Effect of spatial structure on rutting performance of asphalt mixture based on wheel tracking test

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Abstract. Rutting of asphalt pavement is one of major patterns premature damage modes experienced during the service period of pavement. Aggregate characteristics, especially aggregate gradation can affect the rutting performance of asphalt pavement. In order to investigate the influence of spatial structure on rutting performance, the volumetric indices such as VV, VMA and VCA were employed to characterize the spatial structure of asphalt mixture, and five different gradations of asphalt mixtures with three types of aggregate skeleton structure were prepared to conduct rutting measurement by wheel tracking test. It is demonstrated that aggregate particle size of 4.75-9.5mm can affect forming aggregate skeleton structure and rutting performance. Rutting depth at a certain period of time are concerned with VV and types of aggregate skeleton structure, and the VCA
ratio equal to one can be used as critical value to evaluate the types of aggregate skeleton structure. It is also indicated that fine aggregate can decrease the value of VMA and excellent stability in high-temperature of asphalt mixture should match suitable VMA. This study provides a significant reference for asphalt design and choice of aggregate gradation.

1. Introduction

Rutting shown the specific form of asphalt layer accumulated plastic deformation is regarded as one of most serious distresses of asphalt pavement in China [1]. Grasping the mechanism of asphalt pavement rutting is of profound significance to design the asphalt mixture with powerful rutting resistance and numerous researchers have been absorbed in reasonably evaluating the rutting resistance of asphalt mixture with various experimental tests like Hamburg rutting test, creep test and wheel tracking test [2]. The wheel tracking test with favorable operability has been regarded as the standard test method of estimation of asphalt mixture rutting in China [3].

A numerical simulation approach, discrete element method (DEM) and lab-based digital image processing (DIP) method have been used to analyze the mesoscopic rutting behavior of asphalt mixture with some indices such as displacement, contact (number of contact, contact length and contact orientation) as well as force and attempt to establish the correlation between internal structure and mechanical response [4-6]. Ma et al. reported that the good interlocking and sufficient contacts within aggregate skeleton were significant to improve rutting resistance of asphalt mixture, and the compressive force was mainly supported by the skeleton aggregate, however, the compressive and tensile force existed in asphalt mastic and between aggregate and asphalt mastic [4, 5]. Simultaneously, Roohi
Sefidmazgi et al. observed that the characterization of internal structure of two-dimensional sawn asphalt sample which included contact length and contact orientation were utilized to build a relationship between the internal structure and the rutting performance of asphalt mixture [6].

The volumetric parameters such as (percentage voids in the mineral aggregate) VMA (percentage voids in the coarse mineral aggregate) VCA and (percentage air voids) VV which are assumed as key indicators of asphalt mixture design have a major impact on pavement performance of asphalt mixture. Additionally, these parameters can reflect the aggregate skeleton well and affect spatial structure of asphalt mixture. Although extensive literature focused on the methods of rutting test, the correlation of rutting performance and mesoscopic structure, current state of investigation on the relationship between spatial structure and rutting performance of asphalt mixture is limited. Such investigation can lead to further understanding the relation between asphalt mixture type and spatial structure and provide a guideline for the application of asphalt mixture and the design of asphalt mixture. The objective of this study is to investigate the effect of spatial structure on rutting performance of asphalt mixture. Three different types of asphalt mixture are prepared to analyze the characteristics of aggregate structure with the spatial structure indices such as VMA, VCA and VV and conduct wheel tracking test.

2. Materials and laboratory test

2.1. Materials

SBS modified asphalt binder commonly used was selected to fabricate asphalt mixture sample and the properties can meet the requirement of Chinese specification [7]. Lignin fiber with content 0.3% and density 1.1g/cm³ was mingled with asphalt uniformly. To avoid the interference of aggregate property, all of the basalt aggregates had an identity source. Fig. 1 shows aggregate gradation of different asphalt mixtures with the same nominal maximum aggregate size of 13.2mm, and the C, M and F represent coarse, middle and fine, respectively. According to the given gradation, the optimum asphalt contents of various types of mixtures were determined using Marshall Test, as shown in Table 1.

![Figure 1. Aggregate gradation of asphalt mixtures.](image)

| Mixtures     | AC-13C | AC-13M | AC-13F | SMA-13 | OGFC-13 |
|--------------|--------|--------|--------|--------|---------|
| Asphalt content/% | 5.0    | 5.1    | 5.3    | 5.9    | 4.7     |

Table 1. Optimum asphalt content of mixtures.
2.2. Laboratory test

Based on the standard test methods [3], the wheel tracking test were conducted at wheel pressure of 0.7MPa and temperature of 60℃ to obtain the rutting deformation and dynamic stability of asphalt mixture. The prepared sample with length and width 300mm and height 50mm was selected to test by wheel rolling back and forth at the specified speed. The dynamic stability can be employed to evaluate the rutting performance of asphalt mixture and is determined as equation (1):

\[
\text{DS} = \frac{15N}{d_{60} - d_{45}} = \frac{15 \times 42}{d_{60} - d_{45}}
\]

(1)

Where, DS is the dynamic stability, N is the wheel load times per minute (42 times/min), and d45 and d60 are the rutting depths under wheel load at 45 and 60 min, respectively.

3. Results and discussion

3.1. Indices of spatial structure

In this study, three indices including VMA, VV and VCA which were recommend to characterize and estimate aggregate skeleton structure of asphalt mixture were briefly introduced as follows. VMA is a significant volumetric parameter to describe whether enough air voids are filled with asphalt mastic and can comprehensively reflect air voids percentage and thickness of asphalt film [7]. A reasonable VMA can guarantee the durability and high-temperature stability of asphalt pavement. VCA is widely used to judge whether the stone-stone contact structure is formed within asphalt mixture [8]. Meanwhile, the VCA can be divided into VCA\text{mix} and VCADRC based on the densification method and mix type. VCA\text{ratio} which is defined as divided VCA\text{mix} by VCADRC is employed to describe aggregate structure. According to the Chinese specification [3, 7].

For VMA, there is great fluctuation in sorts of asphalt mixtures due to the difference of aggregate skeleton structure. It indicates that the framework-gap structure is better than that of framework-dense structure, and the suspend-dense structure is worst. Although the differences between the VCADRC of different coarse mixtures are small, the differences of VCA\text{mix} are obvious in asphalt mixtures, other than SMA-13 and OGFC-13. According to the value of VCA\text{ratio}, it shows that the aggregate skeleton between SMA-13 and OGFC-13 is adjacent, and for the suspend-dense structure AC-13, its aggregate skeleton is increasingly weak with the fine aggregates increasing, as plotted in Fig. 1. Combination of the Fig. 1, it demonstrates that the aggregate particle size of 4.75-9.5mm has a great influence on forming the strong skeleton structure, which is consistent with the previous study [9].

3.2. Effect of spatial structure on rutting performance

Based on the wheel tracking test, the experiment results of five different asphalt mixtures were obtained, as shown in Fig. 2, and it indicates that the SMA has a better high-temperature stability and lower rutting depth than others. Based on the calculation of VCA\text{ratio}, the aggregate skeleton structure ranges in size order: OGFC-13<SMA-13<AC-13C<AC-13M<AC-13F, and for OGFC-13 and SMA-13, the percentage of aggregate size of 4.75-9.5mm are 43.17% and 44.88%, respectively, meanwhile, the magnitude of VCA\text{ratio} are 0.976 and 0.983, respectively. Although there are no obvious differences in VCA\text{ratio} and critical aggregate size of 4.75-9.5mm, the difference of rutting depth is notable since the asphalt mastic of SMA-13 has a powerful cohesive and adhesive strength. According to the theory of Mohr-Coulomb Intensity, the OGFC-13 has a low strength due to deficiency of bond strength of asphalt mixture.
As shown in Fig. 3, the dynamic stability increases with the VCAratio increasing except OGFC-13. On the contrary, the rutting depth of 60min decreases with the VCAratio increasing apart from SMA-13. Seemingly there is a contradiction between rutting depth and dynamic stability. In fact, due to the various asphalt mixtures with different designed VV, for the suspend-dense structure AC-13 and the framework-gap structure OGFC-13, the more VV is; the more rutting depth is. However, the framework-dense structure SMA-13 possesses the strong bond strength and powerful interlocking force, and it leads to the smallest rutting depth. Therefore, it shows that the value of rutting depth at a certain period of time is concerned with VV and aggregate skeleton structure. Moreover, the VCAratio equal to one can be defined as critical value to evaluate the aggregate skeleton structure.

As shown in Fig. 4, with the VMA increasing, the dynamic stability of asphalt mixture starts to increase, then reaches the peak value, and last decreases. According to the VMA, the asphalt mixture ranges in order size: OGFC-13>SMA-13>AC-13C>AC-13M>AC-13F, which is contrary to that of order in the light of VCAratio. Furthermore, the fine aggregate can result in decreasing the VMA and goes against forming strong aggregate skeleton structure. It indicates that excellent stability in high-temperature of asphalt mixture should match rational and reasonable VMA.
Figure 4. VMA vs. rutting depth (a) and dynamic stability (b) of asphalt mixtures.

4. Conclusion
The volumetric parameters including VV, VMA and VCA are used to describe spatial structure of asphalt mixture and investigate the spatial structure effect on rutting performance of five different asphalt mixtures by wheel tracking test. The following conclusions are drawn:

(1) The aggregate particle size of 4.75-9.5mm can affect forming the powerful skeleton structure and has a significant influence on rutting resistance.

(2) Rutting depth at a certain period of time is related to VV and aggregate skeleton structure, and the VCA ratio equal to one can be regarded as critical value to judge the aggregate skeleton structure.

(3) The fine aggregate can lead to decreasing the VMA and goes against forming strong aggregate skeleton structure, and excellent stability in high-temperature of asphalt mixture should match suitable VMA.

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