Article

Gradual Meso-Structural Response Behaviour of Characteristics of Asphalt Mixture Main Skeleton Subjected to Load

Liwan Shi 1,2, Zhen Yang 2,3,*, Duanyi Wang 2, Xiao Qin 1,4, Xin Xiao 1,2 and Masley Kwaku Julius 2

1 School of Transportation and Civil Engineering and Architecture, Foshan University, Foshan 528225, Guangdong, China; slwan1223@163.com (L.S.); qinnao@126.com (X.Q.); xiaoxin5230302@sina.com (X.X.)
2 School of Civil Engineering and Transportation, South China University of Technology, Guangzhou 510640, Guangdong, China; tcdywang@scut.edu.cn (D.W.); julimas2@yahoo.com (M.K.J.)
3 School of Automotive and Transportation Engineering, Hefei University of Technology, Hefei 230009, Anhui, China
4 School of Highway, Chang’an University, Xi’an 710064, Shanxi, China
*
Correspondence: 201410101329@mail.scut.edu.cn; Tel.:+86-138-2623-6026

Received: 20 May 2019; Accepted: 11 June 2019; Published: 14 June 2019

Abstract: In order to provide a reference for the gradation design of dense skeleton asphalt mixtures (DSAM), this study conducts a thorough analysis of the gradual meso-structural response behaviour of characteristics of the asphalt mixture main skeleton subjected to load using the digital image processing (DIP) technique. Moreover, gradation optimisation measures and the design criteria of mesoscopic evaluation indices for the main skeleton are proposed. The results indicate that aggregates with particle sizes of 2.36–4.75 mm can effectively increase the number of contact points; however, the stability of the main skeleton remains insufficient. Furthermore, coarse aggregates with a particle size larger than 4.75 mm provide the most significant contribution to the formation of a steady main skeleton; this is the critical particle size for the formation of a steadier main skeleton. Gradation is the major determinant of mesoscopic evaluation indices, including average coordination number (\(n_c\)) and the ratio of the quantity of coarse aggregates without contact points to the total quantity of coarse aggregates (C value) for the asphalt mixture of the main skeleton. On the other hand, the performance of asphalt has an insignificant influence on mesoscopic evaluation indices; it mainly affects the development trend of macroscopic rutting. In the design process of DSAM, it is necessary to optimise gradation with the aim of increasing \(n_c\) and reducing the C value so as to enhance the load resistance capacity of the primary skeleton. When preparing asphalt mixture specimens using the wheel rolling method, the design criteria for the aforementioned indices are \(n_c \geq 1.5\) and \(C \leq 15\%\), which can be used as bases for the design of DSAM with a nominal maximum particle size of 13.2 mm to ensure that the coarse aggregates are interlocked and form a steady main skeleton.

Keywords: dense skeleton asphalt mixture; digital image processing; meso-structural response; mesoscopic evaluation index; main skeleton

1. Introduction

The dense skeleton asphalt mixture (DSAM) is a type of heavy-duty traffic pavement material. The typical characteristics of the material structure are as follows: the coarse aggregates in the asphalt mixture constitutes the main skeleton; the fine aggregates, asphalt, and other admixtures constitute the asphalt mortar that fills the voids of the main skeleton formed by the coarse aggregates and bind and restrain them so that the asphalt mixture forms a high-strength integrated material. With the
rapid increase in the utilisation of heavy-duty vehicles, the DSAM has been widely used in China’s highway construction because of its good anti-rutting performance [1]. Currently, the evaluation of the skeleton structure is mainly based on the description of the dense skeleton structure in the ‘SMA mixing proportion design method’ proposed by the Federal Highway Administration and the National Asphalt Pavement Association, USA. A qualitative inequality empirical formula, $VCA_{mix} < VCA_{DRC}$, is used as the evaluation index for the coarse aggregate skeleton [2]. Here, $VCA_{mix}$ is defined as voids in the coarse aggregate of compacted asphalt mixture, and $VCA_{DRC}$ pertains to the voids in the coarse aggregate under a compacted condition. Both are macro-indices calculated from laboratory tests; for this purpose, the bulk specific gravity of coarse aggregates with different particle sizes should be measured accurately. Based on the definitions and calculation processes of $VCA_{mix}$ and $VCA_{DRC}$, it can be noted that there are considerable differences not only in the preparation process of specimens but also in the calculation method of their volume indices. It is probable that calculation results will have errors because of certain factors, such as the value of empirical coefficients and the accumulation of artificial errors; hence, it is necessary to measure accurately the bulk specific gravity of coarse aggregates with different particle sizes.

In order to ascertain the behaviour of the characteristics of asphalt mixture with heterogeneous composite materials, it is necessary to overcome the limitations of previous macroscopic studies and analyse the internal skeleton of the asphalt mixture from the micro-scale and meso-scale perspectives. From the mesoscopic perspective, the stability of the coarse aggregate skeleton is affected by material gradation and position relationship among particles. When the proportion of coarse to fine aggregates is appropriate, the coarse aggregates will be interpenetrated, and the voids they have formed will be properly filled by the fine aggregates. If the proportion is not suitable, the coarse aggregates will be suspended, or the fine aggregates will not satisfactorily fill the voids; consequently, such will lead to the decrease in skeleton stability. At present, there are two main methods employed to identify and analyse the internal meso-structure of the asphalt mixture: digital image processing (DIP) techniques and numerical analysis methods (NAM). Some studies have analysed the mesoscopic characteristics of the coarse aggregate skeleton within the asphalt mixture by DIP and NAM. Based on the particle packing theory, Roque et al. proposed the main skeleton dominant aggregate size range (DASR) method, which separates the particles in the mixture into main skeleton aggregates and fine aggregates [3–6]. Based on the particle packing theory, the void characteristics of the main skeleton are obtained, the minimum particle size of the interference on skeleton embedding is determined, and the relationship between the particle interference and macroscopic performance of asphalt mixture is established. On this basis, Yideti et al. performed further research on the influence of the skeleton structure of loose aggregates and asphalt mixture on the rutting performance [7–9]. Tan [10] established the interference coefficient of the particle gradation evaluation index based on the particle packing theory, obtained the relationship between the spatial distribution of voids and particle contact in the asphalt mixture, and studied the influence of gradation on the meso-structure of the asphalt mixture. A discrete element model of an asphalt mixture with different coarse aggregate morphologies and particle sizes has been established using the Partial Flow Code in Two Dimensions (PFC 2D) software. The virtual test results of the aggregate skeleton mesoscopic analysis show that the discrete element method (DEM) can rapidly and accurately predict the stress–strain characteristics of the coarse aggregate; the results are consistent with those obtained from laboratory tests [11]. A three-dimensional DEM model has also been established using the Particle Flow Code in Three Dimensions (PFC 3D) software to track the rutting deformation of the asphalt mixture. From a mesoscopic mechanical view, the aggregate shape has a significant influence on the horizontal, vertical, and rotational movement characteristics of the asphalt mixture. There is good interlocking at the contact points among aggregates that restricts the movement of coarse aggregates, and there is sufficient contact within the aggregate skeleton to bear the contact force. The foregoing is important to guarantee the rutting resistance of an asphalt mixture [12,13]. Meanwhile, research findings show that there is a strong correlation between the internal skeleton structure indices of contact points, the aggregate size, the inclination angle,
and the rutting performance of the asphalt mixture [14–17]. In relation to the voids in the mineral aggregate (VMA), the aggregate skeleton of the asphalt mixture is a significant factor that affects critical asphalt mixture properties, such as durability, workability, permeability, rutting resistance, and cracking resistance. An analytical approach for estimating changes in the VMA because of gradation variation and determining the relevant aggregate skeleton characteristics of asphalt mixtures is the linear-mixture packing model, which is an analytical packing model that considers the mechanisms of particle packing, filling, and occupation [18]. Furthermore, a skeleton penetration test is developed to evaluate the skeleton strength of porous asphalt mixtures; the results show that skeleton strength correlates well with the rutting resistance [19].

The investigations on the skeleton structure from a mesoscopic perspective mainly include the statistics and analysis of the main skeleton’s meso-structural characteristics, the motion tracking of coarse aggregates subjected to load, and the numerical simulation and validation of the skeleton structure. However, based on the DIP, the gradual meso-structural response behaviour of characteristics of the asphalt mixture main skeleton subjected to load has not been quantitatively analysed, and quantitative mesoscopic evaluation indices and criteria for the main skeleton have not been established. Based on the above background and through the design of unique experiments, this study applies the DIP to analyse the aforementioned gradual meso-structural response behaviour from a mesoscopic perspective. According to the evaluation of the meso-performance of the designed main skeleton of the asphalt mixture, the gradation optimisation measures and experimental criteria for the quantitative mesoscopic evaluation indices for the main skeleton are proposed. It is anticipated that these can be used as references for the design and gradation optimisation of DSAM.

2. Research Approach

In this study, the DIP is employed to examine the gradual meso-structural response behaviour of the asphalt mixture main skeleton. On the one hand, it is necessary to select appropriate mesoscopic quantitative evaluation indices for the main skeleton in order to objectively assess its performance. On the other hand, it is necessary to obtain clear cross-sectional images of the asphalt mixture to ensure analysis accuracy.

2.1. Mesoscopic Evaluation Indices for the Main Skeleton

In the composition of asphalt mixture materials, aggregates with a mass ratio of more than 90% constitute the skeleton. The main skeleton is composed of coarse aggregates that are in contact, and such contact provides a path for the transmission of load stress. A contact point is a part of the main skeleton and is a connecting medium of load stress transfer. Because a contact point is a weak link in the skeleton, it is an important parameter that reflects the performance of the main skeleton [20,21]. At present, there are no unified mesoscopic indices to evaluate the meso-structure of asphalt mixtures. Previous researches have demonstrated that the number of aggregate-to-aggregate proximity zones, total proximity zone length and proximity zone plane orientation [22], the number of contact points and the orientation of coarse aggregates [14,16], as well as the contact force at the contact points [23,24], as the indices to evaluate the stress characteristics of the main skeleton. In this study, the DIP is used to evaluate the interlocked characteristics of the main skeleton; moreover, appropriate mesoscopic evaluation indices, including the coordination number, average coordination number, and C value are proposed.

(1) Coordination number and average coordination number

The coordination number—as one of the main factors that affects stress transfer, strength, and deformation properties of granular materials—is defined as the quantity of contact points between a particle in the aggregate and its adjacent particles. It is an important meso-structure parameter that reflects the accumulation and mesoscopic mechanical behaviour of granular materials.

The average coordination number is defined as the average contact quantity of the particles in the particle system. The larger the average coordination number, the closer the main skeleton structure
and the better the stability of the mixture when subjected to load. The calculation expression is shown in Equation (1) [25]:

\[
\bar{n}_c = \frac{1}{N} \sum_{i=1}^{N} n_{c_i}
\]

where \(\bar{n}_c\) is the average coordination number; \(N\) is the quantity of coarse aggregates in the asphalt mixture; \(n_{c_i}\) is the coordination number of coarse aggregates, \(i\).

(2) C value of the ‘suspended’ coarse aggregate content

Asphalt mixture is composed of coarse aggregate and asphalt mortar; non-uniformity is one of its characteristics. Some coarse aggregates in asphalt mixtures do not come into contact with other aggregates and are ‘suspended’ in the asphalt mortar. The C value of the ‘suspended’ coarse aggregate content is defined as the ratio of the quantity of coarse aggregates without contact points to the total quantity of coarse aggregates. The smaller the C value, the closer the main skeleton structure. The calculation method is expressed in Equation (2):

\[
C = \frac{n}{N}
\]

where \(N\) and \(n\) are the total quantity of coarse aggregates in the asphalt mixture and the quantity of coarse aggregates without contact points, respectively.

2.2. Image Processing and Acquisition Method of Mesoscopic Evaluation Indices for the Main Skeleton

(1) Obtain cross-sectional images of asphalt mixture method

In order to ensure the accuracy of the analysis, the method of obtaining the cross-sectional images of the asphalt mixture is extremely important. Currently, there are two main technical methods to obtain cross-sectional images: photography using a charge-coupled device (CCD) digital camera and scanning based on X-ray computed tomography (X-ray CT). As listed in Table 1, the two methods have different characteristics, accuracies, and scopes of application.

| Image Acquisition Method | Advantages | Disadvantages | Cross-Sectional Image of Specimen |
|--------------------------|------------|---------------|----------------------------------|
| Scanning based on X-ray CT | 1. Non-destructive; testing method causes no damage to specimens 2. Continuous asphalt mixture tomographic images can easily be obtained; 3D reconstruction can be achieved with a computer | 1. A long debugging time is necessary to acquire the cross-sectional image of the same position before and after loading; errors are easily produced 2. Acquired image is blurred, making it difficult to identify the boundary between aggregate and asphalt; the error of subsequent image processing and analysis is relatively large | ![Cross-Sectional Image](image1) |
| Photography by CCD digital camera | 1. Affords shooting of specimen before and after dynamic loading; precise shooting position is guaranteed when the specimen is cut 2. Cross-sectional image is clear and highly precise; greyscale typically shows an ideal ‘bimodal’ distribution and facilitates subsequent processing and analysis | 1. Specimen can be damaged by cutting 2. Multiple groups of specimens are required to obtain more cross-sectional images; test workload is large | ![Cross-Sectional Image](image2) |

In order to ensure the rationality of the design test and the accuracy of data analysis presented in Section 3.2, the requirements for the cross-sectional image of the asphalt mixture are as follows: (1) the cross-sectional image of the same position must be obtained before and after loading; (2) the contact analysis threshold should be 0.54 mm, and the accuracy of the identification of aggregate boundary has to be considerably high. After a comprehensive comparison of the advantages and disadvantages between X-ray CT scanning and CCD digital camera photography summarised in Table 1, a special
cutting machine (a high-precision diamond double-sided saw) is employed in this experiment to cut the asphalt mixture specimens. Thereafter, a CCD digital camera is employed to photograph the specimen cross-sections. This method not only ensures that the same position in the specimen is photographed before and after loading, but also guarantees image clarity. To ensure accurate data analysis, the technique of fabricating multiple groups of specimens is adopted to obtain a sufficient number of images for statistical analysis.

(2) Image processing and contact analysis method

Image processing and contact analysis procedures are performed mainly according to the method proposed in a previous study [26]. Generally, the grey histogram distribution curve of the asphalt mixture image acquired by the digital camera has distinct ‘double peak’ characteristics. After determining the grey value demarcation points (T1 and T2) of voids, asphalt mortar, and aggregates, the image is binarised using the double peak method; the effect of image processing is good, as shown in Figure 1.

![Figure 1. Image processing](image1)

After the image binarisation is completed, the contact analysis is performed using iPas software, designed by Prof. Hussain Bahia of the University of Wisconsin–Madison and Prof. M. Emin Kutay of Michigan State University [26]. The main steps are as follows. Based on the two-dimensional section binary image of the mixture and input parameters, such as raw materials, asphalt mixture gradation, and volume indices, the software calculates the equivalent diameter of each coarse aggregate according to the equivalent diameter method and numbers it. Thereafter, the parameters of the calculated minimum particle size and the aggregate contact threshold are inputted to quantify the coarse aggregate contact details, such as contact point location, number and particle size of contact aggregates, and quantity of contact points. After obtaining the number and particle size of the coarse aggregates, the quantity of contact points around each coarse aggregate, i.e., the coordination number \( \pi_c \) and C value, can be obtained by the statistical analysis of data, as shown in Figure 2. The surface distance threshold (SDT) value is related to the calculated minimum particle size of aggregates that has a significant influence on the contact analysis results of coarse aggregates. Existing studies show that the SDT value is generally 0.20–0.25 times of the calculated minimum particle size of aggregates [27,28]. Therefore, the minimum calculated particle size of aggregates is 0.23 times the SDT value in this study; the minimum particle size is 2.36 mm, and the SDT value is set to 0.54 mm.

![Figure 2. Image processing and contact analysis](image2)
3. Materials and Test Design

3.1. Materials

Three types of asphalt mixtures are tested in the study—70# asphalt AC-13C: AC-13C asphalt mixture with 70# binder; rock asphalt AC-13C: AC-13C asphalt mixture with UM native rock modified binder based on 70# asphalt (the UM native rock asphalt content is 8%, as percentages of 70# asphalt by weight, which is the optimum content); SMA-13: SMA-13 asphalt mixture with SBS modified asphalt.

The material, gradation and asphalt aggregate ratio of 70# asphalt AC-13C and rock asphalt AC-13C are the same; the only difference is that the latter incorporates 8% UM natural rock asphalt to improve the performance of the asphalt mortar. The material properties are listed in Tables 2–4, and the gradation is summarised in Table 5.

**Table 2.** Asphalt properties.

| Parameters                              | Technical Parameters |
|----------------------------------------|----------------------|
|                                        | 70# Binder | SBS Modified Binder |
| Penetration (25°C, 100 g, 5 s, 0.1 mm) | 66         | 62                   |
| Ductility (5 cm/min, 5°C, cm)          | 135        | 147                  |
| Softening point (°C)                   | 50.0       | 79.0                 |
| Density of bitumen (15°C, g cm⁻³)      | 1.058      | 1.033                |

**Table 3.** Properties of UM native rock asphalt.

| Appearance | Ash Content (%) | Water Content (%) | Asphalt Content (%) | Density (g cm⁻³) |
|------------|-----------------|-------------------|--------------------|-----------------|
| Black powder | 12               | 1.28              | 88                 | 0.765           |

**Table 4.** Properties of additive dosages.

| Type of Mixture     | Type of Aggregate | Cement Content (%) | Mineral Powder Content (%) | Lignin Fibre Content (%) | Asphalt Content (%) |
|---------------------|-------------------|--------------------|---------------------------|-------------------------|---------------------|
| 70# asphalt AC-13C  | Granite            | 2.0                | –                         | –                       | 4.9                 |
| Rock asphalt AC-13C | Granite            | 2.0                | –                         | –                       | 5.0                 |
| SMA-13              | Basalt             | –                  | 11.0                      | 3.5                     | 6.0                 |

**Table 5.** Gradation of mixtures.

| Sieve Size (mm) | AC-13C Passing Rate (%) | SMA-13 Passing Rate (%) |
|-----------------|-------------------------|-------------------------|
| 16              | 100                     | 100                     |
| 13.2            | 99.5                    | 99.5                    |
| 9.5             | 75.9                    | 75.9                    |
| 4.75            | 40.3                    | 40.3                    |
| 2.36            | 31.4                    | 27.3                    |
| 1.18            | 23.5                    | 22.5                    |
| 0.6             | 16.5                    | 18.9                    |
| 0.3             | 9.8                     | 14.0                    |
| 0.15            | 6.7                     | 12.8                    |
| 0.075           | 4.3                     | 10.0                    |

3.2. Test Design

In order to study the gradual meso-structural response behaviour of the asphalt mixture main skeleton subjected to load, on the one hand, it is necessary to select the appropriate loading method.

On the other hand, it is necessary to obtain the cross-sectional images of the asphalt mixture at different loading stages, process the images, and perform contact analysis to obtain the main skeleton’s mesoscopic evaluation indices, including coordination number, average coordination number, and C value. In this study, the indoor rutting test is used to simulate the effect of repeated vehicle load on the asphalt mixture. According to the current standard of asphalt mixtures in China [29], rut specimens with dimensions of 300 mm × 300 mm × 50 mm are prepared using a wheel rolling machine, and the number of rolling times is 24 (12 round trips); 100% + 1% of the Marshall standard density is reached.
The three groups of specimens are made from each mixture to obtain more images, and ensure the accuracy of the analysis. The average volume indices of each mixture are listed in Table 6.

Table 6. Volume indices of the asphalt mixtures.

| Type of Mixture       | \(\gamma_f\) (g cm\(^{-3}\)) | \(\gamma_t\) (g cm\(^{-3}\)) | VV (%) | VMA (%) | VFA (%) |
|-----------------------|-------------------------------|-------------------------------|--------|---------|---------|
| 70# asphalt AC-13C    | 2.405                         | 2.505                         | 4.0    | 14.8    | 73.2    |
| Rock asphalt AC-13C   | 2.412                         | 2.506                         | 3.8    | 14.8    | 74.6    |
| SMA-13                | 2.362                         | 2.467                         | 4.3    | 17.0    | 75.0    |

The method for obtaining images at different loading stages is as follows: after preparing the specimen, it is cut along the middle line in the wheel rolling direction using a high-precision double-sided diamond saw; the specimen is cut into two parts of equal lengths. Thereafter, the specimen section is photographed using a high-definition digital camera to obtain a cross-sectional image of the asphalt mixture, as shown in Figure 3. Since the thickness of double-sided saw is 4 mm, there will be a small gap between the edge of the mould and specimen when the cut specimen is replaced into the mould. In order to ensure that the sidewall of the mould has a strong restraining effect on the specimen, the gap between the edge of the mould and specimen is filled with a rubber pad; this eliminates the influence of specimen cutting on test results.

![Figure 3. Specimen cutting and image acquisition methods. (a) Specimen cutting; and (b) image acquisition.](image)

In the rutting test, the temperature is maintained at 60 ± 0.5 °C, the load is 0.7 MPa, and the wheel rolling speed is 42 times/min (one way). Every loading hour (2520 loading times), the specimen is taken out of the mould to be photographed for obtaining a cross-sectional image of the asphalt mixture; thereafter, the specimen is replaced into the mould for the next stage of loading until the change in the number of contact points is insignificant or some coarse aggregates break up, as shown in Figure 4d. The loading durations of 1, 2, 3, and 4 h correspond to 2520, 5040, 7060, and 10,080 times, respectively. To ensure the accuracy of test data according to the analysis listed in Table 1, the only approach is to prepare several specimens and obtain as many images as possible; this is because only two cross-sectional images can be obtained for each specimen. In this test, at least five groups of specimens are made for each mixture.

![Figure 4. Original cross-sectional image and broken aggregates. (a) 70# asphalt AC-13C; (b) rock asphalt AC-13C; (c) SMA-13; and (d) broken aggregates.](image)
3.3. Effect of Specimen Cutting on the Test Results

The test pieces are cut and, thereafter, assembled together for the rutting test. A rubber pad is used to fill the small gap at the edge of the mould to eliminate the influence of specimen cutting on test results. However, the change in the spatial position of aggregate particles in the asphalt mixture subjected to load after cutting is different from that of the uncut specimen. In order to compare their differences, 70# asphalt AC-13C mixture and SMA-13 mixture are used in the comparative tests. Six groups of specimens for rutting are made for each mixture. In the test, three groups of specimens are cut and photographed after 1-h loading, and the other three groups are cut after 2-h loading to obtain the images of their cross-sections. By comparing the quantity of contact points between the cut and uncut specimens, the difference between the two test methods can be verified. The results are summarised in Table 7.

Table 7. Effect of specimen cutting on quantity of contact points.

| Specimens         | Quantity of contact points (total quantity) | Before loading | After 1-h Loading | After 2-h Loading |
|-------------------|---------------------------------------------|----------------|------------------|-------------------|
| 70# asphalt AC-13C| Cut specimen                                | 207            | 233              | 257               |
|                   | Uncut specimen                              | 234            | 209              | 274               |
| SMA-13            | Cut specimen                                | 162            | 192              | 207               |
|                   | Uncut specimen                              | 155            | 203              | 219               |

The results listed in Table 7 indicate that the number of contact points in the cut specimens has relative errors at all loading stages compared with the uncut specimens; the errors in SMA-13 and 70# asphalt AC-13C are approximately 5.4% and 9.8%, respectively. Although specimen cutting has caused some errors on the test results, these are still within the allowable range of accuracy.

4. Results and Discussion

4.1. Gradual Microscopic Contact Behaviour of the Main Skeleton

4.1.1. Mesoscopic Contact Characteristics of the Main Skeleton

Figure 5 shows the mesoscopic contact characteristics of the main skeletons of 70# asphalt AC-13C, rock asphalt AC-13C, and SMA-13 before loading, as well as the spatial distribution of coarse aggregates and contact points. The gradual change in the mesoscopic contact characteristics of SMA-13 main skeleton at different loading stages are shown in Figure 6.

Figure 5. Mesoscopic contact characteristics of main skeleton before loading. (a) 70# asphalt AC-13C; (b) rock asphalt AC-13C; and (c) SMA-13.
4.1.2. Gradual Development of Contact Point Characteristics

4.1.3. Contribution Rate of Coarse Aggregate Particle Size to Contact Points

Figure 6. Gradual change in mesoscopic contact characteristics of SMA-13 main skeleton. (a) Before loading; (b) after 1-h loading; (c) after 2-h loading; and (d) after 3-h loading.

The following can be observed in Figures 5 and 6.

(1) Gradation is the main determinant of the spatial distribution of aggregates and contact points. As shown in Figure 5, in AC-13C and SMA-13 mixtures, not only are the particle size and distribution of aggregates different, but also the quantity of contact points, the uniformity of aggregates, and contact points considerably differ.

(2) The inhomogeneous distribution of aggregates and contact points is a typical feature of an asphalt mixture because it is composed of granular materials. As a typical DSAM, the distribution of coarse aggregates and contact points in SMA-13 are inhomogeneous. For the three types of asphalt mixtures, considerable quantities of ‘suspended’ coarse aggregates do not come into contact with other aggregates and are not involved in the formation of the main skeleton. Although AC-13C has more contact points, their distribution is more inhomogeneous than that in SMA-13; moreover, there are more ‘suspended’ coarse aggregates in the former.

(3) Coarse aggregates move under the action of load; accordingly, the quantity of contact points and contact position will change. Hence, the quantity of contact points will increase, and the quantity of ‘suspended’ coarse aggregates will decrease.

4.1.2. Gradual Development of Contact Point Characteristics

Under the action of load, the asphalt mixture macroscopically manifests deformation and microscopically manifests an increase in the number of contact points and a decrease in the number of ‘suspended’ coarse aggregates. Figure 7 shows the total number of contact points in the three types of asphalt mixtures at each loading stage. In order to study the quantity of contact points and the development trend of rutting when the material is subjected to loading, the relationship between the quantity of contact points and rut depth (RD) at each loading stage is shown in Figure 8.

Figure 7. Gradual development of contact point.
The following can be observed in Figures 7 and 8:

(1) Under the load action, the asphalt mixture is continuously compacted, and the macroscopic rut depth increases as the number of mesoscopic contact points increases. The rut depth and number of contact points increase rapidly at the initial loading stage and tend to be steady at the end of loading. The quantity of contact points formed by coarse aggregates larger than 2.36 mm has a good linear correlation with the RD.

(2) The quantity range of contact points in the two-dimensional cross-sectional images is determined by gradation; it has no relationship with the type of asphalt. A large number of contact points do not indicate that the mixture has a better rutting resistance performance. For instance, as shown in Figure 8, although the quantity of contact points in SMA-13 is less than that in AC-13C, the rutting resistance of the former is better than the latter; this resistance may be related to the coarse aggregate content. By comparing the passing rates of 13.2-, 9.5-, and 4.75-mm coarse aggregates, it is found that the amount of coarse aggregates with particle sizes larger than 4.75 mm in SMA-13 is considerably higher than that in AC-13C, whereas the amount of aggregates that are 2.36–4.75 mm in AC-13C is considerably higher than that in SMA-13. Although the aggregates in the size range 2.36–4.75 mm can provide more contact points, the smaller particle size could result in an unsteady skeleton structure. For this reason, when the material is subjected to load, relative displacements are easily generated; this leads to poor rutting resistance. The main skeleton structure constituted by a moderately large quantity of coarse aggregates with particle sizes larger than 4.75 mm is steadier and has a better ability to resist external loads. Therefore, the quantity of contact points cannot be used to evaluate the rutting resistance of asphalt mixture; the stability of contact points in the main skeleton is the key factor that affects rutting resistance.

(3) The asphalt performance has an insignificant influence on the initial quantity of contact points; however, it has a certain influence on the increase in the number of contact points. In Figure 7, it can be noted that there is only a slight difference in the number of initial contact points between 70# asphalt AC-13C and rock asphalt AC-13C. However, with the increase in loading time, the quantity of contact points in 70# asphalt AC-13C slightly increases faster than that in rock asphalt AC-13C although both mixtures have the same gradations. The harder the asphalt, the more it can restrain the movement of aggregates and ensure the stability of contact points in the main skeleton; consequently, the rutting deformation is relatively small.

In summary, the internal friction is larger in the main skeleton that contains more coarse aggregates with particle sizes larger than 4.75 mm, whereas the cohesion of asphalt with a higher peformance grade (PG) is greater. Hence, in the design of asphalt mixtures, increasing the amount of coarse aggregates with particle sizes larger than 4.75 mm and using asphalt with a higher PG grade are important considerations to form a steadier main skeleton and increase its rutting resistance performance.
4.1.3. Contribution Rate of Coarse Aggregate Particle Size to Contact Points

The rutting resistance of asphalt mixtures is closely related to the size of coarse aggregates constituting the main skeleton. The contribution of coarse aggregates with different particle sizes to the contact points is an important factor for determining the stability of the main skeleton. The contact analysis is performed using iPas software; the coordination number of each coarse aggregate can be obtained by statistical analysis after determining the number and particle size information of each coarse aggregate. The contact distribution statistics of coarse aggregates with different sizes at different loading stages are summarised in Table 8, in which the bold italic numbers indicate the peak value positions. In this table, 2.36 mm $\rightarrow$ 2.36 mm indicates that the coarse aggregates with particle sizes of 2.36–4.75 mm come into contact with 2.36–4.75 mm coarse aggregates; 2.36 mm $\rightarrow$ 4.75 mm indicates that the coarse aggregates with particle sizes of 2.36–4.75 mm come into contact with 4.75–9.5 mm coarse aggregates; the rest may be deduced by analogy.

| Type of Mixture | Loading Time (h) | Contact Distribution of Coarse Aggregates with Different Particle Sizes (mm) |
|-----------------|------------------|----------------------------------------------------------------------------|
|                 | Before loading   | $\downarrow$ $\downarrow$ $\downarrow$ $\downarrow$ $\uparrow$ $\uparrow$ $\uparrow$ $\uparrow$ $\downarrow$ |
|                 | After 1-h loading| $\downarrow$ $\downarrow$ $\downarrow$ $\downarrow$ $\uparrow$ $\uparrow$ $\uparrow$ $\uparrow$ $\downarrow$ |
|                 | After 2-h loading| $\downarrow$ $\downarrow$ $\downarrow$ $\downarrow$ $\uparrow$ $\uparrow$ $\uparrow$ $\uparrow$ $\downarrow$ |
| SMA-13          | After 3-h loading| $\downarrow$ $\downarrow$ $\downarrow$ $\downarrow$ $\uparrow$ $\uparrow$ $\uparrow$ $\uparrow$ $\downarrow$ |
| Before loading  | 6 30 11 2       | 63 37 5 7 1 0 |
| After 1-h loading| 2 39 12 2      | 81 42 4 8 2 0 |
| After 2-h loading| 5 46 15 2      | 78 48 4 8 1 0 |
| After 3-h loading| 4 47 17 2      | 82 49 4 8 1 0 |

**Remark:** The bold italic numbers indicate the peak value positions.

The data summarised in Table 8 indicate the following.

1. In 70# asphalt AC-13C and rock asphalt AC-13C, the maximum quantities of contact points among coarse aggregates with different particle sizes are found when the particles are 2.36 $\rightarrow$ 4.75 mm, 4.75 $\rightarrow$ 4.75 mm, and 2.36 $\rightarrow$ 2.36 mm; the peak value of contact points is found in coarse aggregates that are 2.36 $\rightarrow$ 4.75 mm, and the contribution rate of coarse aggregates with particle sizes larger than 4.75 mm to the number of contact points is less than 60%. In SMA-13, the maximum quantities of contact points among coarse aggregates are found when the particles are 4.75 $\rightarrow$ 4.75 mm, 4.75 $\rightarrow$ 9.5 mm, and 2.36 $\rightarrow$ 4.75 mm; the peak value of contact points is found in coarse aggregates that are 4.75 $\rightarrow$ 4.75 mm, and the contribution rate of coarse aggregates with particle sizes larger than 4.75 mm to the number of contact points reaches 80%. In AC-13, although aggregates with particle sizes of 2.36–4.75 mm can effectively increase the quantity of contact points, the mixture’s rutting resistance is relatively poor because of the smaller particle sizes and the insufficient stability of the main skeleton. When particle sizes are larger than 4.75 mm, especially when the contribution rate of coarse aggregates larger than 9.5 mm to the number of contact points is high, the coarse aggregates can form a relatively steady main skeleton structure. Therefore, coarse aggregates with particle sizes larger than 4.75 mm provide the largest contribution to the formation of a steady main skeleton.

2. The total number of contact points in the coarse aggregates increases with the increase in loading time. The quantity of contact points that involves coarse aggregates with particle sizes less than...
9.5 mm increases rapidly under load, whereas the number of contact points involving coarse aggregates with particle sizes larger than 9.5 mm increases gradually. In coarse aggregates with particle sizes of 13.2–16.0 mm, the quantity of contact points tends to be steady and barely changes during loading.

4.2. Gradual Change Behaviour of Mesoscopic Evaluation Indices for the Main Skeleton

4.2.1. Gradual Trend of Coarse Aggregate Coordination Number

The distribution characteristics of the coordination number in the three types of asphalt mixtures at different loading stages are summarised in Table 9; the bold italic numbers represent the peak positions.

Table 9. Coordination number distribution at different loading stages.

| Loading Time (h) | Coordination Number |
|------------------|--------------------|
|                  | 0      | 1      | 2      | 3      | 4      | 5      |
| 0                |        |        |        |        |        |        |
| 1                |        |        |        |        |        |        |
| 2                |        |        |        |        |        |        |
| 3                |        |        |        |        |        |        |
| 4                |        |        |        |        |        |        |
| 5                |        |        |        |        |        |        |

The data listed in Table 9 indicate the following:

(1) The maximum and minimum coordination numbers of coarse aggregates are 5 and 0 respectively. The particles with coordination numbers of 4 and 5 are mainly coarse aggregates with particle sizes larger than 4.75 mm; the number of these particles is relatively small. There are more coarse aggregates with coordination number of 0 in the three types of asphalt mixture; this indicates that there are more coarse aggregates that do not come into contact with other coarse aggregates and can be regarded as ‘free’ coarse aggregates.

(2) With the increase in loading time, the quantity of coarse aggregates with coordination numbers of 0 and 1 decreases gradually, whereas the quantity of coarse aggregates with coordination numbers larger than 2 increases continuously. Before loading, the proportion of coarse aggregates with a coordination number of 0 to the total coarse aggregates decreases from 30% to approximately 7%. At the end of the loading stage, the proportion of coarse aggregates with a coordination number larger than 3 to the total coarse aggregates increase gradually from 11% to 36% and from 7% to 24% in SMA-13 and AC-13C, respectively.

(3) With the asphalt mixture being continuously compacted under the load action, the peak position of the coordination number gradually moves to the direction of increase. The peak value of coordination number in the three types of asphalt mixtures before loading and after 1-h loading is 1. The peak value at the end of the loading stage is 2; at this point, the amount of coarse aggregates with the peak coordination number is approximately 35% of the coarse aggregate amount.
(4) The Gauss regression model can well describe the relationship between the coordination number and the corresponding amount of coarse aggregates; the general regression equation is expressed by Equation (3) below:

\[ N = y_0 + \frac{A}{W \times \sqrt{\pi/2}} e^{-\frac{(n-x_c)^2}{2w^2}} (n > 0) \]  

where \( n \) is the coordination number, whose value is always larger than 0; \( N \) is the natural number, which represents the total quantity of coarse aggregates corresponding to each coordination number; \( y_0, x_c, W, \) and \( A \) are the coefficients of the Gaussian distribution function. For the three types of asphalt mixtures in the tests, Figure 9a,b shows Gaussian fitting curves before loading and after 3-h loading, respectively; the coefficients are both greater than 0.9. The coefficients of the Gaussian distribution function are listed in Table 10.

![Figure 9. Gaussian fitting curves. (a) Before loading; and (b) after 3-h loading.](image)

| Coefficient | \( y_0 \) | \( x_c \) | \( W \) | \( A \) | \( R^2 \) |
|-------------|-------------|-------------|-------------|-------------|-------------|
| 70# asphalt AC-13C | Before loading | -0.937 | 0.886 | 2.372 | 338.191 | 0.9717 |
| | After 3-h loading | 4.506 | 1.776 | 1.916 | 268.700 | 0.9962 |
| Rock asphalt AC-13C | Before loading | -1.091 | 1.124 | 2.182 | 313.786 | 0.9890 |
| | After 3-h loading | 3.897 | 1.685 | 1.870 | 266.512 | 0.9827 |
| SMA-13 | Before loading | 4.700 | 0.857 | 1.982 | 213.012 | 0.9829 |
| | After 3-h loading | 0.617 | 2.016 | 2.382 | 224.909 | 0.9154 |

### 4.2.2. Gradual Change Trend of \( \bar{\pi}_c \) and C Value

The \( C \) value and \( \bar{\pi}_c \) are obtained by contact analysis using iPas software and, thereafter, by statistical analysis of the data. For the three types of asphalt mixtures in the tests, the gradual change in the trends of \( \bar{\pi}_c \) and \( C \) value with loading time is shown in Figure 10.

According to Figure 10, the following can be concluded:

1. The value of \( \bar{\pi}_c \) increases with the increase in loading time. When the asphalt mixture is loaded to the ultimate bearing capacity of the main skeleton, the \( \bar{\pi}_c \) values of SMA-13 and AC-13C approach 2 and 1.6, respectively. In the design process of DSAM, gradation should be optimised with the goal of increasing \( \bar{\pi}_c \) so as to enhance the main skeleton’s load resistance.

2. The \( C \) value decreases with the increase in loading time. The asphalt mixture is continuously compacted under the load action, the ‘suspended’ coarse aggregates without contact points gradually come into contact with other coarse aggregates, and the quantity of coarse aggregates gradually decreases. The proportion of coarse aggregates with a coordination number of 0 to the total coarse aggregates gradually decreases from 30% before loading to approximately 7% at the end of the loading.
stage. In the design process of DSAM, a reasonable compaction standard should be selected to ensure the compaction power and to minimise the amount of ‘suspended’ coarse aggregates.

![Graph showing gradual change trends of \( \bar{c}_n \) and C value.](image)

**Figure 10.** Gradual change trends of \( \bar{c}_n \) and C value.

### 4.3. Design Criteria of Mesoscopic Evaluation Indices for the Main Skeleton

#### 4.3.1. Relationship between Mesoscopic Evaluation Indices and the Macroscopic Index of the Main Skeleton

The typical characteristics of DSAM are as follows: coarse aggregates in the asphalt mixture constitute the main skeleton; fine aggregates, asphalt, and other admixtures constitute the asphalt mortar that fills the voids of the main skeleton formed by the coarse aggregates and binds as well as restrains the main skeleton so that the asphalt mixture forms a high-strength integrated material. This means that the strength of asphalt mixture is mainly composed of two parts: the main skeleton composed of coarse aggregates and the asphalt mortar, which binds and restrains the main skeleton. The relationship between the mesoscopic evaluation indices (\( \bar{c}_n \) and C value) and macroscopic index (RD) of the main skeleton is shown in Figure 11. At the end of the loading stage, when the main skeleton has exerted its maximum capacity to resist the load and has reached the critical value, its corresponding mesoscopic and macroscopic indices are those listed in Table 11.

![Graph showing relationship between \( \bar{c}_n \), C value, and RD.](image)

**Figure 11.** Relationship between \( \bar{c}_n \), C value, and RD.

| Material Type | Average Coordination Number (70# asphalt AC-13C) | Average Coordination Number (Rock asphalt AC-13C) | Average Coordination Number (SMA-13) | C Value (70# asphalt AC-13C) | C Value (Rock asphalt AC-13C) | C Value (SMA-13) |
|---------------|-----------------------------------------------|-----------------------------------------------|----------------------------------|----------------------------|----------------------------|-----------------|
| AC-13C        | 1.78                                          | 1.88                                          | 2.15                              | 1.95                       | 6.55                       | 1.82            |
| AC-13M        | 1.78                                          | 1.88                                          | 2.15                              | 1.95                       | 6.55                       | 1.82            |
| SMA-13        | 1.82                                          | 1.88                                          | 2.15                              | 1.95                       | 6.55                       | 1.82            |

Table 11. Corresponding mesoscopic and macroscopic indices when main skeleton reaches critical value.
Table 11. Corresponding mesoscopic and macroscopic indices when main skeleton reaches critical value.

| Type of Mixture | Mesoscopic Indices | Macroscopic Indices |
|-----------------|--------------------|---------------------|
|                 | Coordination       | C (%)               |
|                 | Number Peak Value  | DS (times·mm⁻¹)     |
|                 |                     | RD at Loading Time of 1 h (mm) | RD at Loading Time of 3 h (mm) |
| 70# asphalt AC-13C | 1.78               | 7.48               | 2136               | 5.88               | 10.26               |
| Rock asphalt AC-13C | 1.69               | 7.29               | 3980               | 2.50               | 5.25               |
| SMA-13          | 2.02               | 4.89               | 4222               | 1.46               | 3.64               |
| Average value   | 1.83               | 6.55               | 3446               | 3.28               | 6.38               |

Based on Figure 11 and Table 11, the following can be concluded.

1. Asphalt mixture is continuously compacted under the load action; \( \bar{n}_e \) increases with the increase in RD, whereas the C value gradually decreases. At the end of the loading stage, the mesoscopic characteristics of the main skeleton indicate that the quantity of contact points only slightly increases, and some coarse aggregates break up; the macroscopic characteristics indicate that rutting develops gradually. At this point, it can be considered that the main skeleton has exerted its maximum ability to resist load and has approached the critical value.

2. When the main skeleton reaches the critical value, the mesoscopic evaluation indices and the macroscopic index for each asphalt mixture are as follows. For 70# asphalt AC-13C: \( \bar{n}_e = 1.88 \), \( C = 7.48\% \), \( RD = 10.26 \) mm; for rock asphalt AC-13C: \( \bar{n}_e = 1.82 \), \( C = 7.29\% \), \( RD = 5.25 \) mm; for SMA-13: \( \bar{n}_e = 2.15 \), \( C = 4.89\% \), \( RD = 3.64 \) mm. The mesoscopic and macroscopic indices show that gradation is the major determinant of the mesoscopic evaluation indices for the main skeleton of the asphalt mixture, and the asphalt performance mainly affects the development trend of macroscopic rutting.

4.3.2. Design Criteria of Mesoscopic Evaluation Indices for the Main Skeleton

According to the specifications [30], in the hot summer zone of China, the dynamic stability (DS) of the asphalt mixture rutting test must be 1000, 2800, and 3000 times/mm for non-modified asphalt mixture, modified asphalt mixture, and modified SMA mixture, respectively. In order to ensure the rutting resistance of the asphalt mixture, it is assumed that the DS standard of the designed asphalt mixture should be more than 2000 and 5000 times/mm for the non-modified asphalt mixture and modified asphalt mixture, respectively. According to the calculation of DS given by Equation (4), the deformations between 45 and 60 min during the rutting test are 0.315 and 0.126 mm, respectively:

\[
DS = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \times C_1 \times C_2
\]

where \( t_1 = 45 \) min; \( t_2 = 60 \) min; \( d_1 \) is the deformation at time \( t_1 \); \( d_2 \) is the deformation corresponding to time \( t_2 \); \( C_1 \) is the type coefficient of the rutting test machine (generally, its value is 1.0); \( C_2 \) is the test coefficient when the 300-mm wide specimen is prepared in the laboratory (its value is 1.0); \( N \) is the rolling speed of the test wheel (usually 42 times/min).

There are several internal factors that affect the rutting resistance of asphalt mixture; these include coarse aggregate performance, asphalt performance, and gradation and admixture performance. According to the test results and reports in literature, it is typically assumed that the compaction deformation of the initial rutting tests for 0–45 min is 2.0 mm [31]. Therefore, during the standard rutting test of asphalt mixture, when the deformation of non-modified asphalt mixture reaches 2.315 mm and that of modified asphalt mixture reaches 2.126 mm, the main skeleton reaches the critical value of the external load. Based on the data in Figure 11 and Table 11, to ensure that the DS of the non-modified asphalt mixture should be more than 2000 times/mm and that of modified asphalt mixture should be more than 5000 times/mm, the corresponding main skeleton mesoscopic evaluation indices of asphalt mixtures should be at least \( \bar{n}_e \geq 1.5 \) and \( C \leq 15\% \). Accordingly, this paper proposes that the design criteria of mesoscopic evaluation indices for the main skeleton be \( \bar{n}_e \geq 1.5 \) and \( C \leq 15\% \) in the preparation of asphalt mixture specimens using the wheel rolling method. The foregoing can be used...
as basis for the design of DSAM with a nominal maximum particle size of 13.2 mm; this will ensure that the coarse aggregates interlock, form a steady main skeleton, and improve the rutting resistance of the asphalt mixture.

5. Conclusions

Based on the DIP, in this study, the gradual meso-structural response behaviour of the asphalt mixture main skeleton subjected to load is investigated; moreover, the design criteria of mesoscopic evaluation indices for the main skeleton are proposed in this paper. The main conclusions are as follows:

(1) Aggregates with particle sizes of 2.36–4.75 mm can effectively increase the total quantity of contact points, but the stability of the main skeleton is insufficient. Coarse aggregates with a particle size larger than 4.75 mm provide the most significant contribution to the formation of a steady main skeleton; hence, it is the crucial particle size for the formation of such skeletons. Increasing the content of coarse aggregates with particle sizes larger than 4.75 mm in the gradation design process aids to stabilise the formation of the main skeleton, and the use of asphalt with a higher PG grade can effectively restrain the movement of coarse aggregates and improve the rutting resistance of the asphalt mixture.

(2) For the mixture with a nominal maximum particle size of 13.2 mm, the maximum and minimum coordination numbers of coarse aggregates are 5 and 0, respectively. The coordination number peak position gradually moves to the direction of increase under load action; the peak coordination number is 2 when the main skeleton has exerted its maximum capacity to resist the load and has approached the critical value. The Gauss regression model can well describe the relationship between the coordination number and the corresponding amount of coarse aggregates.

(3) Gradation is the major determinant of the mesoscopic evaluation indices, $\bar{n}$ and C value, for the asphalt mixture main skeleton. The performance of asphalt has an insignificant influence on the mesoscopic evaluation indices; it mainly affects the development trend of macroscopic rutting. In the design process of DSAM, it is necessary to optimise the gradation with the aim of increasing the coordination number and reducing the C value so as to enhance the load resistance capacity of the main skeleton. In the preparation of asphalt mixture specimens using the wheel rolling method, the design criteria of mesoscopic evaluation indices for the main skeleton are $\bar{n}_C \geq 1.5$ and $C \leq 15\%$, which can be used as reference for the design of DSAM with a nominal maximum particle size of 13.2 mm.

(4) The conclusions of this study, particularly the design criteria of mesoscopic evaluation indices for the main skeleton, are obtained from limited laboratory tests. Consequently, the conclusions have limitations; nevertheless, better reference values have been achieved for the research concepts. More of the factors that affect the main skeleton structure should be considered, and various asphalt mixtures should be analysed in a follow-up study. The mesoscopic evaluation indices, test criteria, and design criteria of the main skeleton should be demonstrated further and optimised based on large amounts of indoor and outdoor test data to better guide the gradation design of DSAM.

Author Contributions: Conceptualization: L.W.S., Z.Y. and D.Y.W.; data curation: L.W.S., Z.Y., X.Q., and X.X.; funding acquisition: L.W.S. and D.Y.W.; investigation: L.W.S., X.Q., X.X., and M.K.J.; methodology: D.Y.W. and L.W.S.; project administration: L.W.S. and Z.Y.; resources: D.Y.W.; writing—original draft: L.W.S.; writing—review and editing: Z.Y. and D.Y.W.

Funding: The research was funded by the National Natural Science Foundation of China, grant number 51278203.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Yang, Z.; Zhang, G.Y.; Wei, X.S.; Wei, J.; Yu, H.; Xu, W. Quantitative analysis of the blending degree of virgin and RAP binders in recycled asphalt mixtures with a high RAP content. *Appl. Sci.* **2018**, *8*, 2668. [CrossRef]

2. Asi, I.M. Laboratory comparison study for the use of stone matrix asphalt in hot weather climates. *Constr. Build. Mater.* **2006**, *20*, 982–989. [CrossRef]
3. Roque, R.; Birgisson, B.; Kim, S.; Guarin, A. Development of Mix Design Guidelines for Improved Performance of Asphalt Mixtures; Florida Department of Transportation: Tallahassee, FL, USA, 2006.
4. Guarin, A.; Roque, R.; Kim, S.; Sirin, O. Disruption factor of asphalt mixture. *Int. J. Pavement Eng.* 2013, 14, 472–485. [CrossRef]
5. Kim, S.; Roque, R.; Birgisson, B.; Guarin, A. Porosity of the dominant aggregate size range to evaluate coarse aggregate structure of asphalt mixtures. *J. Mater. Civ. Eng.* 2009, 21, 32–39. [CrossRef]
6. Kim, S.; Guarin, A.; Roque, R.; Birgisson, B. Laboratory evaluation for rutting performance based on the DAR porosity of asphalt mixture. *Road Mater. Pavement Des.* 2008, 8, 421–440. [CrossRef]
7. Yideti, T.F.; Birgisson, B.; Jelagin, D.; Guarin, A. Packing theory-based framework to evaluate permanent deformation of unbound granular materials. *Int. J. Pavement Eng.* 2013, 14, 309–320. [CrossRef]
8. Liba, B.; Jelagin, D.; Birgisson, B. Gradation based framework for asphalt mixture. *Mater. Struct.* 2013, 46, 1401–1414.
9. Yideti, T.F.; Birgisson, B.; Jelagin, D.; Guarin, A. Packing theory-based framework to evaluating resilient modulus of unbound granular materials. *Int. J. Pavement Eng.* 2014, 15, 689–697. [CrossRef]
10. Tan, Y.Q.; Xing, C.; Ren, J.D.; Zhang, L. Research on mesostructured characteristics of asphalt mixture based on particle packing theory. *China J. Highw. Transp.* 2017, 30, 1–8.
11. Ding, X.; Ma, T.; Gao, W. Morphological characterization and mechanical analysis for coarse aggregate skeleton of asphalt mixture based on discrete-element modeling. *Constr. Build. Mater.* 2017, 154, 1048–1061. [CrossRef]
12. Ma, T.; Zhang, D.; Zhang, Y.; Hong, J. Micromechanical response of aggregate skeleton within asphalt mixture based on virtual simulation of wheel tracking test. *Constr. Build. Mater.* 2016, 111, 153–163. [CrossRef]
13. Gong, F.; Zhou, X.; You, Z.; Liu, Y.; Chen, S. Using discrete element models to track movement of coarse aggregates during compaction of asphalt mixture. *Constr. Build. Mater.* 2018, 189, 338–351. [CrossRef]
14. Sefidmazgi, N.R.; Tashman, L.; Bahia, H. Internal structure characterization of asphalt mixtures for rutting performance using imaging analysis. *Road Mater. Pavement Des.* 2012, 13, 21–37. [CrossRef]
15. Ding, X.; Ma, T.; Zhang, W.; Zhang, D.; Yin, T. Effects by property homogeneity of aggregate skeleton on creep performance of asphalt concrete. *Constr. Build. Mater.* 2018, 171, 205–213. [CrossRef]
16. Cai, X.; Wang, D.Y. Evaluation of rutting performance of asphalt mixture based on the granular media theory and aggregate contact characteristics. *Road Mater. Pavement Des.* 2013, 14, 325–340. [CrossRef]
17. Cai, X.; Wu, K.H.; Huang, W.K.; Wan, C. Study on the correlation between aggregate skeleton characteristics and rutting performance of asphalt mixture. *Constr. Build. Mater.* 2018, 179, 294–301. [CrossRef]
18. Pouranian, M.R.; Haddock, J.E. Determination of voids in the mineral aggregate and aggregate skeleton characteristics of asphalt mixtures using a linear-mixture packing model. *Constr. Build. Mater.* 2018, 188, 292–304. [CrossRef]
19. Wang, X.; Gu, X.; Jiang, J.; Deng, H. Experimental analysis of skeleton strength of porous asphalt mixtures. *Constr. Build. Mater.* 2018, 171, 13–21. [CrossRef]
20. Shi, L.W.; Wang, D.Y.; Xu, C.; Liang, H.H. Investigation into meso performance of asphalt mixture skeleton based on discrete element method. *J. South China Univ. Technol. Nat. Sci. Ed.* 2015, 43, 50–56.
21. Ying, H.; Zhou, J.; Wu, Q.; Liu, Y. Variation of the contact form of coarse aggregate particles in skeleton type asphalt mixture. *J. Build. Mater.* 2016, 19, 292–298.
22. Sefidmazgi, N.R.; Bahia, H.U. Effect of compaction conditions on aggregate packing using 2-Dimensional image analysis and the relation to performance of HMA. *Mater. Struct.* 2014, 47, 1313–1324. [CrossRef]
23. Gopalakrishnan, K.; Shashidhar, N. Structural characteristics of three-dimensional random packing aggregates with wide size distribution. *Int. J. Inf. Technol.* 2006, 3, 201–208.
24. Chen, J.; Huang, X.M. Evaluation of aggregate skeleton structure using the discrete element method. *J. Southeast Univ. Nat. Sci. Ed.* 2012, 42, 761–765.
25. Rothenburg, L.; Kruyt, N.P. Critical state and evolution of coordination number in simulated granular materials. *Int. J. Solids Struct.* 2004, 41, 5763–5774. [CrossRef]
26. Coenen, A.R.; Kutay, M.E.; Sefidmazgi, N.R.; Bahia, H.U. Aggregate structure characterization of asphalt mixtures using 2-Dimensional image analysis. *Road Mater. Pavement Des.* 2012, 13, 433–454. [CrossRef]
27. Elseifi, M.A.; Al-Qadi, I.L.; Yang, S.H.; Carpenter, S.H. *Validity of Asphalt Binder Film Thickness Concept in Hot-Mix Asphalt*; Transportation Research Board: Washington, DC, USA, 2008; Paper No: 08-0603.
28. Cai, X.; Wang, D.Y.; Li, K.; Wan, C. Prediction of shear modulus of asphalt mixtures based on granular mechanics. *China J. Highw. Transp.* 2013, 26, 38–46.

29. Ministry of Transport of the People’s Republic of China. *Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering*; China Communications Press: Beijing, China, 2011.

30. Ministry of Transport of the People’s Republic of China. *Technical Specification for Construction of Highway Asphalt Pavements*; China Communications Press: Beijing, China, 2004.

31. Javilla, B.; Fang, H.; Mo, L.; Shu, B.; Wu, S. Durability of innovative construction materials and structures test evaluation of rutting performance indicators of asphalt mixtures. *Constr. Build. Mater.* 2017, 177, 1215–1223. [CrossRef]

© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).