) and (4) are used to predict VMA value, they are only valid within specific ranges, namely, the bulk specific gravity of aggregate is within 2.600–2.800 and the VMA of a compacted asphalt mixture specimen is within 10–17%.

3. Material and mix design

3.1. Materials

3.1.1. Aggregates

Crushed stones of limestone were used as coarse and fine aggregates. In order to reduce test errors, the aggregates were sieved into each particles size group following China Standard T0302-2005 [18]: six particle size groups of coarse aggregates (26.5–31.5 mm, 19–26.5 mm, 16–19 mm, 13.2–16 mm, 9.5–13.2 mm, and 4.75–9.5 mm) and two particle size groups of fine aggregates (2.36–4.75 mm and 0.0–2.36 mm). Properties of aggregates are shown in Table 1, according to Chinese specifications [19].

3.1.2. Asphalt binder

An asphalt binder with penetration grading of 70 (Pen 70) from a commercial petroleum company was used in this study. Properties of Pen 70 asphalt binder are shown in Table 2. The results meet Chinese specifications for asphalt binders [19].

3.1.3. BRA

BRA used in this study was from a rock asphalt supplier. It is a black solid powder at room temperature, as shown in Fig. 1, containing about 25% asphalt and 75% mineral powder. The physical properties of BRA and the gradation of the rock mineral powder in BRA are shown in Tables 3 and 4, respectively.

3.2. Mix design

3.2.1. Trial gradation

When the grading design is carried out, based on the recommendation of the supplier, economic consideration, and field experience, the dosage of mineral powder in BRA was determined to be 2% by the total mass of mineral aggregates, which means that BRA was mixed with the rest of aggregates and limestone mineral filler in a proportion of 2.67:98. According to Superpave mix design procedure [20], three initial gradation curves of the nominal maximum-size of 26.5 mm were used as trial gradations, which located in the upper (gradation 1), the middle (gradation 2), and the lower (gradation 3) of the range of the control points, respectively, as shown in Fig. 2. For asphalt mixtures with the nominal maximum-size 26.5 mm, research showed that the VMA has the minimum value when the percent passing of 2.36 mm ($P_{2.36}$) is near 24–30% [21]. Gradation with such a $P_{2.36}$ is a skeleton-dense

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