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The influence of compaction frequency on the skeleton characteristics of asphalt mixtures

Yichong Chen[1*], Xianglin Lu[1], Junlin Zhou[1], Leizhou Cai[2], Cansheng Wang[2], Cheng Lu[2]

1. *Guangxi Liubin Highway Construction and Development Co., Ltd, Nanning, Guangxi 530004, China*;
2. *China Highway(Beijing) Engineering Materials Technology Co., Ltd., Beijing 100076, China*

Abstract: In order to understand the influence of compaction energy on the skeletal structure of dense-graded asphalt mixtures, it is essential to establish a stable skeletal framework. This study addresses the limitations of existing research regarding the effects of compaction energy on asphalt mixtures by analyzing the volumetric parameters of specimens subjected to varying compaction stages, specifically ranging from 25 to 1,000 gyrations. Digital image processing techniques are employed to investigate the microstructural characteristics of asphalt mixtures under different compaction energies. The results indicate: (1) For both Granite Asphalt Concrete (GAC) and Stone Matrix Asphalt (SMA) mixtures, the density initially increases rapidly, then slows down after 250 gyrations, without exhibiting a consistent trend. (2) Throughout the compaction process, the contact points and average coordination numbers of 4.75 mm aggregates in SMA mixtures surpass those observed in GAC mixtures. As compaction frequency increases, the contact points and average coordination numbers of coarse aggregates initially rise before subsequently declining, with some coarse aggregates becoming suspended within the fine aggregates. (3) By excluding the aggregates that do not make contact, the effective Voids in Coarse Aggregates (VCA_{effect}) are calculated to assess the skeletal changes within of the mixture. The SMA mixture demonstrates a more robust skeletal structure compared to GAC, with VCA_{effect} initially decreasing before increasing. As increase in the compaction frequency correlates with a rise in the number of no-contact coarse aggregates, ultimately leading to the degradation of the destruction of the skeletal structure of the asphalt mixture .

Keywords: road engineering; digital image processing techniques; skeleton characteristics; compaction energy; effective VCA

Dense-graded asphalt mixtures with outstanding resistance to rutting are widely used in highways and urban roads in China. Their typical characteristics include: (1) Coarse aggregates in the asphalt mixture form the skeleton, transmitting loads downward through contact points; (2) Fine aggregates, asphalt, and other additives form a mortar, partially adhering to coarse aggregates to create bond strength between them and filling voids within the skeleton, resulting in a cohesive structure with higher strength. Therefore, a sound skeletal structure plays a crucial role in the deformation resistance of asphalt mixtures. Unfortunately, current research lacks a clear understanding of the influence of compaction energy on the skeleton. Traditional empirical methods base compaction energy determination on macroscopic compaction degree, neglecting changes in the mixture's skeletal structure.

Both China and the United States use VCA_{mix} < VCADRC as the criterion for determining mixture skeletal structure. However, the calculation method for the skeletal void content (VCA) of specimens employs numerous empirical formulas, leading to significant errors and an inaccurate reflection of skeletal structure quality. Factors influencing mixture skeleton include aggregate gradation and compaction energy. Appropriate compaction energy ensures a dense structural skeleton, enhancing pavement durability. Most road engineers believe that higher compaction energy results in denser mixtures

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* *E-mail address*: 2541353789@qq.com

and superior skeletal structure. The American Association of State Highway and Transportation Officials (AASHTO) has proposed using theoretical density as a compaction standard. For every 1% increase in compaction, pavement service life extends by 10%. Studies by Harvey and others[1] on low air void asphalt mixtures suggest that reducing air voids increases the stiffness modulus and fatigue strength of asphalt mixtures. Many scholars utilize computer image processing techniques to study the internal micro structure of mixtures. Using digital image processing technology, researchers like Shi, et al.[2-3] accurately measure the VCA_{mix} of mixtures and propose the concept of $VCA_{\text{effective}}$. Cai et al.[4] establish rutting prediction models based on grading blending methods and optimize grading blending design methods. M. Emin Kutay, et al.[5] reconstruct three-dimensional models of asphalt mixture specimens using CT technology and find that in the early stages of compaction, the main axis direction of coarse aggregates is already established, with minimal impact on the angle between the aggregate's main axis and the horizontal line as compaction energy increases.

This study utilizes digital image processing technology to analyze changes in the skeletal characteristics of asphalt mixtures at various compaction stages, thereby affecting macroscopic performance. It elucidates the shortcomings of skeletal contact characteristics under under-compaction and over-compaction conditions. While ensuring the optimal skeleton, it comprehensively considers compaction energy, thereby creating possibilities for determining compaction energy based on skeletal characteristic parameters. It also opens up a new approach for determining field compaction energy during construction.

1 Raw materials

To obtain volumetric indicators of mixtures under different compaction energies, this study employed rotating compaction specimens with the same gradation but different compaction frequencies. The aggregates used were all granite, with technical specifications as shown in Table 1, while the asphalt binder was SBS modified asphalt, with technical specifications as shown in Table 2.

Table 1 Technical parameters of aggregate

Material name	Testing item	Quality requirement	Aggregate test result
Coarse aggregate	Crushing value (%)	⩽26	18.25
	Los angeles abrasion value (%)	⩽28	17.3
	Needle-shaped particles content (%)	<15	10.5
	Water absorption (%)	≯2.0	All meet requirements
	Apparent relative density (g/cm^3)	–	2.569
	Apparent relative density (g/cm^3)	⩾2.6	2.655
Fine aggregate	Apparent relative density	⩾2.5	2.643
	Sand equivalent (%)	⩾60	65

Table 2 Technical parameters of asphalt

Testing item	Unit	Test result
Penetration (25 ℃, 100 g, 5 s)	0.1 mm	54
Softening point (TR&B)	℃	80
Ductility (5 ℃, 5 cm/min)	cm	27
Density (25 ℃)	g/cm^3	1.035

Wang Hainian, et al.[6] demonstrated that an increase in the needle-shaped aggregate content will increase the number of contact points of coarse aggregate in asphalt mixture. Needle-shaped aggregates have a significant influence on the skeletal strength of the mixture. However, the conclusions of this study are limited to the performance analysis of mixtures with a needle-shaped aggregate content of 10.5%.

2 Skeleton structure analysis

2.1 Acquisition of digital images

According to Table 3, rotating compaction specimens

Table 3 Gradation of asphalt mixtures

Gradation type	The mass percentage (%) passing through the following sieves (%)										Asphalt-stone ratio (%)
	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	
GAC-13	100	97.5	65	34.5	25	18.5	12.5	9.5	7.5	5	5.0
SMA-13	100	95	65	25	20	18	16	14	12	10	6.0

were formed with 25, 50, 75, 150, 200, 300, and 1 000 gyrations, with two specimens formed at the same rotation frequency. The mixing temperature was determined as 160 ℃ (viscosity 0.28 Pa·s) based on asphalt viscosity, and the compaction temperature was set at 145 ℃ (viscosity 0.17 Pa·s). During the forming process, specimen heights were recorded at different compaction frequencies to calculate volume and density. Subsequently, the specimens were longitudinally cut three times using a cutting machine, as illustrated in Figure 1. Figure 2 presents some of the rotating compaction specimens and their sectional views. The specimens were placed and cut according to the forming direction, labeled from left to right as A, B, C, and parallel specimens as D, E, F, totaling six faces. The sectional data represents the average of the left and right sides at the cutting point.

To avoid errors caused by shadows from the light source, vertical photography should be employed. To minimize errors in the size of aggregate in photos caused by the lens not being parallel to the specimen's cross-section, the camera-to-specimen distance should be consistent, ensuring parallel photography[7]. The cross-sectional images of the specimens are shown in Figure 3.

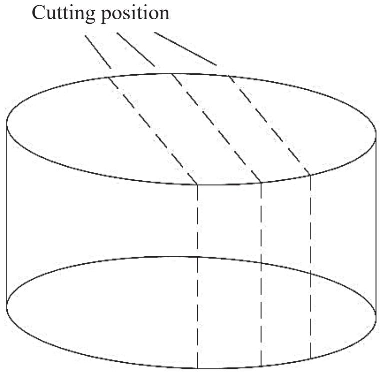


Fig. 1 Cutting example

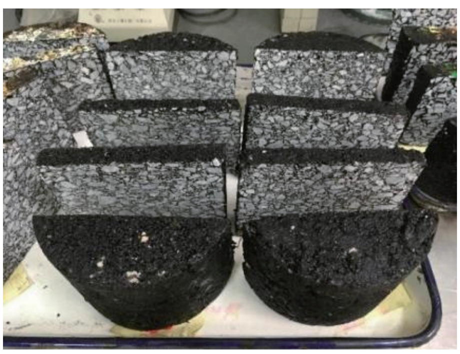


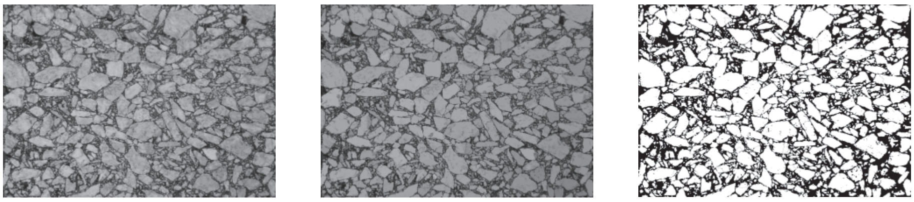
Fig. 2 Rotary compacted specimens

Fig. 3 Obtain section of specimen

2.2 Digital image processing

The current technologies for obtaining images of asphalt mixture slices mainly involve CCD digital cameras and industrial CT scans. Due to the dissipation of X-ray energy during the process of scanning specimens and acquiring digital image information in industrial CT scans, some aggregates may be difficult to distinguish from the asphalt boundary. Even with the use of the OTSU algorithm, which is considered to have high segmentation accuracy, there are still issues with particle agglomeration due to limitations in the quality of the original image, which significantly affects measurement results[8]. Furthermore, in contact analysis, the contact threshold is typically set at around 1 mm. However, the original images obtained from CT scans obviously cannot meet this requirement. Previous studies[4] have indicated that the pixel accuracy should be less than 0.04 mm/pixel for contact analysis. Given these limitations, this study utilized high-definition digital cameras to capture images of asphalt mixture slices.

Since electronic noise during photography significantly affects the quality of the images, the obtained images need to undergo denoising processing first before subsequent analysis steps. The main steps are as follows: (1) Denoising the images and then performing binary image processing to segment boundaries. (2) Inputting basic parameters of asphalt mixture raw materials and proportions. A Matlab program calculates the equivalent diameter of coarse aggregates based on their equivalent diameter and assigns them numbers. (3) Inputting the contact threshold and calculating the positions of coarse aggregate contact points, the numbers of contacting aggregates, and their areas[9-10]. Taking the cross-section with 1 000 compactions as an example, as shown in Figure 4.



(a) Median filtering (b) Watershed transformation (c) Binarized image

Fig. 4 Image processing

2.3 Contact point calculation

When analyzing the spatial distribution characteristics of aggregates using two-dimensional image analysis, the threshold for determining whether coarse aggregates are in contact should consider the smallest particle size of the analyzed aggregates. Previous studies[11] have set this threshold at 25% of the calculated minimum particle size, but the rationale behind this value has not been discussed. Cai Xu, et al.[4] argued that in analyzing the three-dimensional spatial distribution through two-dimensional image analysis, the effects of cutting position and asphalt film thickness must be simultaneously considered. They applied a contact probability analysis and found that setting the contact threshold at 23% of the minimum calculated particle size was more reasonable. In this study, the minimum particle size in contact was determined to be 4.75 mm, with a contact threshold of 1.092 5 mm.

2.4 VCA_{effect} calculation

Empirical methods for calculating VCA_{mix} involve numerous volume parameters and estimations, inevitably leading to large errors. Therefore, some scholars have proposed using digital image processing technology to accurately calculate VCA_{mix}[12]. This method only requires extracting the area of coarse aggregates within the cross-section, eliminating intermediate variables such as bulk volume relative density and adsorbed asphalt that are difficult to control and measure. The calculation method is shown in Equation (1):

$$VCA_{\mathrm{mix}} = \left(1 - \frac{M}{N}\right) \times 100\% \tag{1}$$

where, M is the area of all coarse aggregates in the cross-section obtained from digital image processing; N is the cross-sectional area.

The skeleton inside the asphalt mixture is composed of mutually contacting coarse aggregates, and the skeleton state is closely related to the contact characteristics of internal aggregates[13]. Previous studies have shown that asphalt mixtures of any gradation possess a skeleton. However, the nature of the basic "unit" forming the skeleton (such as aggregate properties, surface contours, and particle size) differs, leading to different abilities exhibited by the skeleton. According to the multiple-point support theory, stress is primarily distributed along lines of high modulus of elasticity during the transmission process, i.e., according to the contact points of the skeleton[14]. However, during this process, stress concentration inevitably occurs at certain contact points, and when these contact points fail, the asphalt mixture promptly undergoes failure.

Wang Zhen, et al.[15] argued that stress is dispersed to the contact points of each aggregate in the skeleton, so there must be aggregates primarily bearing the stress. Their research results showed that 4.75 mm aggregates have certain strength characteristics and can provide a sufficient number of contact points, serving as stable force-bearing points and the transition points between coarse and fine aggregates. Therefore, this study mainly focuses on investigating the skeleton formed by aggregates of 4.75 mm and above.

During the study of contact characteristics, it was found that there are coarse aggregates with zero contact points inside the mixture, indicating that the structural system for transmitting force through the skeleton is not functioning as expected. Instead, these aggregates are "suspended" within the fine aggregates and asphalt[14], as shown in Figure 5. However, these coarse aggregates have the same function as the fine aggregates in filling the gaps between the skeleton. Therefore, it is more reasonable to deduct these coarse aggregates when calculating the skeleton void content. Traditional empirical methods cannot accurately calculate this, so this study introduced the calculation method of VCA_{effect}[1], as shown in Equation (2):

$$VCA_{\text{effect}} = \left(1 - \frac{M - \mathrm{m}}{N}\right) \times 100\% \tag{2}$$

where m is the area of coarse aggregates with zero contact points.

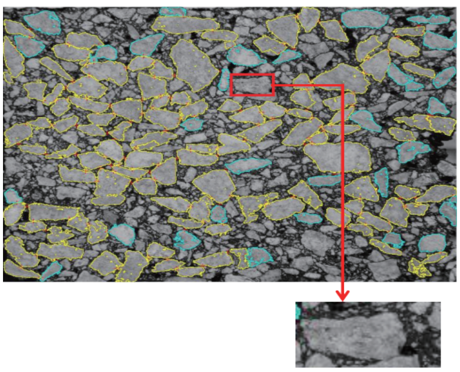


Fig. 5 Contact analysis and coarse aggregate without contact

This calculation method divides the coarse aggregates into two parts: those involved in forming the skeleton and the remaining coarse aggregates. It accurately reflects the characteristics of skeleton embedding in the mixture, without considering the interference of fine aggregates and asphalt, making it a more optimized approach based on Equation (1).

2.5 Coordination number calculation

For the evaluation of the internal dense structure of the skeleton, the coordination number is defined as the number of contacts between a particle and its neighboring particles within a particle assembly. It is an important micro structural parameter that reflects the packing and microscopic mechanical behavior of granular bodies[16]. Therefore, it is reasonable to use the average coordination number to evaluate the embedding characteristics of the skeleton structure. The larger the average coordination number, the more contacts each individual particle has, indicating a denser skeleton structure. The average coordination number is calculated as the average number of contacts per particle, as shown in Equation (3):

$$\bar{n} = \frac{\sum_{\mathrm{i}=1}^{n} n^{\mathrm{i}}}{N} \tag{3}$$

where, $\bar{n}$ is the average coordination number; N is the total number of calculated particles within the cross-section; n_i is the number of contact points for the i^{th} particle.

3 Experimental setup and results analysis

3.1 Influence of compaction energy on density

The compaction process of asphalt mixtures involves transitioning from loose, plastic states to eventually forming a structure capable of bearing loads and exhibiting high tensile strength. In this study, rotating compaction specimens were formed with different compaction frequencies, and density curves for GAC and SMA gradations under different compaction energies were plotted, as shown in Figure 6.

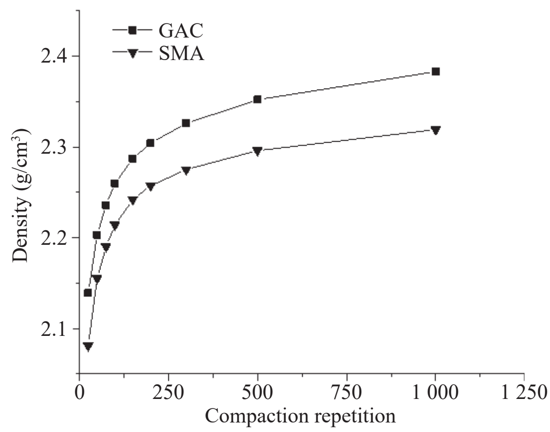


Fig. 6 Compactness curve

The relationship between mixture density and compaction frequency is illustrated in Figure 6. In the early stages of mixture formation, the mixture density increases rapidly with the increase in compaction energy. However, after reaching 150 compaction cycles, the increase in mixture density slows down, but there is no stable trend; it continues to increase slowly. This is because as the compaction energy increases, the aggregates within the mixture automatically seek stability through rotation to form a skeleton. As the skeleton forms, increasing compaction energy gradually fills the voids inside the specimen, and the center of gravity of the specimen gradually decreases.

From the above figure, it can be observed that throughout the entire compaction process, the density of GAC is greater than that of SMA. This is because the SMA gradation is coarser, and the fine aggregates are insufficient to completely fill the gaps between coarse aggregates, preventing the mixture from achieving maximum density.

3.2 Coarse aggregate contact points and coordination number

Generally, with the increase in compaction energy, the skeleton structure of the specimen becomes denser, and the number of contact points increases. Considering the situation of under-compaction, the effect of compaction energy on the change in internal contact points of the specimen is shown in Figure 7.

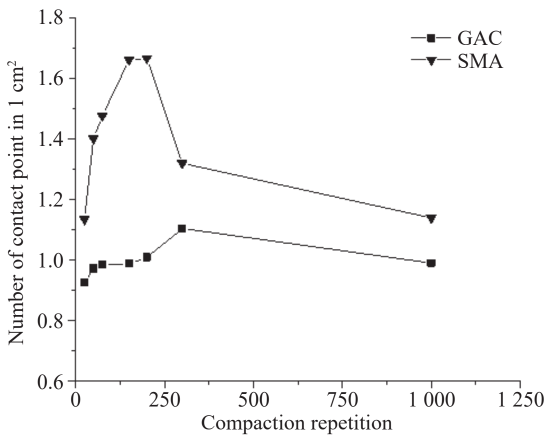


Fig. 7 The number of contact point change trend

From Figure 7, it can be observed that the internal contact points increase rapidly in the early stages of mixture compaction. For GAC mixtures, the number of contact points reaches its peak at 300 compaction cycles, which is twice the number of contact points at 25 compaction cycles. For SMA mixtures, the maximum number of contact points occurs at 200 compaction cycles, similar to the number of contact points at 150 compaction cycles. Traditional empirical methods typically suggest compaction cycles of 100-130 for GAC and SMA mixtures. However, the number of contact points does not reach its peak within this range, and it continues to increase with increasing compaction energy. When the compaction cycles reach 1 000, which is eight times the traditional compaction energy, it falls into the category of over-compaction. Beyond 300 compaction cycles, the number of contact points starts to decline, indicating potential damage to the skeleton structure.

Coordination number, defined as the ratio of contact points to the number of coarse aggregate particles, is shown in Figure 8 for different compaction cycles, representing the average coordination number within the mixture.

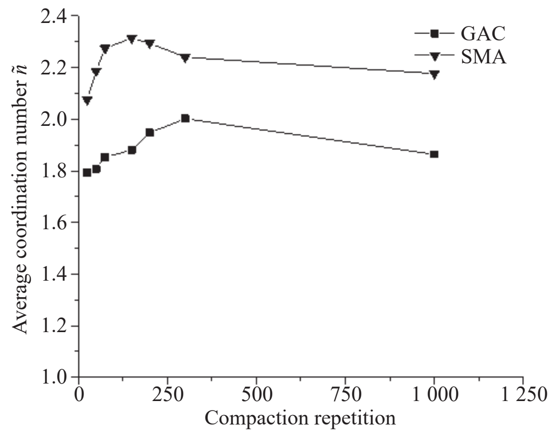


Fig. 8 Mean coordination number

Figure 8 indicates that the average coordination number of SMA mixtures is significantly higher than that of GAC mixtures. Coarser aggregate gradations are more prone to contact, hence resulting in a higher coordination number. When the compaction cycles reach 1 000, both the number of contact points and the coordination number start to decrease. This may be due to the denser composition and higher content of fine aggregates in the central portion of the specimen. As the compaction energy continues to increase, the center of the specimen gradually densifies, causing the fine aggregates and asphalt binder to spread outward. This leads to the rupture of contact between coarse aggregates due to the intrusion of fine aggregates, thereby disrupting the skeleton structure. According to the principle of effective stress in the triaxial test (where σ is the normal stress provided by the rammer at 0.6 MPa, σ' is the effective stress provided by the aggregate, and μ is the pore water pressure), the asphalt binder exhibits fluid-like characteristics under high temperature conditions during the compaction process. As the specimen is compressed, it generates positive pore water pressure, leading to a decrease in effective stress between aggregates. Consequently, the contact between aggregates decreases, and some coarse aggregates involved in forming the skeleton structure become "suspended" in the fine aggregates. This phenomenon may also be attributed to over-compaction-induced aggregate breakage and refinement of the mixture gradation.

3.3 Mixture *VCA*

Comparison between the VCA_{mix} calculated using the empirical method and the VCA_{effect} calculated considering contact characteristics is illustrated in Figure 9.

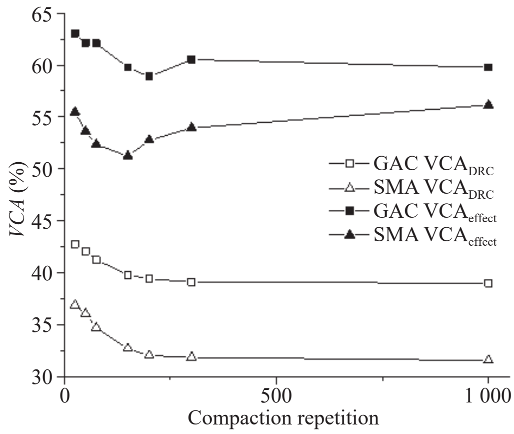


Fig. 9 Calculation results of *VCA*

From Figure 9, it can be observed that the traditional empirical VCA_{mix} is 13% to 20% smaller than the VCA_{effect} considering contact characteristics. Based on the empirical method, the determination of the skeleton is made by comparing VCA_{mix} with VCADRC. The void ratios of coarse aggregate skeleton for GAC and SMA are 43.03% and 42.09%, respectively. The mixture has already formed a densified skeleton when the compaction cycles reach 75 for GAC, and the skeleton becomes denser with increasing compaction cycles, although this trend does not align with the internal contact characteristics of the mixture. However, for SMA mixture, the skeleton is formed when compacted 25 times. The trend of VCA_{effect} aligns with the contact characteristics, showing a decrease followed by an increase after excluding the coarse aggregates that have not made contact. Therefore, the calculation method for effective VCA_{mix} is more rigorous and accurate.

When evaluating the skeleton structure based on the number of contact points, the skeleton is not disrupted until the compaction cycles exceed 300. However, when using VCA_{effect} to evaluate the skeleton structure, the disruption begins after 200 cycles. This may be because during the compaction cycles between 200 and 300, some particles are surrounded by more fine aggregates and asphalt binder, which disrupt the original contact between coarse aggregates, causing them to "suspend" in the fine aggregates. Meanwhile, as the compaction continues, the skeleton becomes denser, and the number of contact points per aggregate increases from single to double or even triple contacts. At this stage, although some coarse aggregates are "suspended," the skeleton characteristics are still significant, indicating a somewhat conflicting phase that requires further research on its impact on the rutting resistance of asphalt mixtures.

3.4 Compaction energy analysis

Based on the internal contact characteristics of the mixture and the rutting test results, it is determined that the maximum compaction cycles for the mixture should not exceed 300. The compaction energy required for 8 to 100 cycles and 100 to 300 cycles is calculated by integrating the density curve, as shown in Figure 10.

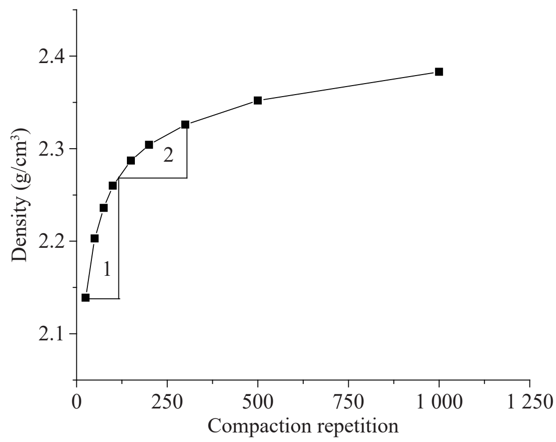


Fig. 10 Compaction energy

The variations in compaction energy for SMA and GAC mixture specimens were separately calculated. Table 4 presents the compaction energy required for the two types of gradation mixtures over 8 to 100 cycles and 100 to 300 cycles of compaction. The segment from 8 to 100 cycles represents the energy required for the mixture under traditional compaction efforts, while the segment from 100 to 300 cycles represents the energy required for the mixture from achieving a certain level of compaction to the onset of skeleton disruption.

The results indicate that when the mixture is subjec-

Table 4 Compaction energy

Compaction stage	8-100	100-300
GAC	14.64	7.95
SMA	15.51	7.65

ted to 1.5 times the traditional compaction energy, the mixture skeleton begins to break down, and the resistance to rutting performance begins to decrease. SMA initially experiences higher compaction energy, indicating that SMA gradation is easier to compact compared to GAC gradation, likely due to SMA having a higher asphalt content and better aggregate surface lubrication compared to GAC mixture. Additionally, the SMA mixture receives less energy from completion of compaction to the onset of skeleton breakdown, implying that within the same number of compaction cycles, there is minimal change in density, indicating a stronger ability to resist external loads.

4 Conclusions

(1) With an increase in the number of compaction cycles, both SMA and GAC mixture specimens show a rapid increase in density in the early stages, followed by a gradual rise in the later stages. The density of the coarser SMA mixture is consistently lower than that of the GAC mixture, but neither mixture reaches a stable density state throughout the compaction process.

(2) For the GAC mixture, the number of contact points increases rapidly at 100 compaction cycles, remains stable between 100 and 200 cycles while the average coordination number increases, indicating a denser skeleton. At 1000 compaction cycles, the gradation of the mixture may vary due to aggregate breakage, resulting in more fine aggregates and fewer contact points for coarse aggregates, possibly leading to skeleton disruption, with a decrease in contact points and average coordination number. For the SMA mixture, the number of contact points and coordination number peak at 250 cycles, and begin to decrease at 300 cycles.

(3) Traditional skeleton determination methods have limitations and cannot accurately reflect the state of the skeleton structure. By excluding coarse aggregates that have not made contact in the calculation of VCA_{effect}, the trend of change aligns with the trend of internal skeleton characteristics of the mixture, increasing before decreasing. In the compaction cycle range of 200 to 300 cycles, the number of contact points and coordination number increase for both mixtures, while VCA_{effect} decreases, showing inconsistency in the trends.

(4) At 100 compaction cycles, the mixture receives traditional compaction energy; at 300 cycles, the mixture skeleton structure begins to break down. To improve mixture skeleton characteristics, compaction energy is calculated both traditionally and at the limit of over pressure compaction. When the mixture receives 1.5 times the traditional compaction energy, the skeleton characteristics begin to deteriorate. Therefore, it is recommended that the compaction energy applied to the mixture should be 1.1 to 1.3 times the traditional compaction energy, not exceeding 1.5 times.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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References

[1] Harvey, J. T.; Tsai, B. W. Effects of asphalt content and air void content on mix fatigue and stiffness[J]. Transportation Research Record Journal of the Transportation Research Board, 1996, 1543(1): 38-45. DOI:10.3141/1543-05.

[2] Shi, L. W.; Wang, D. Y. Evaluation indexes of asphalt mixture main skeleton based on digital image processing[J]. China Journal of Highway and Transport, 2017, 30(5): 52-58.

[3] Shi, L. W.; Wang, D. Y.; Cai, X.; et al. Distribution characteristics of coarse aggregate contacts based on digital image processing technique[J]. China Journal of Highway and Transport, 2014, 27(8): 23-31.

[4] Cai, X. Rutting resistance evaluation and structure optimization of asphalt pavement[D]. Guangzhou: South China University of Technology, 2013.

[5] Kutay, M.; Edith, A.; Nelson, G.; et al. Three-dimensional image processing methods to identify and characterise aggregate in compacted asphalt mixtures[J]. International Journal of Pavement Engineering, 2010, 11(6): 511-528.

[6] Wang, H. N.; Wang, H. M.; Kong, Q. X.; et al. Effect of coarse aggregate morphology on compaction characteristics and skeleton tructure of stone matrix asphalt mixture[J]. Journal of Chongqing University, 2022, 1-14. http://kns.cnki.net/kcms/detail/50.1044.N.20220712.1230.002.html.

[7] Tang, H. Z. Simplified skeleton construction and identification of internal stress paths for coarse aggregates in asphalt mixtures[D]. Guangzhou: Guangzhou University, 2022.

[8] Lin, F. H.; Shi, L. W.; Liao, W. J.; et al. Study on Meso-

Distribution uniformity of coarse aggregate based on image processing[J]. Journal of China & Foreign Highway, 2023, 43(5): 214-218.

[9] Zhu, H. Z.; Tan, Q. Q.; Fan, S. P.; et al. Research progress of bituminous mixture meso-structure based on image technology[J]. Journal of Chongqing Jiaotong University (Natural Science), 2021, 40(10): 97-110.

[10] Yu, H. N.; Ao, D.; Qian, G. P.; et al. Review on digital twin model of asphalt mixture performance based on mesostructure characteristics[J]. China Journal of Highway and Transport, 2023, 36(3): 20-44.

[11] Coenen, A. R.; Kutay, M. E.; Sefidmazgi, N. R.; et al. Aggregate structure characterization of asphalt mixtures using 2-Dimensional image analysis[J]. Road Materials and Pavement Design, 2012, 13(3): 433-454.

[12] Wang, L. B.; Wang, L.; Mohammad, L.; et al. Application of mixture theory in the evaluation of mechanical properties of asphalt concrete[J]. Journal of Materials in Civil Engineering, 2004, 16(2): 167-174.

[13] Yang, M. Research on skeleton structure and performance of asphalt mixture based on Balance Mix Design[D]. hangsha: Changsha University of Science & Technology, 2022.

[14] Zheng, Q.; Yan, H.; Sun, X. L.; et al. Contacting condition and stability evaluation of three-dimensional skeleton of asphalt mixture during compaction[J]. Guangdong Highway Communications, 2022, 48(6): 1-7.

[15] Wang, Z.; Huang, X. M.; Zhao, Y. L. Rules and mechanism of aggregates fragmentation[J]. Journal of Southeast University (Nature Science Edition), 2011, 41(5): 1092-1097.

[16] Wang, X.; Shi, L. W.; Wang, Y. C.; et al. Design and evaluation of asphalt mixture skeleton structure based on image[J]. Highway, 2023, 68(2): 40-48.