THE EFFECTS OF ANGULARITY OF COARSE AGGREGATES ON ASPHALT MIXTURE'S HIGH-TEMPERATURE PERFORMANCE AND COMPACTION PERFORMANCE

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ABSTRACT

High-temperature and compaction performance are related to service performances, safety and durability of asphalt pavement. Presently, the research on their influence factors focuses on the properties of asphalt, gradation composition, pavement structure and so on. However, the geometrical characteristics of coarse aggregate, especially its angularity, are ignored. This paper investigates the effects of angularity of coarse aggregate on the high temperature performance and compaction performance of asphalt mixtures. Three-dimensional angularity was proposed by X-ray Computed Tomography (XCT). The dynamic stability and rutting depth of different angular mixtures were tested by the rutting test. The changes of the height of the specimen with different angular asphalt mixtures during the compaction process were tested through the Superpave Gyratory Compactor (SGC). The dynamic modulus of the asphalt mixtures were tested and analyzed by the simple performance test (SPT) and the generation of master curves. The results show that three-dimensional angularity could characterize the angularity of the coarse aggregate. The angularity greatly influences high temperature performance and compaction performance of asphalt mixtures, and the higher the angularity, the better the high-temperature stability, while the more difficult compaction is. The angularity also has different effects on the dynamic modulus of different gradation asphalt mixtures. With the decrease of angularity, the dynamic modulus decreases and the changes' trend becomes smaller with the increase of the loading frequency. This study could provide support for further research and application of the macroscopic properties of asphalt mixtures.

Keywords: road engineering; coarse aggregate; angularity; high temperature performance; compaction performance

1 INTRODUCTION

Asphalt mixture is a multi-phase composite material; it is mainly composed of aggregate with a gradation and asphalt binder (Liu Y., 2011). The macroscopic performance including high-temperature performance and compaction performance of asphalt mixtures are a concrete manifestation of its mechanical behavior. Good macro performance is the guarantee of the actual performance of pavement and the ultimate goal of basic research. Since the aggregates make up a high volume (over 80%) and a high mass (about 95%) of the asphalt mixture, the macroscopic performances of asphalt mixtures are greatly influenced by the characteristics of aggregate particles, such as morphological characteristics, grain shapes and grain size (Browne C., 2011; Wang H., 2016).

Recently, there are a lot of studies on the macroscopic performances of asphalt mixtures and the characteristics of aggregates. Tan et al analyzed the influences of the surface texture, the angularity and the content of flat particles on the high-temperature performance of asphalt mixtures (Tan Y., 2009). Shu et al characterized the coarse aggregate properties through fractured surface counts, resilient modulus tests and direct shear (Shu X., 2006). Kane et al studied the relationship between the mineralogical composition of aggregates and the road performance after the polishing action of traffic (Kane M., 2013). It is worth mentioning that the polishing process of aggregates affects their morphological properties, which are related to the macroscopic properties of asphalt mixtures. Therefore, many research efforts on aggregates have been done in different aspects including laboratory measurements and imaging-based mathematical analysis (Masad E., 2011). Most of the image analysis systems were used to evaluate the changes in angularity and texture after the polishing process (Al-Rousan T., 2007; Chen J., 2001). The characteristics of the morphological parameters were determined by a two-dimensional analysis based on the aggregate imaging system (AIMS), at the same time, a three-dimensional (3D) parameter characterizing the shape of the aggregates was captured with the aid of X-ray Computed Tomography (XCT) (Zelelew H., 2013).

However, the research mentioned above was based on a two (or three) -dimensional scope, which means that the assessment of the characteristics of the coarse aggregate mainly depends on the orientation and it is not quantitative. Meanwhile, the effects of the angularity of coarse aggregate on high-temperature performance and compaction performance were rarely studied. Therefore, it is favorable to facilitate a more exact and reproduced method of measuring morphological properties of coarse aggregate. In addition, some conventional tests on asphalt mixtures were conducted to analyze the influences of angularity of the coarse aggregate on the macroscopic performances of asphalt mixtures.

2. OBJECTIVE OF THE STUDY

The specific objectives of this study are as follows:

(1) To propose the quantitative characterization method of angularity of coarse aggregate based on X-ray Computed Tomography (XCT).

(2) To investigate the effects of the angularity of coarse aggregate on the macroscopic performances of asphalt mixtures through rutting tests, the Superpave Gyratory Compactor (SGC) and simple performance tests (SPT).

The flowchart of research plans is shown in Fig. 1.

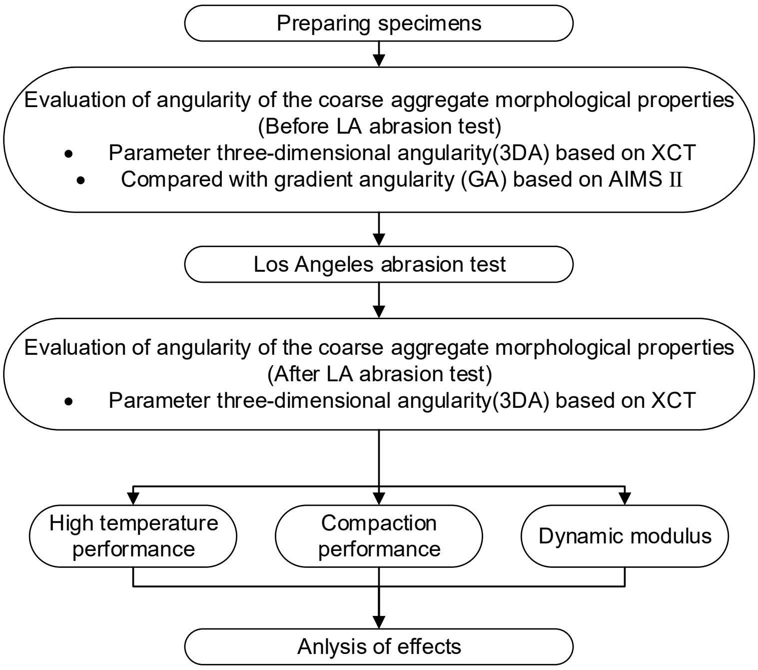


Fig. 1 Flowchart of research plans

3 MATERIALS AND METHODS

3.1 Materials

The coarse aggregate, fine aggregate and mineral filler used in this study was limestone, which was produced in Huxian County, Shaanxi Province, China. In order to better evaluate the effect of coarse aggregate angularity on the high-temperature performance of the mixture, a virgin asphalt binder SK-90# (the penetration grade is 90) was selected. The coarse aggregate with different angularity was obtained by changing the polishing times through the Los Angeles abrasive instrument. According to the existing research (Wang D, 2015), polishing times for the study of the coarse aggregate were set at 0 times, 100 times, 300 times and 1000 times.

3.2 The gradation of asphalt mixture and specimen preparation

3.2.1 The gradation of asphalt mixture and optimum asphalt content

Two commonly used gradation types of AC-16 and SMA-16 were selected in this study. The specific gradation composition is shown in Table 1.

Table 1 The specific gradation of asphalt mixture

Gradation types	Percentage passing（%）of the sieve（mm）listed below										
	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
AC-16	100	93	80	62	40	30	22	17.5	12.5	9.5	6
SMA-16	100	95	75	55	26	19.5	18	15	12.5	11.5	10

In this study, the coarse aggregate of 0 (no polishing) was used to determine the optimum asphalt content through the Marshall compaction method based on the *Technical Specification for Construction of Highway Asphalt Pavements (JTG F40-2004),* the optimum asphalt content of the AC-16 mixture and the SMA-16 mixture were determined to be 4.1% and 5.5%, respectively.

3.2.2 Specimen preparation and test programs

The rutting test was conducted according to the *Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011)*. The test wheel tire pressure was 0.7 MPa, and the test temperature was 60 °C. The rutting slab samples were prepared through the rolling method, the size was 300mm×300mm×50mm, and they were formed with different aggregates of different sizes after polishing 0 times, 100 times, 300 times and 1000 times.

The Superpave Gyratory Compactor (SGC) was used to study the compaction performance of asphalt mixtures. The diameter of the AC-16 and SMA-16 asphalt mixture specimens was 150 mm. The compaction angle during rotary compaction was 1.25°, the speed was 30 r/min, and the compaction strength was 600 kPa. In the compaction process, the height of the specimen was recorded in real time. The specimens were controlled with 4% air void content during formation.

The rotary compaction specimen for the dynamic modulus test with a diameter of 100 mm were drilled from the formed SGC specimen. The dynamic modulus of asphalt mixtures at two temperatures (35 ℃, 50 ℃) and six frequencies (0.1Hz, 0.5Hz, 1Hz, 5Hz, 10Hz and 25Hz) were measured by the simple performance test (SPT).

3.3 Quantitative evaluation method of three-dimensional morphological characteristics for coarse aggregate

X-ray Computed Tomography (XCT) was selected to evaluate the morphological characteristics of coarse aggregate on a three-dimensional (3D) scope (Wang H., 2017). The X-ray CT equipment utilized in this study was the YXLON-industrial 225 kV, as shown in Fig. 2. The resolution of this imaging system for the X-ray scan of the aggregates exhibits an accuracy of 60 μm. It utilizes X-rays to scan the material and generates a mass of different three-dimensional layers with 0.1 mm increments between each layer and three perspectives of images: top, side, and front view. Additionally, for scanning more than one sample simultaneously, a new type of cubical box with four layers (see Fig. 2) was designed to contain the aggregates. Pictures from different views were obtained by XCT, as shown in Fig. 3. The characteristics of the aggregates before and after polishing can be vividly observed and evaluated through these pictures.

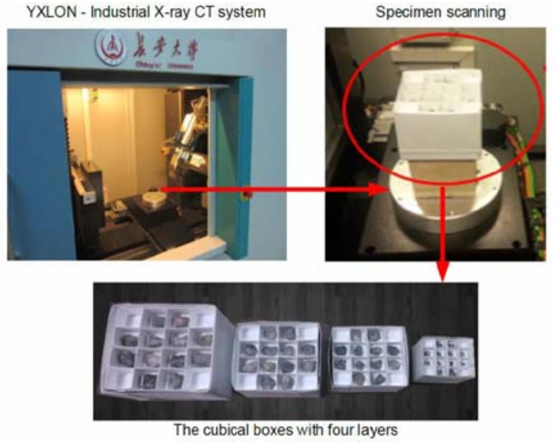


Fig. 2 X-ray CT system and cubical boxes

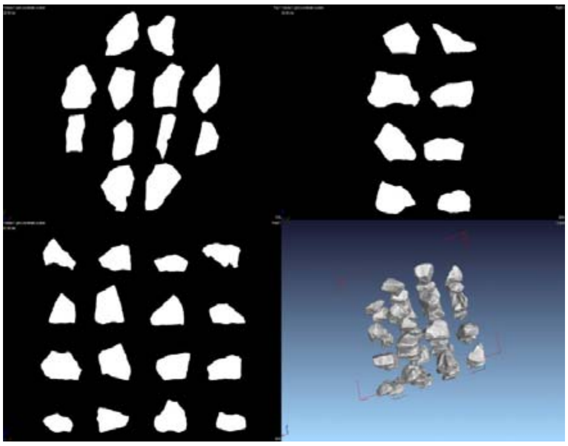


Fig. 3 three-dimensional characterization

During the polishing process, the X-ray computed tomography tests were conducted to evaluate the angularity evolution at a polishing process of 0, 100, 300 and 1000 times. Various parameters including the circumference, volume, and surface area of aggregates can be measured and determined by volume-analysis with the application of VG Studio MAX 2.0. Finally, the results can be represented as three-dimensional angularity (3DA), as Equation (1).

$$3DA = \frac{1}{3}\left(\frac{\sum_{i=1}^{n_t} \frac{P_{ti} \cdot A_{ti}}{P_{te}}}{\sum_{i=1}^{n_t} A_{ti}} + \frac{\sum_{i=1}^{n_r} \frac{P_{ri} \cdot A_{ri}}{P_{re}}}{\sum_{i=1}^{n_r} A_{ri}} + \frac{\sum_{i=1}^{n_f} \frac{P_{fi} \cdot A_{fi}}{P_{fe}}}{\sum_{i=1}^{n_f} A_{fi}} \right) \tag{1}$$

where:

P_{ti}, P_{ri} and P_{fi} are the perimeters of aggregates outlines at the ith CT image of the top, right, and front views, respectively, mm;

P_{te}, P_{re} and P_{fe} are the equivalent ellipse perimeters of aggregate particles of the top, right, and front views, respectively, mm^2;

A_{ti}, A_{ri} and A_{fi} are the areas of aggregate outlines at the ith CT image of the top, right, and front views, respectively, mm;

n_t, n_r and n_f are the total numbers of CT images of the top, right and front views, respectively.

Subscript i denotes the ith CT image of aggregate.

Meanwhile, the gradient angularity (GA) method based on AIMS was analysed by quantifying the change in the gradient on a particle boundary and was related to the sharpness of the corners of the 2D images of the aggregate particles (Masad 2005; Wang H.N., 2017). The average change in the inclination of the gradient vectors is taken as an indication of angularity shown in Equation (2). A higher GA value indicates a more angular particle.

$$GA = \frac{1}{\frac{n}{3} - 1} \sum_{i=1}^{n-3} \left| \theta_i - \theta_{i+3} \right| \tag{2}$$

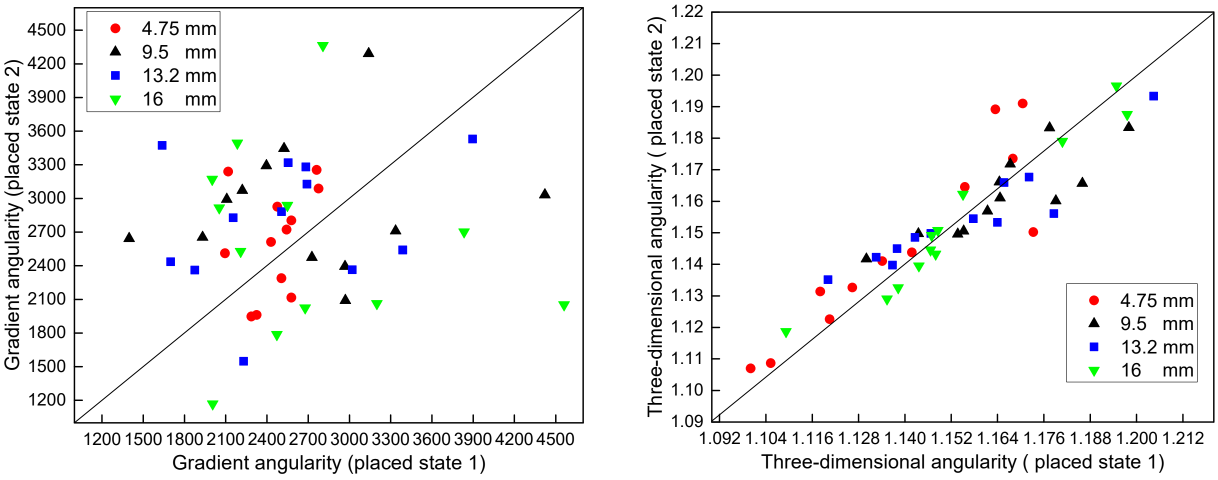
where θ is the angle of orientation of the edges, n is the total number of points and subscript i denotes the i^{th} point on the edge of the particle.

4 RESULTS AND DISCUSSION

4.1 Accuracy analysis of three-dimensional angularity (3DA)

A coarse aggregate has many different orientations, thus the contact surface of aggregate and carrier is different. Images of the same aggregate in different placed states, obtained from the fixed direction of the two-dimensional projected images are also different. However, the evaluation of the three-dimensional morphological characteristics of the coarse aggregate based on XCT is not affected by the placement of the aggregates, and the accuracy of the measurement results is high.

Twelve coarse limestone aggregates of four sizes (4.75 mm, 9.5 mm, 13.2 mm and 16 mm) were selected for analyzing the accuracy of three-dimensional angularity (3DA). For each selected coarse aggregate, the current commonly used two-dimensional evaluation method based on the Aggregate Image Measurement System II (AIMS II) (Wang D.,2015; Wang H., 2017) and three-dimensional evaluation method based on XCT were used to measure the characteristics under two different placed states (placed state 1, placed state 2). The results are shown in Fig. 4.



(a) AIMS II- Gradient angularity (GA) (b) XCT-Three-dimensional angularity (3DA)

Fig. 4 Discrete situation for two placed states of coarse aggregates using different characterization methods

The results of the correlation analysis of the morphological characteristics of the coarse aggregates with different particle sizes and placed states based on AIMS II and XCT were calculated, and the dispersion coefficients are shown in Table 2.

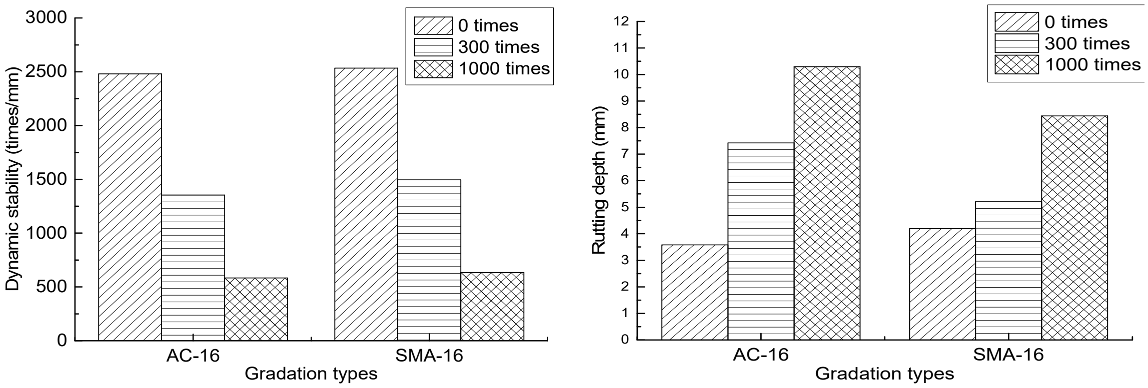
Table 2 Different dispersion coefficients for two placed states of coarse aggregates using different characterization methods

Evaluation indexes of morphological characteristics	4.75mm	9.5mm	13.2mm	16mm
Gradient angularity (GA)	-0.003	-0.088	-0.035	-0.085
Three-dimensional angularity (3DA)	0.81	0.69	0.863	0.945

From Fig. 4 and Table 2, it can be seen that the gradient angularity (GA) method shows large discrepancies for the four different particle sizes of coarse aggregates with different placed states based on AIMS II. The correlation coefficient was very low, which indicated that the coarse aggregates placed state has a great influence on the measurement results of the AIMS II. However, the three-dimensional angularity (3DA) measured by the same coarse aggregate under different placement conditions based on the XCT has more consistent and highly correlated results. The results indicated that the coarse aggregates placed state has less effect on the measurement results of the XCT, three-dimensional angularity could accurately characterize the angularity of the coarse aggregate. This observation is well in agreement with findings of several other research studies (Garboczi, E.J. 2002; Lin, C.L. 2005; Komba. J. 2013) from a different aspect, which have demonstrated that the three-dimensional quantification of coarse aggregate shape properties is more accurate than the two-dimensional.

4.2 High-temperature performance

The high-temperature performance of the asphalt mixtures was evaluated by the dynamic stability (DS) and rutting depth (RD), which are shown in Fig. 5.

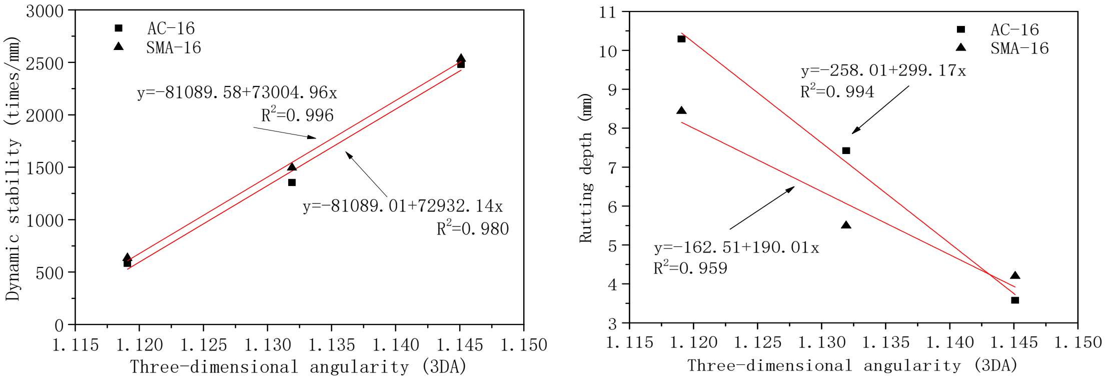


（a）Dynamic stability （b）Rutting depth

Figure. 5 Rutting test results

As can be seen from Fig. 5, with the increase in polishing times, that is, the decrease of the angularity of coarse aggregate, the dynamic stability of the mixture became smaller for the AC-16 and SMA-16 asphalt mixtures, and the rutting depth of both became larger. The results indicated that the angularity of coarse aggregate has a greater influence on the high-temperature performance of asphalt mixtures. The higher the angularity was, the better the high-temperature stability was. The dynamic stability of the AC-16 and SMA-16 asphalt mixtures, which were composed of coarse aggregate polished 1000 times, was very small. It was lower than the requirements of the technical specification for highway asphalt pavement construction. Therefore, in the construction of asphalt pavement, the quality of the coarse aggregate should be strictly controlled to ensure that the coarse aggregate has a high angularity.

In order to establish the relationship between the angularity of coarse aggregate and the high-temperature performance of asphalt mixture, the Origin software was used to perform a linear fit between three-dimensional angularity (3DA) of coarse aggregate and dynamic stability (DS) and rutting depth (RD) of the mixture. The results of the linear fit are shown in Fig. 6.



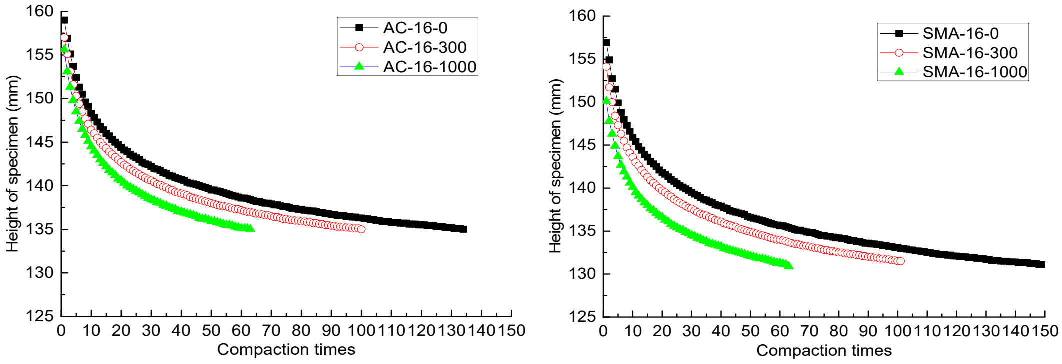
（a）Dynamic stability **（b）Rutting depth**

Figure.6 The relationship between three-dimensional angularity (3DA) of coarse aggregate and dynamic stability/rutting depth of mixture

The results of the linear fit showed that there is a good linear relationship between the three-dimensional angularity of coarse aggregates and the dynamic stability of asphalt mixtures for the AC-16 and SMA-16 asphalt mixtures. The linear correlation coefficient between the 3DA and dynamic stability of the AC-16 asphalt mixture was 0.980, while it was 0.996 for the SMA-16 asphalt mixture. Meanwhile, the linear correlation coefficient between the 3DA and rutting depth of AC-16 asphalt mixture was 0.994, while it was 0.959 for the SMA-16 asphalt mixture. It also indicated that three-dimensional angularity could characterize the angularity of the coarse aggregate and could reflect the high-temperature performance.

4.3 Compaction performance

The changes of the height in real-time of the specimen during the rotational compaction process could reflect the compaction performance of the asphalt mixture. The faster the height of the specimen decreases, the easier it is to be compacted. The results of different asphalt mixtures with different angularity of coarse aggregate are shown in Fig.7.



(a) AC-16 **(b) SMA-16**

Figure. 7 Compaction performance of asphalt mixtures

As can be seen from Fig.7, with the increase of the compaction times for the AC-16 and SMA-16 asphalt mixtures, the height of the specimen decreases during the rotary compaction process. Meanwhile, the more times the coarse aggregates were polished, the faster of the height changed. It illustrated that the lower the angularity of the coarse aggregate, the easier compaction of the asphalt mixture.

In addition, the number of compaction times required to reach the design air void volume can also reflect the compaction performance of the asphalt mixture. From the results, it also can be seen that the compaction times required to achieve the 4% design air void volume for the AC-16 asphalt mixture consisting of 0, 300 and 1000 polished coarse aggregates respectively were 134, 100 and 63, respectively, and the compaction times for the SMA-16 asphalt mixture were 150, 100 and 63, respectively. It indicates that the lower the angularity of the coarse aggregate comprising the asphalt mixture is, the easier it was to compact the mixture. This allowed the mixture to reach the required degree of compactness with less compaction time. In practical engineering, the asphalt mixture consisting of coarse aggregate with high angularity is difficult to be compacted. However, it could be compacted to reach the high degree of compactness by heavy-duty compaction machinery. As a result, the internal friction angle of the asphalt mixture is larger, and the structure of the inlaid skeleton is more stable, which is favorable for improving the performance of the asphalt pavement.

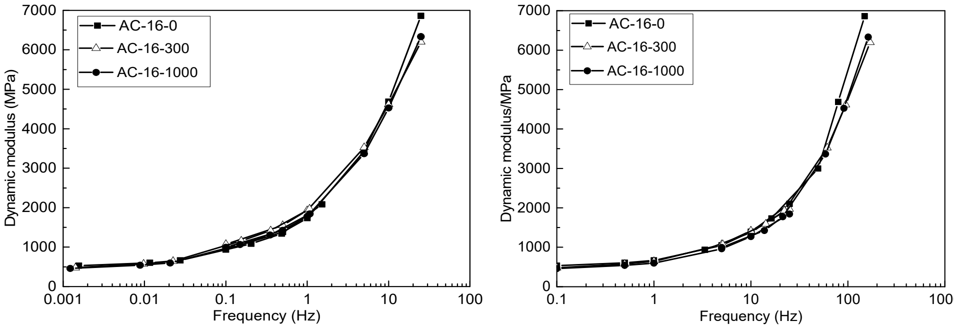
4.4 Dynamic modulus

As a kind of viscoelastic material, asphalt mixtures have time-temperature equivalent mechanical properties. Using the principle of time-temperature equivalence, the dynamic modulus master curves of the asphalt mixtures were generated with two kinds of gradation and three kinds of different angularity coarse aggregates. The reference temperatures were 35 °C and 50 °C, respectively. A sigmoidal function was adopted to fit the dynamic modulus test data of the asphalt mixtures, as shown in eq. [2] (Pellinen T., 2002).

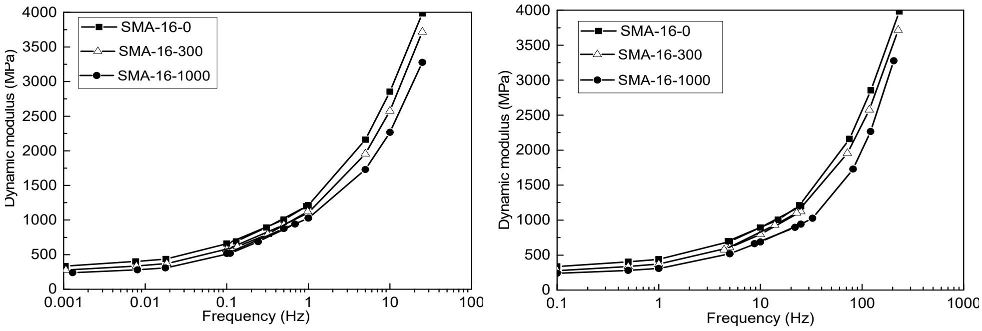
$$\log(|E|^{*}) = \delta + \frac{\alpha}{1+e^{\beta-\gamma(\lg f_r + S_T)}} \tag{2}$$

Where $|E|^{*}$ is dynamic modulus of the asphalt mixture, MPa; δ is the minimum modulus value, MPa; α is the span of dynamic modulus values, f_r is the reduced frequency at reference temperature, Hz; S_T is the shape factor at the reference temperature; and β, γ are the shape parameters.

The master curves of dynamic modulus of the asphalt mixtures with different gradations and different angularity coarse aggregates are shown in Fig. 8.



（a）**AC-16 at reference temperature 35℃** （b）**AC-16 at reference temperature 50℃**



（c）**SMA-16 at reference temperature 35℃** （d）**SMA-16 at reference temperature 50℃**

Figure. 8 Dynamic modulus master curves

As can be seen in Fig. 8, the dynamic modulus of asphalt mixture at all levels increased with the increase of loading frequency. This is because under the action of dynamic load, asphalt mixtures do not produce instantaneous compression when loaded, nor do they have instantaneous complete recovery during unloading, but behaves as a hysteresis reaction. As the load frequency increases, the hysteresis response to the load would be more pronounced, indicating a greater dynamic modulus.

Based on the objective of this study, it can be seen from Fig. 8 that the dynamic modulus of the AC-16 asphalt mixture tended to decrease with the increase of polishing times, that is, the decrease of the angularity of coarse aggregate, however, this trend was not significant. The dynamic modulus of the SMA-16 asphalt mixture decreased with the increase of polishing times, and the change was significant, in addition, as the load frequency increased, the change became more significant.

This is because the AC-16 asphalt mixture is a suspension dense structure, and its strength mainly depends on the cohesion between the aggregate and asphalt, with the aggregate inter-squeeze force and internal friction supplemented. Therefore, the change of the angularity of coarse aggregate, which has great influence on the internal friction, will not obviously change the dynamic modulus of the asphalt mixture. However, the SMA-16 asphalt mixture is a dense framework structure, and its strength mainly depends on the internal friction generated by the intercalation of the aggregates and has less reliance on the cohesive action of the asphalt and aggregate. Therefore, the reduction of the angularity of the coarse aggregate makes the internal friction of the asphalt mixture smaller, and the resilience of the mixture decreases under the action of the stress, which shows that the dynamic modulus of the asphalt mixture becomes obviously smaller.

5 CONCLUSIONS

For this study, three-dimensional angularity (3DA) was proposed on the basis of X-ray Computed Tomography (XCT) measurement. Investigations on the effects of the angularity of coarse aggregate on high-temperature performance and compaction performance of asphalt mixtures were carried out. The following conclusions could be drawn:
(1) The coarse aggregates placed state has less effect on the measurement results of XCT, the three-dimensional angularity could characterize the angularity of the coarse aggregate.
(2) The angularity greatly influences the high-temperature performance and compaction performance of asphalt mixtures, and the higher the angularity, the better the high-temperature stability, while the more difficult compaction is. There is a strong linear relationship between the three-dimensional angularity of the coarse aggregate and the dynamic stability/rutting depth of asphalt mixtures.
(3) When the temperature is constant, the dynamic modulus of asphalt mixtures increases with the increase of the loading frequency. When the loading frequency is constant, the dynamic modulus of asphalt mixtures decreases with the increase of the temperature.
(4) The angularity also has different effects on the dynamic modulus of different gradation asphalt mixtures. The angularity of the coarse aggregate has little effect on the dynamic modulus of the AC-16 asphalt mixture, but has a great influence on the SMA-16 asphalt mixture. With the decrease of angularity, the dynamic modulus decreases and the changes' trend becomes smaller with the increase of the loading frequency.

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