

Influence of RAP content on the mesostructure and mechanical response of recycled asphalt mixtures

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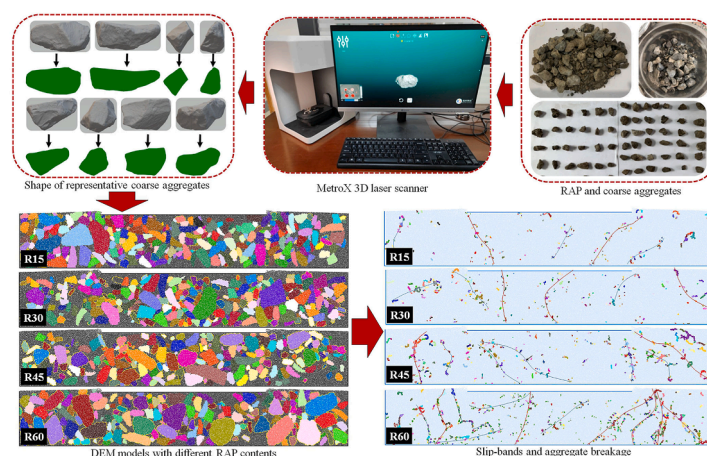
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HIGHLIGHTS

- DEM models with crushable coarse aggregates were developed to accurately distinguish new aggregates and RAP.
- Stress characteristics in different regions and among various meso-structure components were analyzed.
- The concept and characteristics of slip-band structures in recycled asphalt mixtures were defined.
- The evolution laws of slip-bands and aggregate breakage with different RAP contents were revealed.

GRAPHICAL ABSTRACT



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ABSTRACT

The road performance of recycled asphalt pavement (RAP) is crucial for low-carbon road construction. However, existing studies lack refined simulation of the mesostructure involving RAP, new aggregates, aged asphalt, and new asphalt, leaving the effects of different RAP contents on stress distribution and damage mechanisms unclear. This study develops discrete element models to analyze the influence of RAP content on mesoscopic stress evolution, crack propagation, and aggregate breakage. The results show that when RAP content exceeds 45%, aged asphalt and RAP exhibit notably non-uniform distributions. The maximum normal stress occurs at the loading center, while the maximum shear stress is located at the bottom sides of the loading center. As RAP content rises from 15 % to 60 %, the number of effective microcracks increases by 2.04 times. The length and area of slip-bands grows rapidly, and the crack damage index D follows an exponential upward trend. Considering rutting resistance, crack resistance, and resource utilization efficiency comprehensively, the recommended

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1674-2001/© 2026 Chinese Society of Particuology and Institute of Process Engineering, Chinese Academy of Sciences. Published by Elsevier B.V. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

suitable RAP content range is 30 % - 45 %, with the following threshold values: number of slip-bands ≤ 8 , average length of slip-bands ≤ 48 mm, and $D \leq 7.5$ %. The findings provide a theoretical basis for understanding the meso-mechanical behavior of recycled asphalt mixtures.

1. Introduction

With the advancement of global resource recycling and low-carbon road technologies, recycled asphalt pavement (RAP) has gained research attention due to its economic and environmental benefits (Jin et al., 2022, 2024a). However, a high RAP content significantly alters the mesostructure and stress response of recycled mixtures. The performance differences between aged and new aggregates, the bond at asphalt-RAP interfaces, and the influence of microcrack evolution and aggregate breakage on the overall material performance constitute key challenges in the study of recycled asphalt mixtures. Existing studies indicate that a high content of RAP leads to a significant reduction in the fatigue life and crack resistance of asphalt mixtures, which restricts the large-scale application of recycled asphalt mixtures (Shi et al., 2022; Zhang, Guo, et al., 2021). The macroscopic mechanical properties of asphalt mixtures are closely related to their mesostructure. However, current research still cannot accurately characterize the mesostructural differences among new aggregates, RAP, aged asphalt, and new asphalt mortar in recycled mixtures (Liu et al., 2025; Sivilevičius & Vislavičius, 2019). Some studies assume the asphalt film on RAP surfaces to be homogeneous and continuous, neglecting the non-uniformity of aged asphalt (Cheng et al., 2024; Nian, Wang, Ge, et al., 2024; Sheng et al., 2020). The discrete element method (DEM) offers distinct advantages in modeling heterogeneous materials and simulating the mesostructure of asphalt mixtures (Liang, Shi, et al., 2025; Liu et al., 2024; Nian et al., 2022). The DEM has been applied to investigate recycled asphalt mixtures, including RAP content optimization (Wang & Yang, 2022), mesoscopic mechanical performance (Daniel et al., 2021; Tan et al., 2024; Zhang, Cai, et al., 2021), fatigue and cracking behavior (Alae et al., 2023; Gao et al., 2017), and virtual mechanical simulation (Wang et al., 2024; Yang et al., 2024; Zhao et al., 2021), yielding substantial research outcomes. However, conventional DEM models typically assume aggregates to be rigid and non-crushable, which deviates significantly from the actual crushing behavior of RAP under loading. Shi et al. (Shi et al., 2023) established DEM models of recycled asphalt mixtures with different material characteristics, but the coarse aggregates were non crushable. Furthermore, Sun et al. (Sun et al., 2018) examined aggregate breakage characteristics in recycled asphalt concrete using image-based methods. Nevertheless, existing research still shows considerable limitations in accurately distinguishing the mesostructural features of RAP, aged and new asphalt, as well as crushable aggregates (Xue et al., 2024).

Existing studies on the cracking mechanisms of recycled asphalt mixtures primarily focus on the identification and prediction of macroscopic crack characteristics, as well as the evolution of cracks at mesoscopic and microscopic scales. Nian et al. (Nian, Wang, Huang, et al., 2024) established three-dimensional (3D) semi-circular bending test models to analyze crack propagation patterns under different loading modes. Ling et al. (Ling et al., 2020) employed DEM and fracture mechanics approaches to determine the durability limit and macroscopic cracking threshold of recycled asphalt mixture. Dong et al. (Dong et al., 2024) analyzed the meso-mechanical parameters of recycled hydraulic asphalt concrete, revealing the evolution of damage patterns and fracture development. In addition to indoor tests and numerical simulations, digital image processing has also been a common technique for mesostructural analysis (Liang, Guo, et al., 2025). Image processing has been used to study asphalt mixtures in areas such as mesostructural homogeneity (Liu & Oeser, 2021; Yang et al., 2023), skeleton contact structure (Lin et al., 2022; Yang et al., 2021), fatigue performance (Yao & Xu, 2023), asphalt-aggregate bonding (Cui et al., 2024; Fan et al.,

2024), and 3D reconstruction of mixture (Jiang et al., 2022). Yu et al. (Yu et al., 2024) focused on potential durability and cracking issues in asphalt pavements with high RAP content, concluding that high RAP content has little effect on rutting resistance, whereas fatigue and crack development should receive greater attention. Through comparative analysis, Zhou et al. (Zhou et al., 2025) demonstrated that the proportions of cohesive and adhesive damage in epoxy-modified recycled asphalt concrete are significantly lower than those in conventional recycled asphalt pavement. Kou et al. (Kou et al., 2025) employed digital image correlation technology to obtain characteristic parameters of the real-time displacement field at crack tips. Yousefi et al. (Yousefi et al., 2021) evaluated the cracking resistance of warm-mix asphalt with 50 % RAP content based on energy-based parameters, considering different rejuvenators. Zhan et al. (Zhan et al., 2024) proposed a brittleness index to assess the crack-initiation and crack-propagation resistance of recycled asphalt mixtures by analyzing energy evolution across different fracture stages. To promote the effective utilization of reclaimed asphalt pavement (RAP) and industrial solid waste, Zhao et al. (Zhao et al., 2025) developed an environmentally friendly and cost-effective composite recycled pavement material by formulating a novel binder. One of the measures to enhance the crack resistance of recycled asphalt mixtures is to improve the adhesion of asphalt mortar (Li et al., 2026), or to incorporate waste materials such as polyurea elastomer (Sun et al., 2025) and tire rubber particles (Jin, Yin, Nedrich, et al., 2024; Sun et al., 2026), which have been shown to be effective in improving the crack resistance of asphalt mixtures.

Existing studies indicate that further research is still required on the mesostructure of recycled asphalt mixtures, including inadequate characterization of RAP and crushable aggregates at the mesoscale, unclear correlation mechanisms among mesostructure, stress evolution and RAP content, and insufficient understanding of mesoscale mechanisms from microcrack initiation to fracture failure. To address these issues, this study develops discrete element models of recycled asphalt mixtures with crushable aggregates to investigate mesoscopic stress response and cracking mechanisms. The research objectives and contents are outlined as follows.

- (1) DEM models of recycled asphalt mixtures with crushable coarse aggregates are established to accurately characterize the mesostructural features of new aggregates, RAP, aged asphalt, and new asphalt, and the distribution patterns of each mesostructural component are analyzed.
- (2) The stress evolution characteristics in different regions and among different meso-structure components of recycled asphalt mixtures are investigated, and the influence of RAP content on meso-stress distribution is examined.
- (3) The concept and characteristics of slip-band structures formed by microcracks in recycled asphalt mixtures are defined. The influence of RAP content on microcrack propagation, the distribution regions, morphological characteristics, and development trends of slip-bands, as well as the evolution law of aggregate breakage are revealed, and measures to inhibit microcrack development are proposed.

2. DEM models and research scenario

2.1. Materials and gradation

The raw materials for the recycled asphalt mixtures included RAP, new coarse aggregates, fine aggregates, asphalt binder, and additives.

The new aggregates were divided into six size grades: 22–28 mm, 10–20, 10–15, 5–10, 3–5, and 0–3 mm. The RAP material was categorized into three grades: 19–25, 13–19, and 0–8 mm. The lithology of the aggregate is limestone. The technical indicators of RAP and new aggregates are presented in [Tables 1 and 2](#), respectively. To investigate the meso-mechanical properties of recycled asphalt mixtures with different RAP contents, four RAP incorporation levels were compared: 15 %, 30 %, 45 %, and 60 %. To eliminate the influence of gradation, the gradation curves for all RAP contents were designed to maintain consistent sieve passing rates, with deviations at the key sieve sizes of 3.26 and 4.75 mm not exceeding ± 2 %. The sieve passing rates of each grade materials is presented in [Table 3](#), the mixing proportion of aggregates is listed in [Table 4](#), and the designed gradations are provided in [Table 5](#).

2.2. Morphological characteristics of coarse aggregate in DEM model

To improve the realism of the DEM model in representing asphalt mixtures, this study employed a MetroX 3D laser scanner to capture the 3D digital morphology of coarse aggregates through 360° scanning from top to bottom. 2D aggregate contours were then obtained by projection. Eight representative coarse aggregate contours were selected, including elongated, cubic, near-elliptical, and triangular shapes, and used as Clump templates to construct the DEM specimen, as illustrated in [Fig. 1](#) and [Table 6](#). To balance computational efficiency with model accuracy, asphalt mortar was simulated by filling the mixture with spherical particles of 0.2–0.3 mm until the target air void was achieved.

2.3. Recycled asphalt mixture DEM models

This study employs a rutting test to investigate the influence of RAP content on the mesostructure and stress response of recycled asphalt mixtures. The indoor rutting specimen dimensions are 300 mm $\times$ 300 mm $\times$ 50 mm. The 2D DEM models were adopted in this study considering computational efficiency. Although the 2D models cannot precisely capture the actual 3D stress distribution and crack propagation characteristics during rutting development, which presents certain limitations, the 2D DEM models are a commonly used technique capable of distinguishing the mesoscopic mechanical properties of recycled asphalt mixtures with different RAP contents. These properties include stress distribution, aggregate breakage, and crack development during rutting progression, thereby elucidating the correlation mechanism between mesoscopic stress evolution and RAP content in recycled asphalt mixtures and providing technical guidance for the design of recycled asphalt mixtures. Based on these considerations, this study established DEM models of rutting tests with different RAP contents using the software PFC5.0 2D, with model dimensions of 300 mm $\times$ 50 mm. For coarse aggregates larger than 2.36 mm, eight representative 2D aggregate contours listed in [Table 4](#) were used as templates. Fine aggregates and asphalt mortar with particles smaller than 2.36 mm were represented by spherical particles with diameters of 0.2–0.3 mm. The developed DEM models incorporate crushable coarse aggregates and distinguish the mesostructural features of new aggregates, RAP, new asphalt, and aged asphalt. Since coarse aggregates generated by the Clump program are inherently non-crushable, the method adopted in this study to model crushable coarse aggregates is

Table 1
Technical indicators of RAP.

Test indicators	Aggregate grade			
	19–25 mm	13–19 mm	8–13 mm	0–8 mm
Apparent specific gravity	2.701	2.677	2.659	2.667
Bulk specific gravity	2.651	2.615	2.589	2.594
Crushing value (%)	22.31	21.91	21.44	/
Angularity	/	/	/	36.02
Water absorption (%)	0.72	0.91	1.03	1.12
Asphalt content (%)	3.28	3.08	2.75	3.82

Table 2

Technical indicators of new aggregates.

Test indicators	Aggregate grade					
	22–28 mm	10–20 mm	10–15 mm	5–10 mm	3–5 mm	0–3 mm
Apparent specific gravity	2.718	2.732	2.737	2.735	2.737	2.696
Bulk specific gravity	2.694	2.711	2.706	2.708	2.698	2.696
Crushing value (%)	20.34	19.82	18.44	19.36	/	/
Angularity	/	/	/	/	20.62	21.14
Water absorption (%)	0.42	0.46	0.51	0.58	0.63	0.71

illustrated in [Supplementary Fig. S1](#). First, the contours of coarse aggregates were created using the Clump program. Then, the Ball program was employed to generate spherical particles with radius of 0.2–0.3 mm to fill the aggregate contours. Finally, the particles inside the Clump boundaries were deleted, and the remaining particles (Balls) were bonded into an integral unit using a parallel bond model.

This study established DEM models with crushable coarse aggregates and distinct mesostructural features for new aggregates, RAP, new asphalt, and aged asphalt, considering different RAP incorporation levels. Taking the 30% RAP content as an example, the main modeling process is shown in [Fig. 2](#) as below.

- S1 Using the Clump program, coarse aggregates with various contours were randomly placed within the DEM model according to the specified gradation.
- S2 Using the Ball program, the model was filled with small spheres having radius of 0.2–0.3 mm.
- S3 The fine particles inside the Clump regions were deleted, retaining only the coarse aggregate contours. The interior of each coarse aggregate contour was then filled with spheres of radius 0.2–0.3 mm, and all spheres were bonded using a linear parallel bond model.
- S4 To distinguish new aggregates from RAP, a layer of aged asphalt film was applied to the surface of RAP particles. Asphalt mortar was represented by spheres with radius of 0.2–0.3 mm.
- S5 The components of the recycled asphalt mixture were grouped and distinguished by color to identify RAP and aged asphalt, as well as new aggregates and new asphalt mortar.

2.4. Indoor rutting test and mesoscopic parameters of DEM models

2.4.1. Indoor rutting test results for different RAP contents

In recycled asphalt mixtures, new aggregates, RAP, aged asphalt, and new asphalt mortar interact through contact, bonding, and fusion, forming a composite material with complex mechanical performance. The test was conducted under a constant temperature of 60 ± 0.5 °C, a load of 0.7 MPa, and a wheel rolling speed of 42 times/min. The indoor rutting test procedure and the rutting test results of recycled asphalt mixtures with different RAP contents are presented in [Fig. 3](#). In the figure, d_1 and d_2 represent the rut depth (RD) measured at 45 min and 60 min after the start of the test, respectively, and the dynamic stability (DS) is used to evaluate the rutting resistance of the asphalt mixtures.

According to [Fig. 3\(b\)](#), when the RAP content increases from 15% to 60%, the RD gradually decreases while the DS increases by up to 200%, indicating that RAP content has a significant influence on the rutting resistance of recycled asphalt mixtures. Increasing the RAP content helps reduce rut depth and enhance the rutting resistance of the asphalt mixture.

Table 3
Passing rate of each grade materials.

Sieve size (mm)	New aggregate					RAP			
	22-28 mm	10-20 mm	10-15 mm	5-10 mm	3-5 mm	0-3 mm	19-25 mm	13-19 mm	0-8 mm
31.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
26.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0	7.0	95.9	100.0	100.0	100.0	100.0	74.5	100.0	100.0
16.0	1.1	54.6	100.0	100.0	100.0	100.0	33.1	94.7	100.0
13.2	0.8	6.0	89.7	100.0	100.0	100.0	50.2	72.1	100.0
9.5	0.7	0.9	24.6	99.8	100.0	100.0	38.8	39.0	100.0
4.75	0.7	0.5	0.6	18.4	72.2	100.0	25.8	26.5	98.6
2.36	0.7	0.5	0.4	0.5	1.6	68.3	20.2	21.7	67.2
1.2	0.7	0.5	0.4	0.5	1.0	50.7	17.1	18.5	51.1
0.6	0.7	0.5	0.4	0.5	1.0	31.8	13.4	14.5	35.8
0.3	0.7	0.5	0.4	0.5	1.0	20.9	10.7	11.6	26.4
0.15	0.7	0.5	0.4	0.5	1.0	15.8	8.9	9.5	21.1
0.075	0.2	0.5	0.4	0.5	1.0	13.4	7.5	7.9	16.8

Table 4
Aggregate mixing proportions.

Gradation ID	RAP content (%)	Mixing proportion (%)								
		New aggregate					RAP			
		22-28 mm	10-20 mm	10-15 mm	5-10 mm	3-5 mm	0-3 mm	19-25 mm	13-19 mm	0-8 mm
R15	15	22	13	11	18	3	18	3	3	9
R30	30	21	13	9	17	3	7	5	6	19
R45	45	20	6	8	15	5	1	10	15	20
R60	60	9	10	2	13	6	0	24	21	15

2.4.2. Sensitivity analysis of DEM parameters and calibration of mesoscopic parameters

In this study, a linear parallel bond model was used to simulate the bonding behavior between aggregates. The mesoscopic parameters of the DEM models were calibrated based on the curves obtained from indoor rutting tests to replicate the test conditions during the indoor rutting tests (Liang, Shi, et al., 2025; Liu et al., 2024; Nian, Wang, Ge, et al., 2024; Shi et al., 2023). During the calibration of DEM models for different RAP contents, the mesoscopic parameters were calibrated, and it was found that the bond effective modulus (E^*), normal strength (NS), and tangential strength (TS) were identified as key factors influencing specimen deformation. Through parameter sensitivity analysis, the sensitivity ranking of parameters influencing the RD in rutting tests was determined. The sensitivity analysis method involved keeping all other parameters of the DEM model unchanged while adjusting the target parameter within a certain range and observing its effect on the macroscopic RD . Accordingly, using the DEM models with different RAP contents as the baseline and keeping other factors unchanged, the corresponding RD variation rates were calculated by varying the RAP content as well as the E^* , NS , and TS mesoscopic parameters, denoted as RD_{15} , RD_{30} , RD_{45} , and RD_{60} , respectively. For parameter settings, the mesoscopic parameters E^* , NS , TS , and the RAP content were varied by -20% , -10% , $+10\%$, and $+20\%$ relative to their baseline values. The sensitivity analysis results for different RAP contents are presented in Fig. S2. According to the figure, for all RAP content levels, the variation in RAP content causes the largest change rate of RD , significantly greater than the effects of E^* , NS , and TS . The sensitivity ranking of the DEM mesoscopic parameters (E^* , NS , TS) and RAP content on RD is as follows: RAP content $> E^* > TS > NS$, indicating that RAP content is the dominant factor affecting the rutting resistance of recycled asphalt mixtures. By finely adjusting the E^* , TS , and NS parameters, the indoor rutting test results for different RAP contents were brought into agreement with the DEM simulation outcomes. The calibrated mesoscopic parameters are presented in Table 7. A comparison between the indoor rutting test results and the DEM simulation results for different RAP contents is shown in Fig. S3. In this figure, label I represents the indoor test results, and label D represents the DEM simulation results.

Comparing the DEM simulation results with the indoor rutting test parameters for different RAP contents in Fig. S3, the errors of DS and RD parameters are within 10%, indicating that the DEM models have good reliability and can effectively characterize the indoor rutting tests. In Table 7, the meso-parameters for RAP, new coarse aggregates, aged asphalt, and new asphalt are differentiated to reflect the properties of each distinct material. However, the linear parallel bond model parameters cannot simulate the viscoplastic flow of asphalt mortar at 60°C , which poses a certain limitation. Future research will adopt the Burgers model, which is capable of characterizing viscoelastic behavior, to capture the temperature-dependent and time-dependent behavior of asphalt mortar.

Based on the indoor tests and the mesoscopic parameters listed in Table 7, DEM models with different RAP contents were established. After completing the calibration of the mesoscopic parameters of the DEM models, this study further increased the number of loading cycles to 400,000, as shown in Fig. 4. This was done to ensure that the deformation development reached a stable stage and to fully capture the evolution of microcracks, slip-bands, and aggregate breakage under long-term loading conditions, thereby enabling a more comprehensive analysis of the mesoscopic damage characteristics of recycled asphalt mixtures.

3. Results and discussion

3.1. Meso-structure distribution and meso-stress characteristics of recycled asphalt mixture

3.1.1. Distribution characteristics of meso-structure components

In the DEM models, new aggregates, RAP, aged asphalt, new asphalt, and microcracks are represented using distinct colors, as summarized in Table 8.

In recycled asphalt mixtures, new aggregates, RAP, aged asphalt, and new asphalt mortar interact through contact, bonding, and fusion, as shown in Fig. S4. The key features of the mixture components include coarse aggregate contacts, aggregate-asphalt interfacial bonds, and fusion between aged and new asphalt. Aggregate contact types consist of

Table 5
Gradation of recycled asphalt mixture.

Gradation ID	RAP content (%)	Passing rate (%)												
		31.00 mm	26.50 mm	19.00 mm	16.00 mm	13.20 mm	9.50 mm	4.75 mm	2.36 mm	1.18 mm	0.60 mm	0.30 mm	0.15 mm	0.075 mm
R15	15	100	100	78.2	69.9	61.5	53.0	33.9	19.6	14.8	9.8	6.8	5.3	4.4
R30	30	100	100	78.7	69.4	60.9	52.5	33.9	19.9	15.2	10.6	7.7	6.1	5.0
R45	45	100	100	78.6	69.8	64.0	52.7	33.6	19.4	15.2	11.0	8.3	6.7	5.4
R60	60	100	100	78.1	69.3	63.0	52.0	33.3	19.5	15.7	11.6	9.0	7.3	6.0

RAP-RAP, RAP-new aggregate, and new aggregate-new aggregate. Aggregate-asphalt interfacial bonds involve RAP-aged asphalt, RAP-new asphalt, new aggregate-aged asphalt, and new aggregate-new asphalt. Fusion primarily occurs between new asphalt and aged asphalt. The components of new aggregates, RAP, and aged asphalt in the recycled asphalt mixture are distributed non-uniformly, suspended within the new asphalt mortar. To examine the distribution of each component, the DEM model was divided lengthwise into four equal segments and widthwise into two equal segments, resulting in eight equally sized regions, numbered regions 1-8, as presented in Fig. S5.

To evaluate the distribution of mesoscopic components in recycled asphalt mixtures with varying RAP contents, the areas of RAP, aged asphalt, and new aggregates in each of the eight regions were quantified. The standard deviation of each component across the regions was calculated and expressed as non-uniformity coefficient, as defined in Eq. (1) (Lin et al., 2022).

$$N = \sqrt{\frac{\sum_{i=1}^8 (A_i - \bar{A})^2}{7}} \quad (1)$$

Where, N is the non-uniformity coefficient. In this study, the non-uniformity coefficient for RAP is denoted as N_{rap} , with its corresponding area and mean area expressed as A_{rap} and $\bar{A}_{rap}$, respectively. The non-uniformity coefficient for new coarse aggregates is represented by N_{agg} , with its area and mean area given as A_{agg} and $\bar{A}_{agg}$. Similarly, the non-uniformity coefficient for aged asphalt is indicated as N_{aga} , where its area and mean area are designated as A_{aga} and $\bar{A}_{aga}$.

The calculation method for the non-uniformity coefficient of each mesostructural component in the asphalt mixture is as follows. Based on the eight regions divided in the DEM model shown in Fig. S5, the areas of RAP, aged asphalt, and new aggregates in each region were calculated. The non-uniformity coefficient of each mesostructural component was then determined using Eq. (1). The non-uniformity coefficient is a qualitative indicator with a minimum value of zero. For a given mesostructural component, a larger non-uniformity coefficient indicates a more uneven distribution of that component. Fig. 5 illustrates the distribution characteristics of aged asphalt, RAP, and new aggregates in different regions of the recycled asphalt mixture. For the coordinate axis of Fig. 5, RE1 represents region 1, RE2 represents region 2, and so on.

According to Fig. 10, the distributions of aged asphalt, RAP, and new aggregates in each region exhibit significant randomness, with no clear pattern in the non-uniformity coefficients. As the RAP content increases from 15% to 60%, the changing trends of the non-uniformity coefficient for each mesostructural component are as follows. The non-uniformity coefficient of RAP increases from approximately 5 to about 30. The non-uniformity coefficient of aged asphalt increases from approximately 1.5 to about 3, with a maximum value of 6.68. The non-uniformity coefficient of new aggregates gradually decreases from approximately 20 to about 12. Notably, when the RAP content exceeds 45%, both aged asphalt and RAP exhibit particularly pronounced non-uniform distribution, with the non-uniformity coefficient increasing to 3 to 9 times that at 15% RAP content. The Analysis of Variance (ANOVA) was conducted to test the statistical significance, a P-value of 0.046 indicates that the increase in the non uniformity coefficient when the RAP content exceeded 45% was statistically significant. These observations indicate that RAP content exerts a significant influence on the mesostructural composition of recycled asphalt mixtures. Therefore, higher RAP content reduces the homogeneity of the recycled asphalt mixture while increasing the number of weak RAP-aged asphalt interfaces, which adversely affects the performance of the recycled asphalt mixture.

3.1.2. Mesoscopic stress characteristics of different regions and various meso-structure components

The loading process of recycled asphalt mixtures primarily consists of three stages: rapid deformation, stable deformation development, and

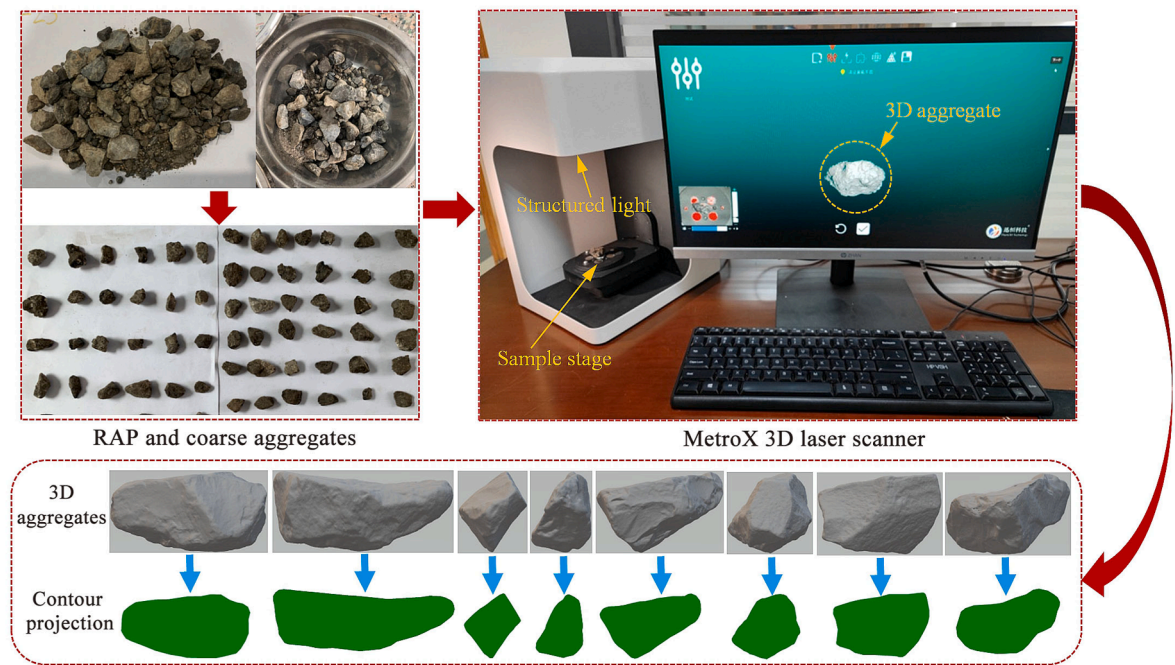


Fig. 1. Coarse aggregate 3D scanning and contour projection.

Table 6
Shape parameters of representative coarse aggregate and fine aggregate.

Type	Coarse aggregate (new aggregate and RAP), particle size≥2.36 mm								Fine aggregate particle size<2.36 mm
Number	1	2	3	4	5	6	7	8	9
Shape									

failure, ultimately leading to material breakdown and loss of serviceability. As particulate materials, recycled asphalt mixtures exhibit distinct mesoscopic stress variations across different regions due to differences in mesostructure. To investigate the meso-mechanical characteristics at different loading stages, multiple sets of measurement circles were arranged in various regions of the DEM model. Focusing on a mixture with 30 % RAP content, two measurement regions were established to study stress distribution in different regions and different mesostructural components, as illustrated in Fig. 6.

Scenario 1: Measurement regions were arranged at characteristic locations of the virtual specimen to study the mesoscopic stress characteristics in different zones of the recycled asphalt mixture. Specifically, following the method illustrated in Fig. 9, the DEM model was divided into eight equally sized zones, and measurement regions were placed at the center of each zone and along the boundaries between zones. A total of 14 measurement regions, numbered #1-14, were deployed in this scenario, each with a radius of 12.5 mm.

Scenario 2: Measurement regions were positioned in zones with different locations and mesostructural compositions to examine their mesoscopic stress characteristics. This scenario included six measurement regions, numbered #15-20, with specific locations and functions as follows.

- (1) Regions #15 and 16 form a group located directly beneath the loading area. Region #15 contains new aggregates and asphalt mortar, while region #16 contains RAP and asphalt mortar. Both measurement regions have a radius of 12.0 mm.
- (2) Regions #17 and #18 form a group situated on both sides of the loading area. Region #17 contains only asphalt mortar, and region #18 contains RAP and asphalt mortar. Both measurement regions have a radius of 8.0 mm.

- (3) Regions #19 and #20 form a group placed near the specimen ends. Region #19 contains new aggregates and asphalt mortar, and region #20 contains RAP and asphalt mortar. Both measurement regions have a radius of 8.0 mm.

The objective of Scenario 1 is to investigate the mesoscopic stress characteristics in different zones of the recycled asphalt mixture, while Scenario 2 aims to examine the mesoscopic stress features in zones with different locations and structural components. By applying loading to the virtual specimen, the variation trends of normal stress and shear stress within the 14 measurement regions defined in Scenario 1 were obtained, as presented in Fig. 7. Similarly, the evolution of normal stress and shear stress with loading time within the six measurement regions specified in Scenario 2 is shown in Fig. 8.

According to Fig. 7, the following conclusions can be drawn.

- (1) In general, continuous loading of the recycled asphalt mixture specimen results in increasing permanent deformation, with the normal stress inside the specimen being significantly greater than the shear stress. Regarding the evolution of the internal stress field, both normal stress and shear stress exhibit a rapid initial increase, followed by a gradual stabilization.
- (2) The distribution of normal stress varies noticeably among measurement regions at different positions. Along the horizontal direction of the specimen, the normal stress is highest directly under the loading center and gradually decreases with increasing distance from it. For instance, measurement regions located at the loading center (regions #7 and #8) record the maximum normal stress. Measurement regions within the loading zone (regions #3, #5, #9, #11 and regions #4, #6, #10, #12) exhibit slightly lower normal stress than that in regions #7 and #8. In contrast,

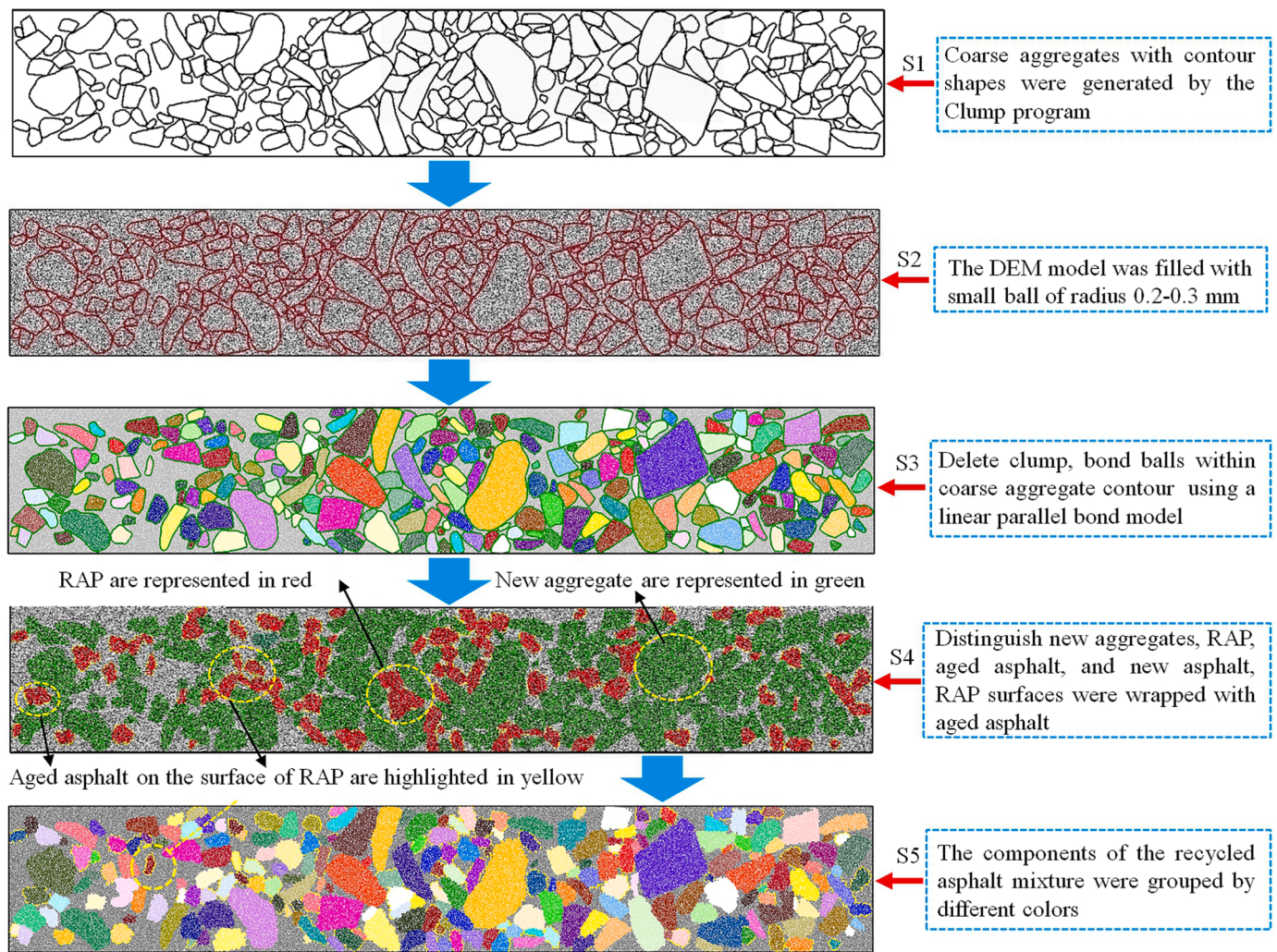


Fig. 2. Flowchart of the refined DEM modeling procedure for recycled asphalt mixture.

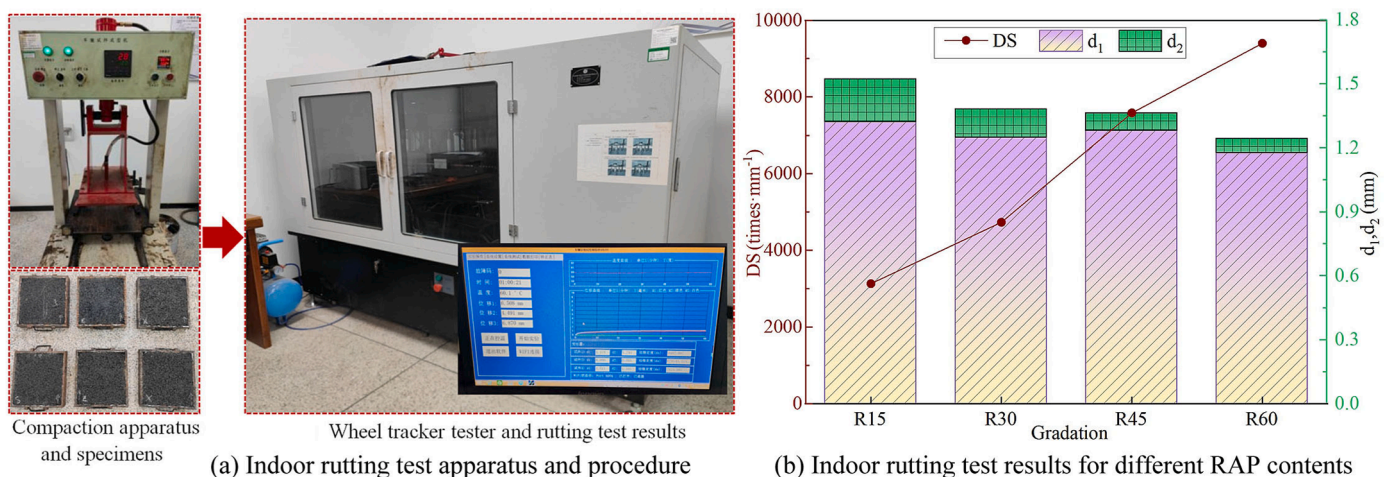


Fig. 3. Indoor rutting test apparatus and test results for different RAP contents.

measurement regions positioned on the sides of the loading zone (regions #1, #13 and regions #2, #14) display the lowest normal stress. As normal stress is transmitted vertically downward through the specimen, its magnitude gradually diminishes. For example, the normal stress in region #8 is about 95 % of that in

region #7. Within the loading zone, the normal stress attenuates to 20–50 % of its original value when transmitted to the bottom. Meanwhile, in the side regions of the loading zone, the transmission of normal stress does not follow a consistent pattern.

Table 7
Meso-parameters of DEM models.

Mesoscopic parameters		Keyword	RAP (ball-ball)	New aggregate (ball-ball)	Aged asphalt	New asphalt
Materials	Density (kg/m ³)	Density	2480	2400	1.036	1.036
	Coefficient of friction	Fric	0.55	0.5	0.5	0.5
	Bond effective modulus E* (N/m)	pb_emod	R15:3.5 × 10 ⁹	R15:3.7 × 10 ⁹	3.2 × 10 ⁹	4.0 × 10 ⁹
			R30:3.6 × 10 ⁹	R30:3.8 × 10 ⁹		
			R45:3.6 × 10 ⁹	R45:3.9 × 10 ⁹		
			R60:3.6 × 10 ⁹	R60:3.9 × 10 ⁹		
	Normal tangential stiffness ratio k*	pb_krat	1.25	1.3	1.3	1.3
	Normal strength (N/m)	pb_ten	R15:2.0 × 10 ⁶	R15:3.0 × 10 ⁶		
			R30:2.2 × 10 ⁶	R30:3.1 × 10 ⁶		
			R45:2.3 × 10 ⁶	R45:3.2 × 10 ⁶		
Others	Tangential strength (N/m)	pb_coh	R60:2.3 × 10 ⁶	R60:3.2 × 10 ⁶	3.2 × 10 ⁶	3.0 × 10 ⁶
			R15:3.8 × 10 ⁶	R15:4.0 × 10 ⁶		
			R30:3.8 × 10 ⁶	R30:4.1 × 10 ⁶		
			R45:3.9 × 10 ⁶	R45:4.2 × 10 ⁶		
	Angle of internal friction (°)	pb_fa	R60:3.9 × 10 ⁶	R60:4.2 × 10 ⁶	26	24
			24.5	24.0		
			0.5	0.5		
			0.5	0.5		
	Bonding radius (mm)	pb_rad	0.5	0.5	0.5	0.5
	Contact threshold (mm)	Bond gap	1.0	1.0	/	/
	Local damping	dp_force	0.7	0.7	0.7	0.7

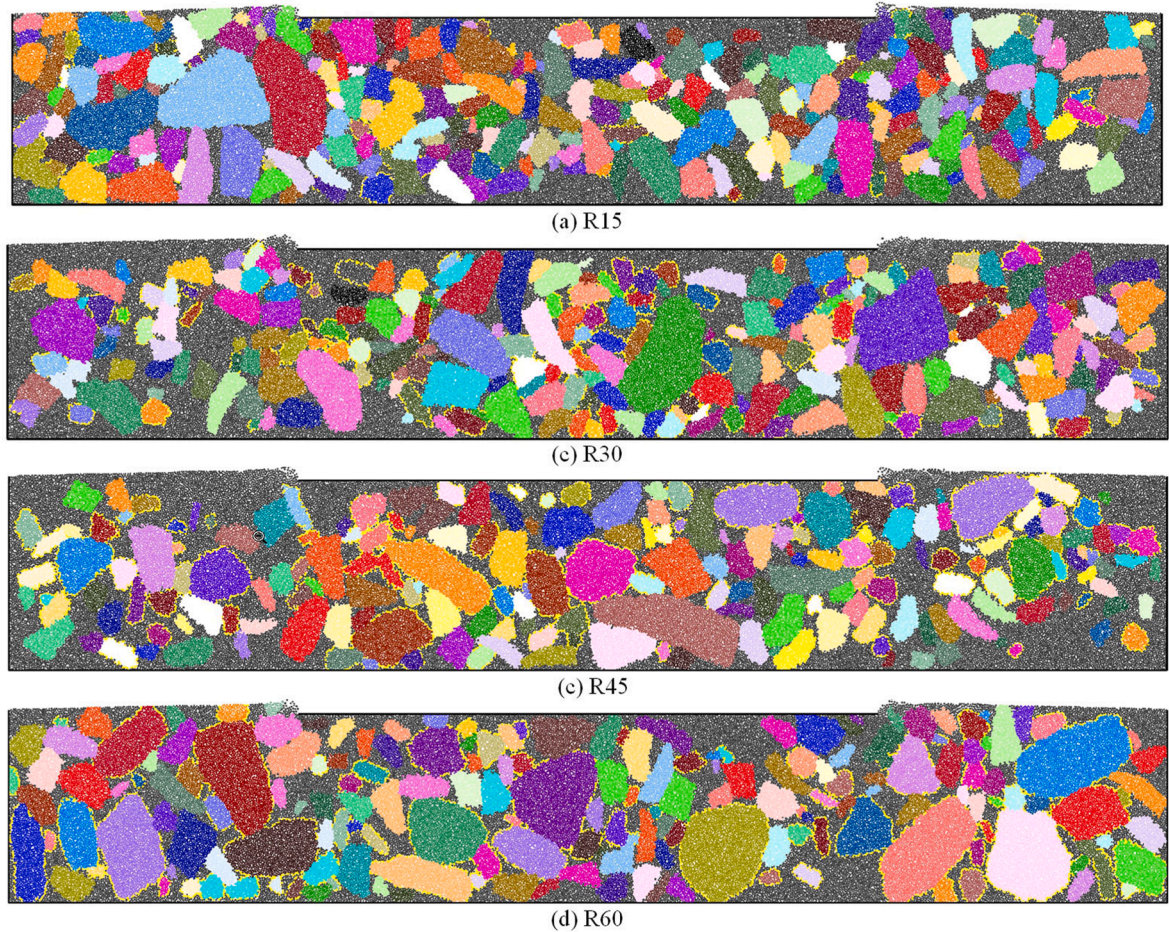


Fig. 4. DEM models of recycled asphalt mixtures with different RAP contents.

(3) The distribution of shear stress varies noticeably among measurement regions at different positions. In measurement regions located at the loading center (regions #7 and #8), the magnitude of shear stress fluctuates significantly. Along the horizontal direction of the specimen, shear stress decreases with increasing distance from the loading center. Within the loading zone, shear stress in regions #5, #6, #9, and #10 is lower than that in regions

#3, #4, #11, and #12. In contrast, measurement regions positioned on the sides of the loading zone (regions #1, #13 and regions #2, #14) exhibit the lowest shear stress, accompanied by pronounced fluctuations. Shear stress along the vertical direction of the specimen is related to the movement of aggregates. Aggregates under the loading center primarily move downward, while those in the lower side regions of the model tend to move

Table 8

Meso-structure components of recycled asphalt mixture.

Mesoscopic component	New coarse aggregate	RAP	Aged asphalt	New asphalt mortar	RAP with microcracks
Visual examples					
Features	New coarse aggregates are distinguished by different colors	RAP is coated with aged asphalt, and represented by spheres with radii of 0.8 - 1.0 mm	Aged asphalt is coated on RAP surfaces and represented in yellow	Asphalt mortar is represented by spheres with radii of 0.2 - 0.3 mm and shown in gray	Shear stress and tensile stress microcracks are represented in blue and red, respectively

horizontally and upward. Specifically, shear stress is relatively small at the loading center; shear stress in region #5 is greater than that in region #6, and shear stress in region #9 is greater than that in region #10. However, shear stress in region #3 is lower than that in region #4, and shear stress in region #11 is lower than that in region #12.

According to Fig. 8, the following conclusions can be drawn.

- (1) The distribution of normal stress varies noticeably depending on the location of the measurement region and the mesostructural composition. As shown in Fig. 8(a), measurement regions #15, #16, and #18, located within the loading zone, exhibit significantly higher normal stress than regions #17, #19, and #20 situated on the sides of the loading zone. Within the loading zone, regions with high RAP content (#16 and #18) show relatively larger normal stress. At the same horizontal level, the normal stress in the RAP region (#16) is about 1.4 times that in the new aggregate region (#15), while the normal stress in the asphalt mortar region (#17) is approximately 40 % of that in region #16. In the side regions of the loading zone, normal stress in both RAP (#20) and new aggregate (#19) region, as well as in the asphalt mortar region (#17), is only 20–30 % of that observed in the loading zone. Therefore, two key characteristics of normal stress in recycled asphalt mixtures are evident: normal stress decreases with increasing distance from the loading center, and the capacity to transfer normal stress among mesostructural components follows the order: RAP > new aggregates > asphalt mortar.
- (2) The distribution of shear stress also differs clearly according to the location of the measurement region and the mesostructural composition. Specifically, the influence of measurement region location on shear stress is more pronounced than that of mesostructural composition. As illustrated in Fig. 8(b), measurement regions #15, #16, and #18, located within the loading zone, exhibit significantly higher shear stress than regions #19 and #20. This indicates that shear stress in the loading zone is markedly greater than that in the side regions. The mesostructural components also noticeably affect shear stress distribution. Based on the shear stress characteristics in regions #15, #16, #17, and #18, it is shown that regions enriched with new aggregates experience relatively higher shear stress, whereas regions rich in RAP exhibit comparatively lower shear stress. Regarding the underlying mechanism of this phenomenon, it is possible that the new aggregates come into contact with each other to form an interlocking structure, which can resist greater shear stress through the bonding of new asphalt. In contrast, the RAP surface is covered with aged asphalt that has poorer adhesion, resulting in relatively weaker shear resistance.

3.2. Characteristics of microcracks, slip-band structures, and aggregate breakage in recycled asphalt mixture

3.2.1. Development trend of microcracks

This section examines the mesoscopic characteristics of microcrack

initiation and propagation in recycled asphalt mixtures. Under loading, deformation continuously accumulates in the mixture, leading to the initiation, development, and gradual expansion of microcracks, accompanied by an increase in their number and density. Ultimately, this process results in cracking and loss of serviceability of the recycled asphalt mixture. The relationships among the number of microcracks, the stress on the loading plate, and the specimen deformation during the loading process are presented in Fig. 9.

According to Fig. 9, the evolution and failure mechanisms of microcracks in recycled asphalt mixtures under loading exhibit the following characteristics.

- (1) Microcrack development follows a three-stage pattern: initiation, stable growth, and rapid increase in number, ultimately leading to specimen failure. Regarding the variation trend of the total number of microcracks with different RAP contents, the total number of microcracks in the specimen with 15% RAP content is approximately 1116. In contrast, the total numbers of microcracks in specimens with 30%, 45%, and 60% RAP content are significantly higher, reaching 3250, 3638, and 4512, respectively. These correspond to increases of 2.91 times, 3.26 times, and 4.04 times compared to the 15% RAP content. During this process, the stress on the loading plate gradually increases until it stabilizes while the number of microcracks rises rapidly. At this stage, the interconnection of microcracks results in macro-cracking and loss of serviceability of the specimen.
- (2) Loading induces increasing deformation in the recycled asphalt mixture, causing movement of the asphalt mortar and initiating microcracks first at the interfaces of RAP and aged asphalt. As mixture deformation continues, microcracks propagate along RAP surfaces and their number gradually increases. Microcrack development is characterized by initial occurrence in RAP-enriched zones, followed by gradual appearance in regions where new and aged aggregates are intermixed as microcracks further extend. When RAP particles are spatially clustered, interfacial microcracks are more likely to connect and form macroscopic slip-band structures, significantly reducing the load-bearing capacity of the recycled asphalt mixture and ultimately leading to structural failure of the specimen.
- (3) When the shear stress between particles in the asphalt mixture exceeds the shear strength, or when the tensile stress surpasses the bonding strength between particles, microcracks initiate at the weakest locations, namely the interfaces between RAP and aged asphalt. Microcracks are predominantly distributed within the loading zone, while their occurrence in the side regions of the loading area is relatively limited. Microcracks are categorized into shear-stress microcracks and tensile-stress microcracks. Both types are present in the loading zone, whereas tensile-stress microcracks dominate in the side regions. The proportional variation in the number of shear-stress (SS) and tensile-stress (TS) microcracks across different loading stages is illustrated in Fig. 10.

According to Fig. 10, the following conclusions can be drawn.

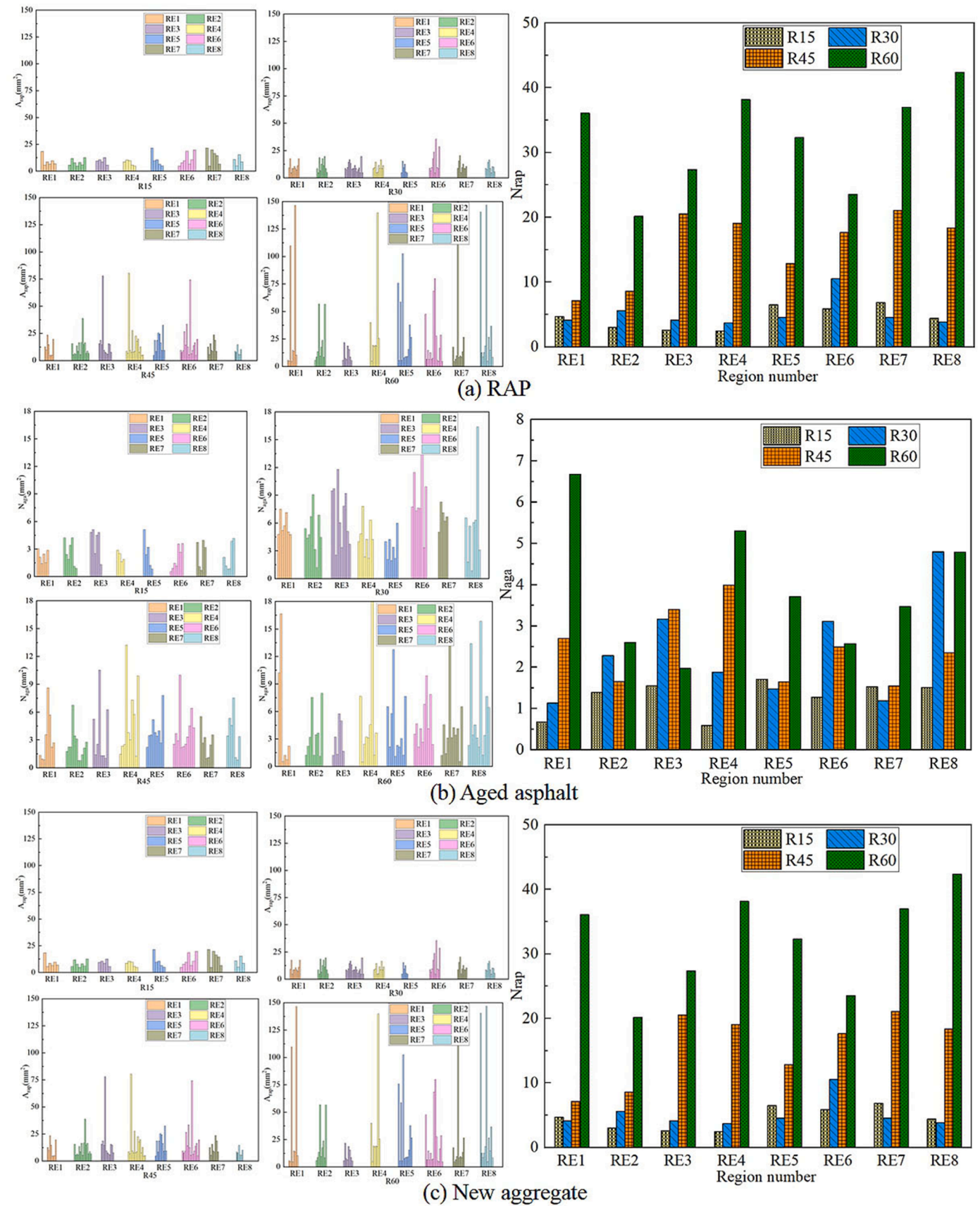


Fig. 5. Distribution characteristics of mesostructural components in different regions.

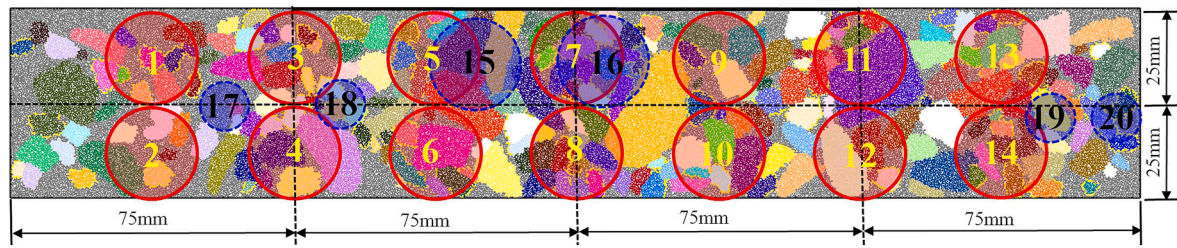


Fig. 6. Layout of measurement regions.

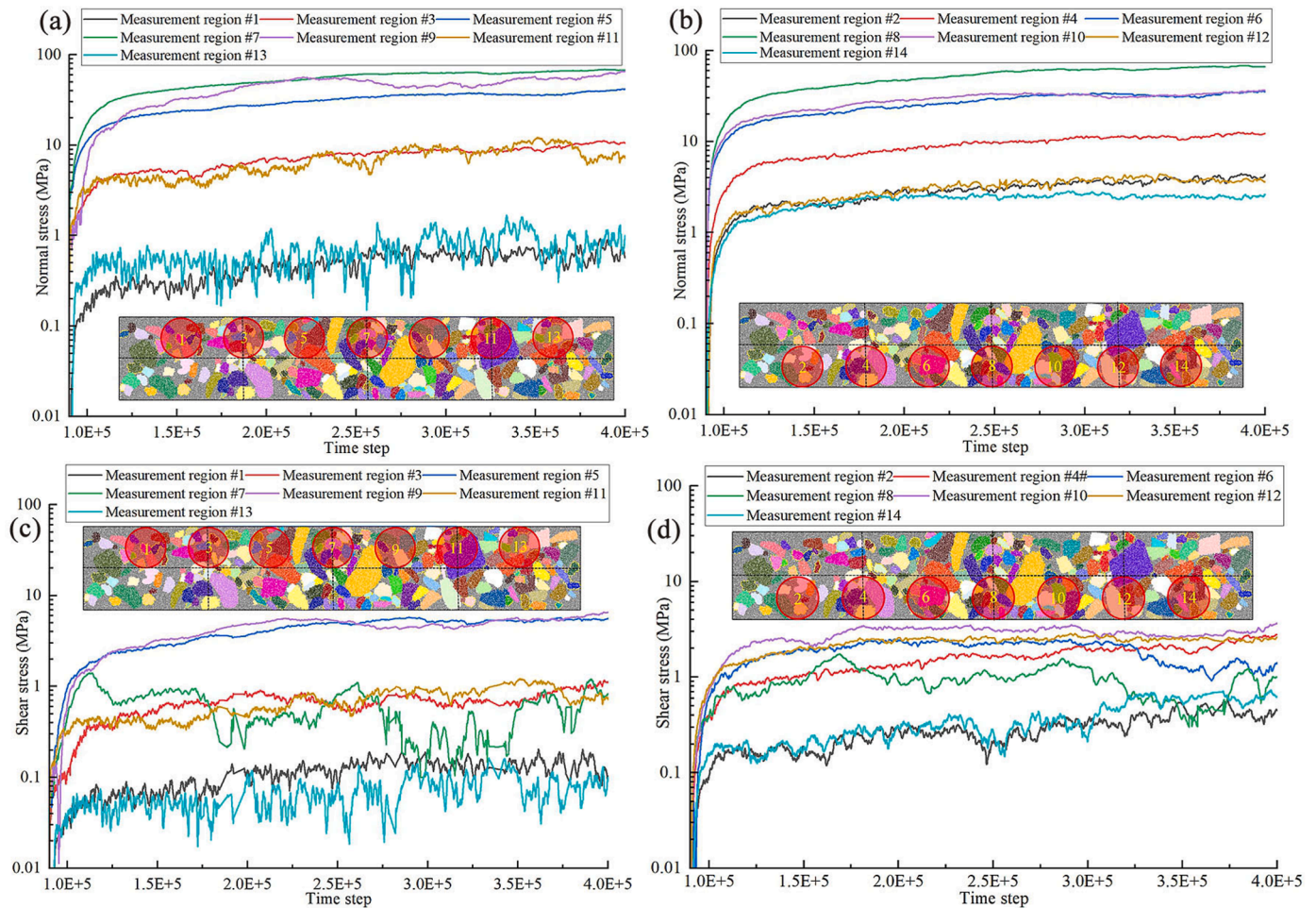


Fig. 7. Evolution of normal stress and shear stress (Scenario 1): (a) Normal stress in the upper DEM model (b) Normal stress in the lower DEM model (c) Shear stress in the upper DEM model (d) Shear stress in the lower DEM model.

- (1) During the loading process, the proportion of SS microcracks gradually increases from about 30 % to approximately 45 %, while the proportion of TS microcracks decreases from around 70 % to about 55 %. Within the loading zone, the number of SS microcracks shows a considerable increase, whereas the number of TS microcracks grows more slowly. In the side regions, the number of TS microcracks rises rapidly, while SS microcracks increase at a slower rate. The observed trend indicates a gradual rise in the proportion of SS microcracks and a corresponding decline in the proportion of TS microcracks. As microcracks multiply and interconnect to form continuous slip-band structures, the recycled asphalt mixture develops macro-cracks and loses its serviceability.
- (2) With increasing RAP content, the amounts of RAP and aged asphalt in the recycled mixture increase, leading to weakened

cohesion at the asphalt-aggregate interfaces and a consequent rapid growth in the number of microcracks. Apart from RAP content, other factors influencing microcrack development in recycled asphalt mixtures include the properties of new and aged asphalt, as well as the characteristics of aggregate breakage.

3.2.2. Characteristics of microcracks and slip-band structures

Microcracks first appear at the interfaces within regions where RAP particles are concentrated. Factors such as numerous micro-voids at RAP-aged asphalt interfaces, local weak zones, and aggregate breakage collectively contribute to the initiation and rapid propagation of microcracks under loading. These microcracks subsequently coalesce to form slip-bands, leading to cracking in the recycled asphalt mixture. Slip-bands represent weak zones in the materials and constitute the regions with the highest risk of cracking failure. Currently, no studies have

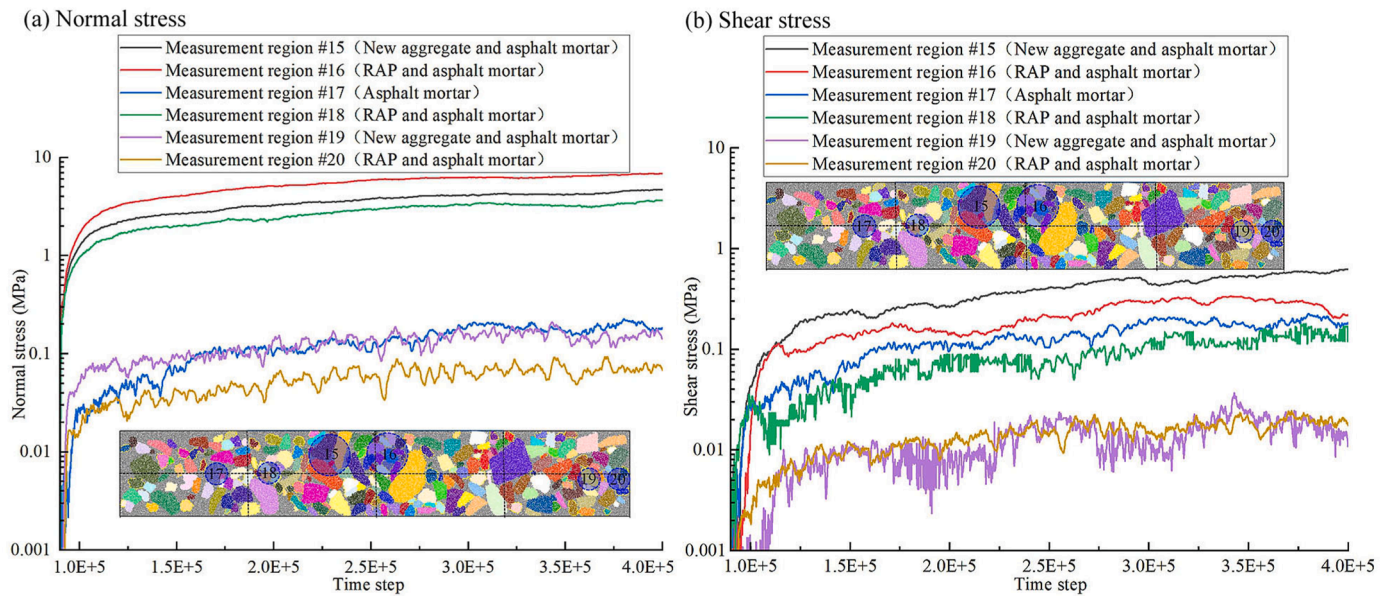


Fig. 8. Evolution of normal stress and shear stress (Scenario 2).

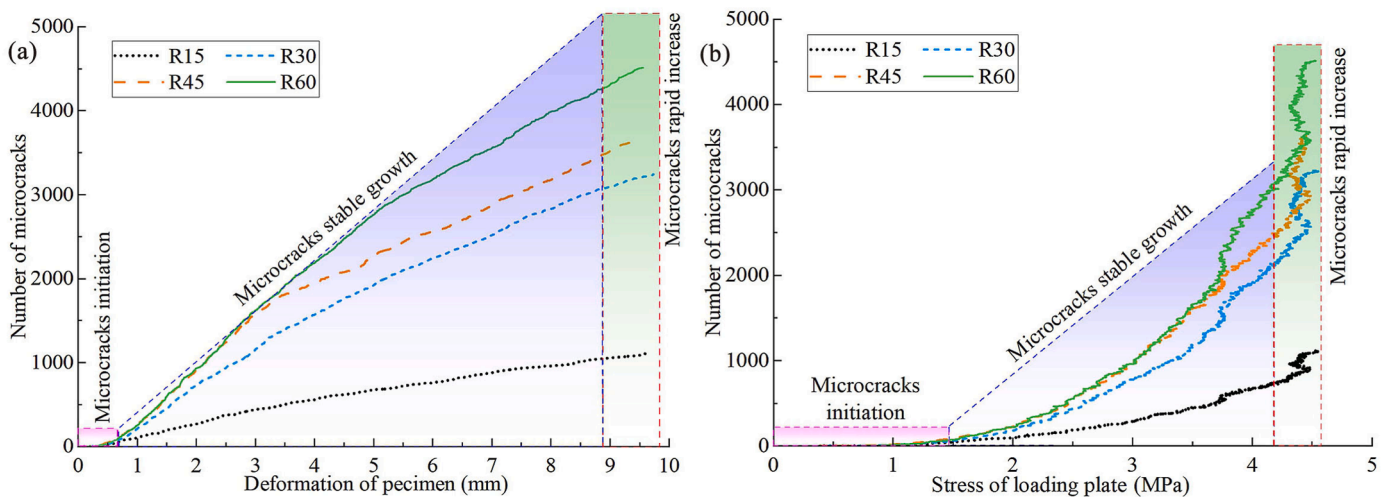


Fig. 9. Relationship between the number of microcracks and specimen deformation (a), as well as loading plate stress (b).

been found to investigate slip-band structures in asphalt mixtures with viscoelastic characteristics. Therefore, this study proposes identification criteria for slip-bands based on the DEM. A slip-band is defined as a zone that causes cracking failure in the specimen with a length of not less than 30 mm. Microcracks around the slip-band are referred to as effective microcracks, while microcracks in other regions are termed other microcracks. As illustrated in Fig. 11, slip-bands are distributed non-uniformly in the recycled asphalt mixture and exhibit the following main characteristics.

- (1) Multiple slip-bands exist, varying in both length and inclination angle.
- (2) The inclination angle of a slip-band is defined as the angle between the slip-band and the loading direction, ranging from 0° to 180° . Slip-bands are categorized at 15° intervals into the following types: compression-dominated (0° - 15° or 165° - 180°), compression-shear (15° - 30° or 150° - 165°), shear-dominated (30° - 60° or 120° - 150°), tension-shear (60° - 75° or 105° - 120°), and tension-dominated (75° - 105°).

- (3) Penetrated slip-bands can cause cracking in the recycled asphalt mixture, whereas non-penetrated slip-bands may only induce damage without necessarily leading to complete fracture.

According to Fig. 11, the characteristics of aggregate breakage and slip-bands are summarized as follows.

- (1) When the RAP content is less than 30%, slip-bands are randomly distributed in the weak zones of the recycled asphalt mixture. When the RAP content exceeds 30%, the number of microcracks, aggregate breakage, and slip-bands in the tensile stress zones on both sides of the loading area are significantly higher than those in the loading area, and the number of penetrated slip-bands increases notably.
- (2) Slip-bands develop along the weak zones of the specimen with various morphologies and no obvious pattern. The development direction of slip-bands is primarily downward along the specimen, with very few slip-bands developing transversely.
- (3) As the RAP content increases, the cracks in the recycled asphalt mixture gradually develop from strip cracks to intersecting

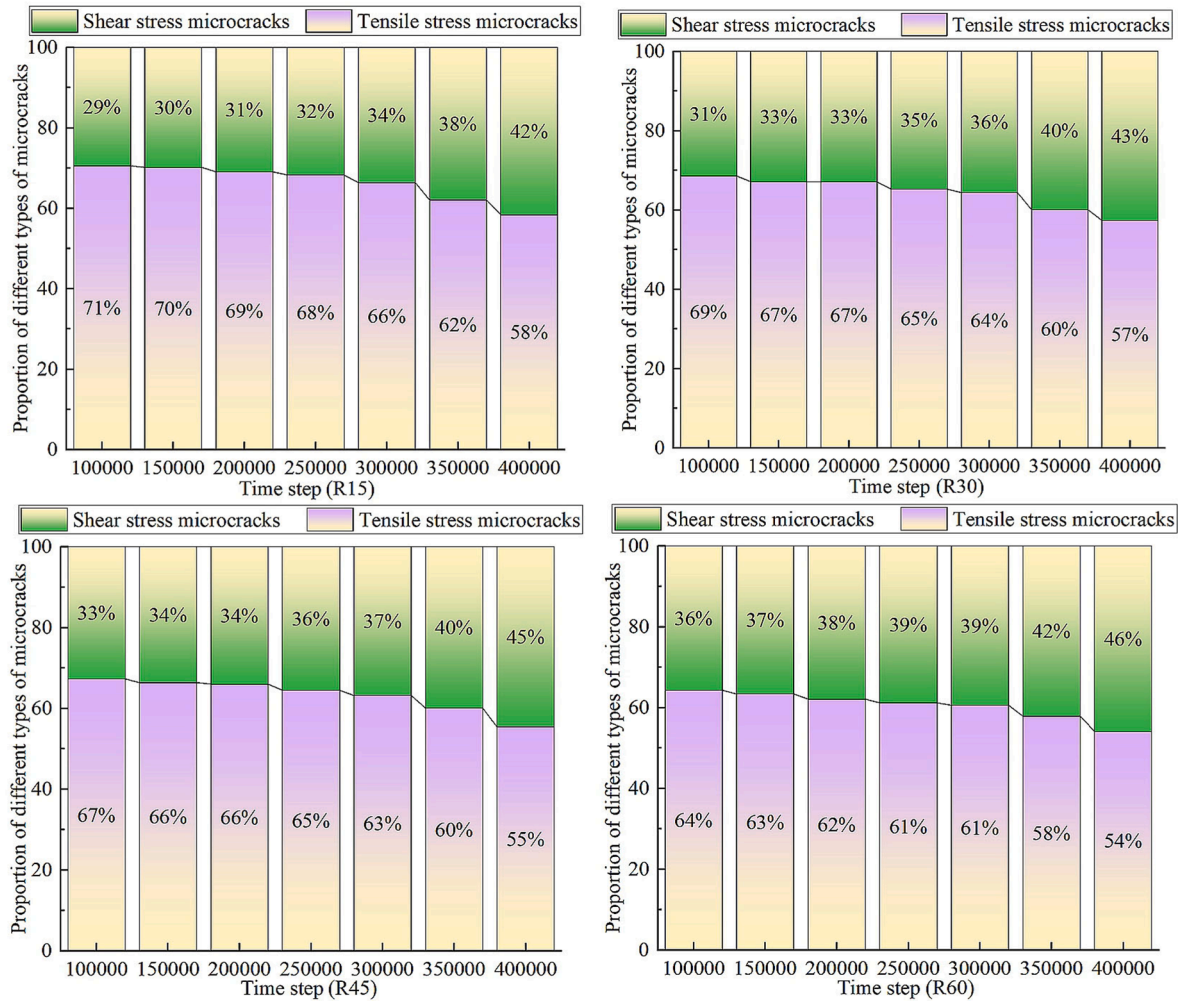


Fig. 10. Proportions of different types of microcracks at each loading stage.

cracks. When the RAP content reaches 60%, multiple penetrated cracks interconnect to form a network of cracks, ultimately leading to failure of the asphalt mixture and loss of serviceability.

The characteristics of microcrack and slip-band indices for recycled asphalt mixtures with different RAP contents after 400,000 loading cycles are detailed in Fig. 12. The microcrack evaluation indices include the maximum and minimum length of a single microcrack, the numbers of SS and TS microcracks, and the numbers of effective and other microcracks. The slip-band evaluation indices comprise the inclination angle, length, and area of the slip-bands.

According to Fig. 12, the characteristics of microcracks and slip-bands for different RAP contents are summarized as follows.

- (1) RAP content has limited influence on the maximum length of a single microcrack. The maximum length of a single microcrack is approximately 0.8 mm, while the minimum length is generally around 0.4 mm. Such small microcracks are predominantly distributed within the asphalt mortar.
- (2) RAP content significantly affects the number of SS and TS microcracks. TS microcracks are distributed throughout the specimen and increase gradually with higher RAP content. SS microcracks are mainly concentrated in the loading zone and remain relatively stable in number when RAP content exceeds 30 %.

- (3) Microcracks in the recycled asphalt mixture are categorized into effective and other microcracks. Effective microcracks are primarily located within slip-bands and ultimately lead to cracking failure of the mixture. Other microcracks cause internal damage but may not necessarily result in cracking. As RAP content increases from 15 % to 60 %, the number of effective microcracks increases by 2.04 times, while the number of other microcracks decreases to 47.61% of that observed at 15% RAP content. These results indicate that higher RAP content substantially increases the cracking risk of recycled asphalt mixtures.

- (4) RAP content shows little notable effect on the inclination angle of slip-bands, but significantly influences slip-band length and area. The inclination angle ranges from 0° to 90°, length varies between 25 and 70 mm, and area falls within 50–3200 mm². All three parameters exhibit a rapid increasing trend with rising RAP content.

Microcracks and slip-bands cause damage to recycled asphalt mixtures, ultimately leading to cracking failure and loss of serviceability. In this study, the effective microcrack regions within slip-bands that result in specimen cracking failure were statistically analyzed, and the crack damage index D was used to characterize the damage degree of the recycled mixture, as defined in Eq. (2).

$$D = d_{\text{ram}} = \frac{A_{\text{ram}}}{A_{\text{to}}} \quad (2)$$

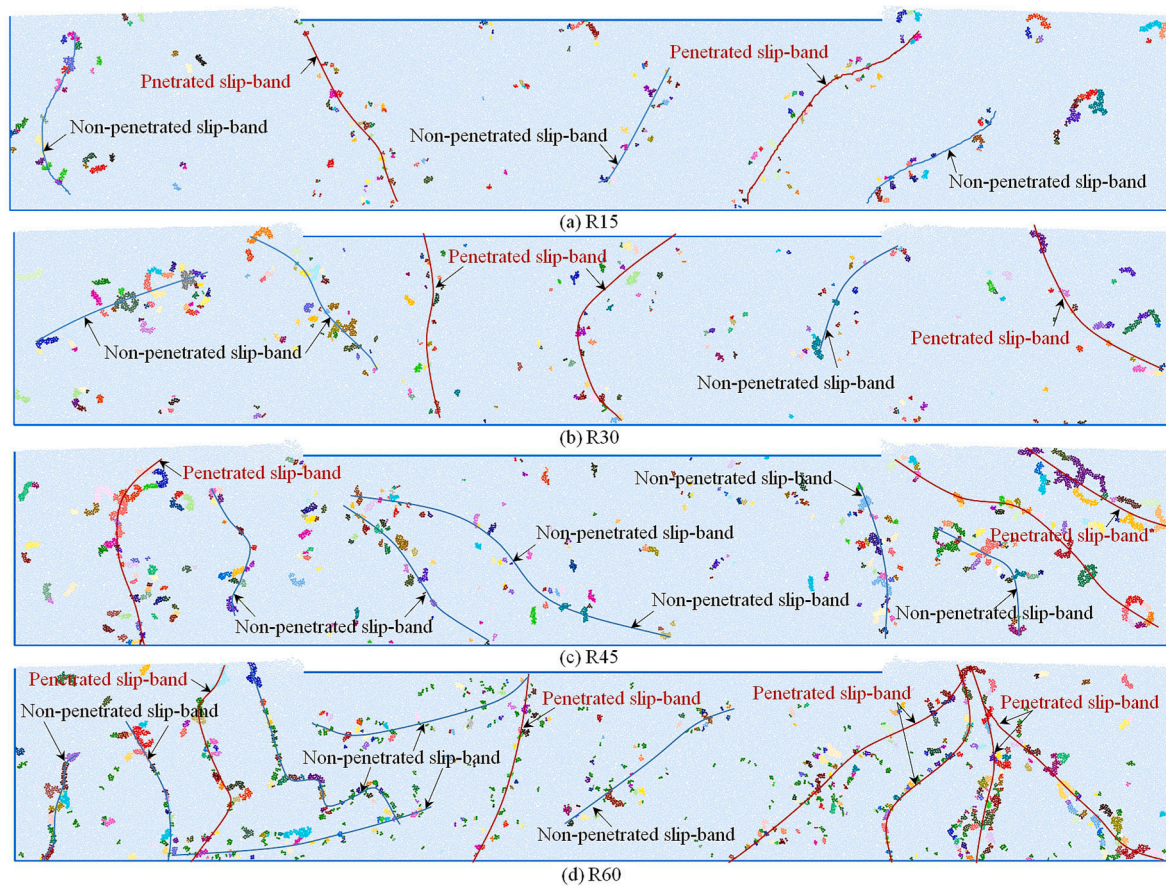


Fig. 11. Characteristics of slip-bands and aggregate breakage in the recycled asphalt mixture.

Where, D is crack damage, %, $0 \leq D \leq 1$; d_{ram} is the density of microcracks within slip bands; A_{ram} is the total area of slip bands, mm^2 ; A_{to} is the total area of the specimen, mm^2 .

From the perspective of DEM mesostructure, the physical meaning of D is the degree of damage to the mesoscopic contact bonds of the recycled asphalt mixture, namely the ratio of the number of broken parallel bonds to the total number of initial bonds in the DEM models. D characterizes the progressive damage and failure characteristics of the recycled asphalt mixture induced by loading; however, D does not directly represent material stiffness or predict fatigue life. Instead, it provides a material crack damage evaluation index based on the mesostructural scale. The D value ranges from 0 to 1, with a higher D indicating more severe internal cracking damage in the recycled asphalt mixture. The development trend of D with different RAP contents and the relationship between the number of slip-bands and the corresponding D value are presented in Fig. 13.

Based on Fig. 13, the following conclusions can be drawn.

- (1) Loading induces microcracks in the recycled asphalt mixture, exhibiting a three-stage evolution pattern of initiation, stable growth, and rapid increase. The D value similarly shows an accelerating damage trend. When the stress on the loading plate reaches its peak, the D value begins to increase rapidly, ultimately leading to accelerated failure of the recycled asphalt mixture. From a mesomechanical perspective, a high RAP content causes parallel bonds to break more easily due to the effect of aged asphalt, resulting in a higher D value. This indicates that the mesostructure of mixtures with high RAP content undergoes more severe instability and failure under the same deformation conditions.

- (2) As the RAP content increases, the number of microcracks in the mixture shows a clear upward trend, with numerous microcracks connecting to form slip-bands and the rut depth increasing. Increasing RAP content leads to an exponential growth trend in both the number of slip-bands and the crack damage index D . The results indicate that when the RAP content exceeds 45%, the number of effective microcracks, the number, length, and area of slip bands increase rapidly, leading to accelerated crack propagation and the formation of more penetrated cracks, thereby significantly increasing the risk of cracking failure. It is recommended that the RAP content should not exceed 45%. Material optimization measures to inhibit crack development include the use of high viscosity modified asphalt or rejuvenators to enhance the adhesion of aged asphalt and reduce the risk of crack initiation.

3.2.3. Characteristics of aggregate breakage in different regions

Under vehicular loading, aggregates in asphalt pavement are subjected to a complex stress state comprising compressive, shear, and tensile stresses, which tends to induce stress concentration in contact zones. When the localized stress exceeds the compressive or shear strength threshold of the aggregate, crushing or fracture failure occurs. The characteristics of aggregate breakage after 400,000 loading cycles are presented in Fig. S6. As shown in the figure, rutting develops in the recycled asphalt mixture under the loading zone due to compression, while flow-type rutting occurs with upward displacement on both sides of the loading area. Aggregates and asphalt mortar in the side regions of the loading zone gradually shift from downward movement to horizontal and upward motion. Aggregate breakage concentrates primarily in the aged asphalt regions on RAP surfaces, predominantly involving crushing at aggregate edges under compression and shear, with fracture

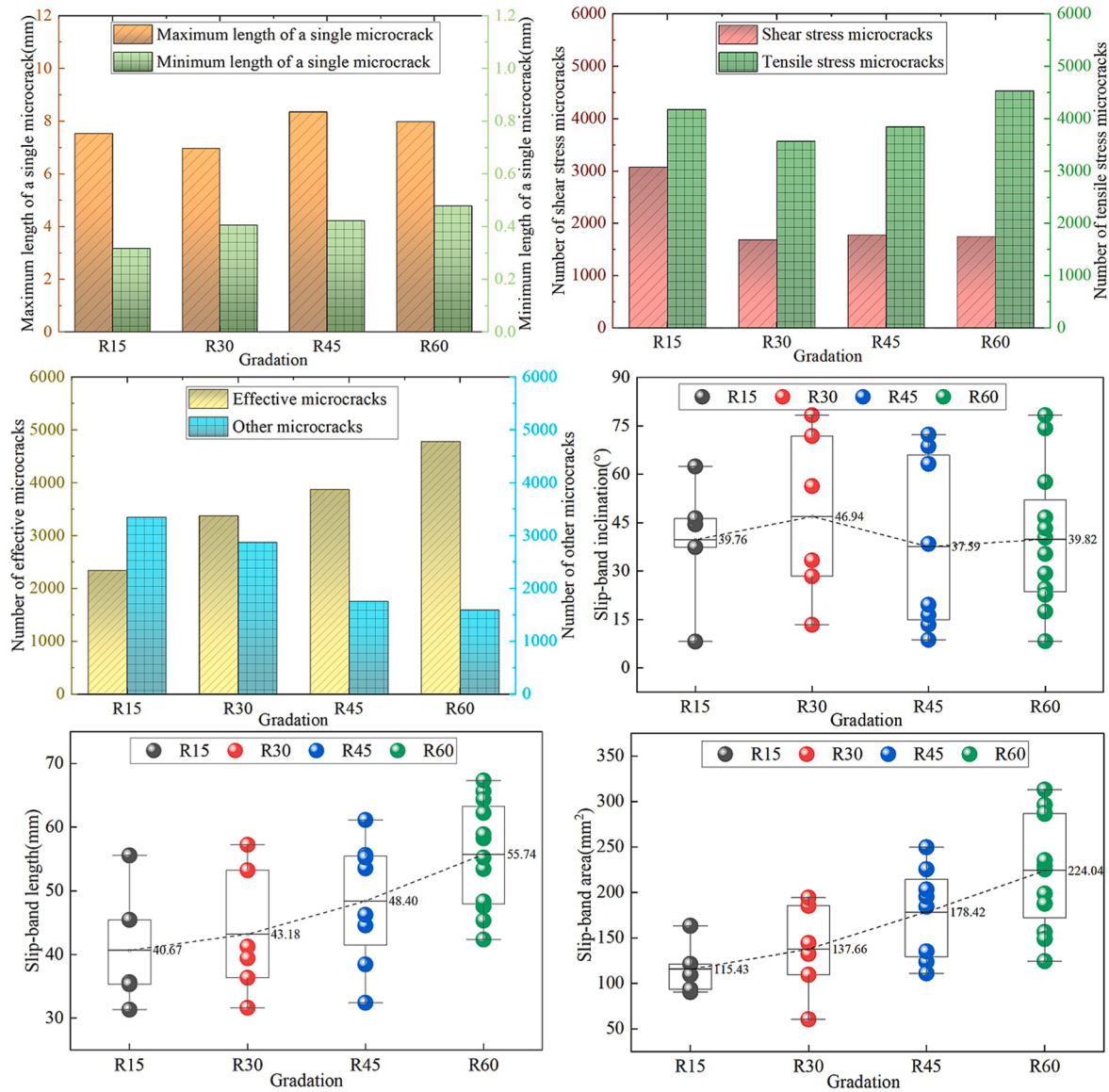


Fig. 12. Characteristics of microcracks and slip-bands in recycled asphalt mixtures.

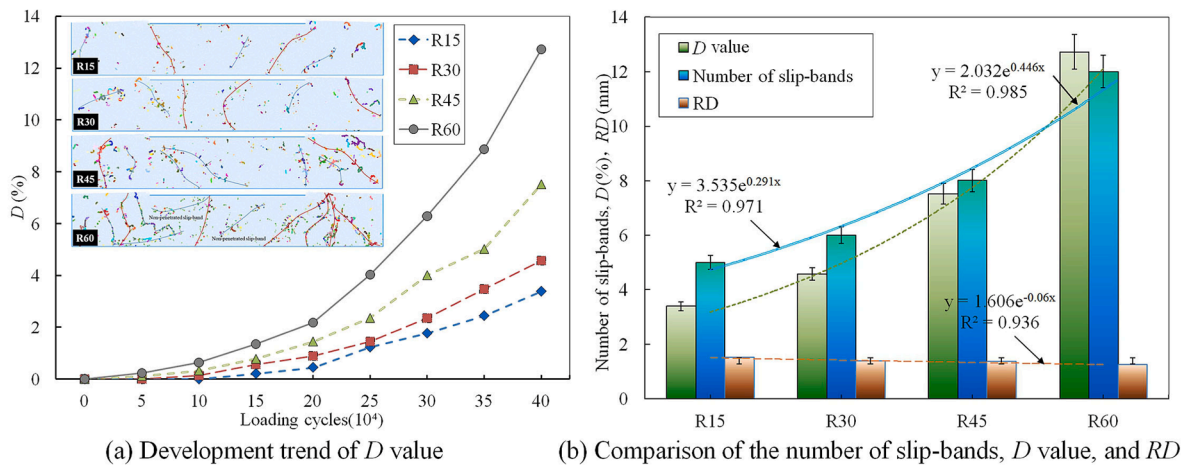


Fig. 13. Development trend of D value and comparison of slip-band number, D value, and RD .

of aggregates being less common. In the DEM models, this behavior is reflected as the failure of Ball-Ball parallel bonds, which corresponds macroscopically to aggregate breakage.

The DEM model was divided into four regions, labeled I–IV. Regions II and III are located within the loading zone, while regions I and IV are situated on the sides of the loading area. The aggregate breakage rate, defined as the ratio of broken aggregate area to the total area of each region, was used to evaluate aggregate breakage characteristics. The aggregate breakage rates in each region for recycled asphalt mixtures with different RAP contents after 400,000 loading cycles are presented in Fig. 14.

According to Fig. 14, the following conclusions can be drawn.

- (1) As RAP content increases, the aggregate breakage rate exhibits an exponential growth trend. For a recycled asphalt mixture with 15 % RAP content, the aggregate breakage rate is approximately 2 %, whereas at 60 % RAP content, the breakage rate reaches about 8.5 %, generally not exceeding 10 %. At 60 % RAP content, the aggregate breakage rate in the loading zone (regions II and III) is about 7 times that at 15 % RAP content, while in the side regions (regions I and IV), it is 3.78 times higher. For mixtures with high RAP content, the combined effects of deterioration at numerous RAP-aged asphalt interfaces and stress concentration likely contribute to the substantial increase in aggregate breakage within the loading zone.

- (2) The aggregate breakage rate differs considerably among different regions. As shown in Fig. 14(b), the loading zone (regions II and III) accounts for about 70 % of the total aggregate breakage, while the side regions (regions I and IV) contribute approximately 30 %. The aggregate breakage rate is closely related to the load transmission path. Due to the direct action of loading stress, more slip-bands develop in the loading zone (regions II and III), resulting in a significantly higher aggregate breakage rate compared to the side regions (regions I and IV).

3.2.4. Cross-scale relationship between mesoscopic indices and macroscopic performance

To apply the mesostructural findings of this study to practical engineering, the cross-scale relationship between mesoscopic indices and macroscopic performance are analyzed to provide guidance for the design and durability enhancement of recycled asphalt mixtures. Considering the convenience of obtaining mesoscopic indices, the selected mesoscopic indices include the number, average length, and area of slip-bands, as well as aggregate breakage indices including breakage rate, breakage area, and the D value. The macroscopic parameter is the RD after 400,000 loading cycles, which is used to differentiate the durability of recycled asphalt mixtures with different RAP contents. The cross-scale relationship between mesoscopic indices and macroscopic performance is presented in Fig. 15.

Based on Fig. 15, the following conclusions can be drawn.

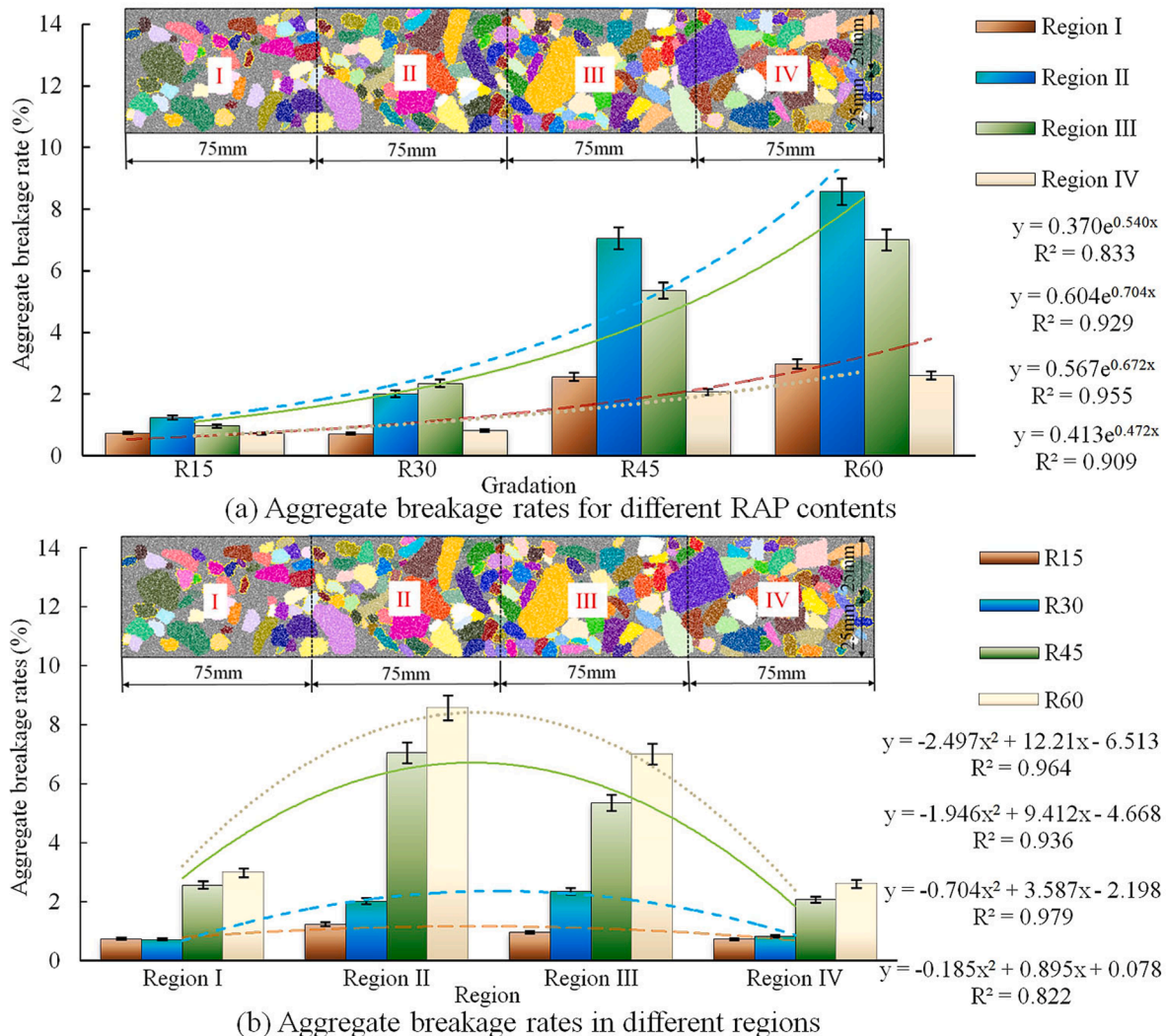


Fig. 14. Characteristics of aggregate breakage rate distribution.

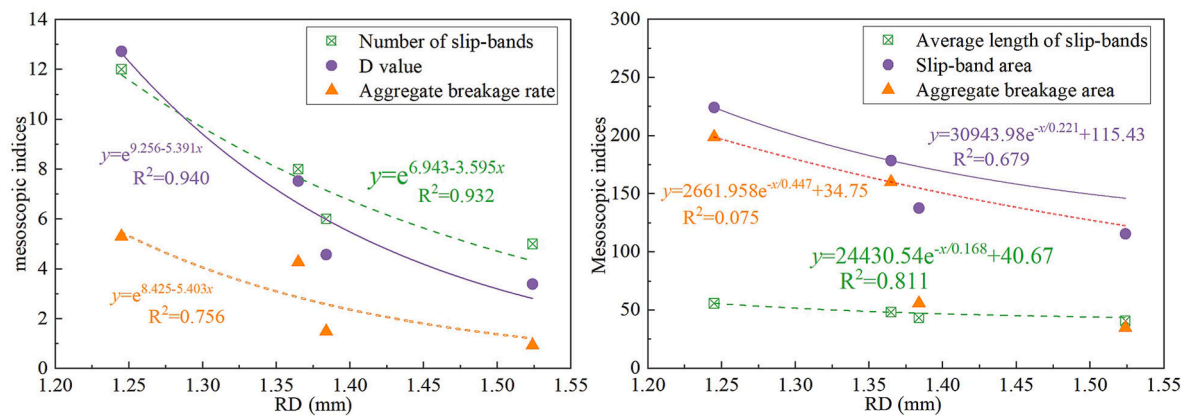


Fig. 15. Cross-scale relationship between mesoscopic indices and macroscopic performance.

- (1) As RAP content increases, the RD value decreases while the mesoscopic indices increase. The number and average length of slip-bands as well as the D value all exhibit an exponential relationship with RD, with $R^2 \geq 0.8$. The aggregate breakage rate and slip-bands area also show exponential relationships with RD, with R^2 values of 0.756 and 0.679, respectively. The relationship between aggregate breakage area and RD yields $R^2 < 0.1$, indicating no significant correlation, which suggests that aggregate breakage has a limited effect on the mechanical performance of recycled asphalt mixtures.
- (2) The number of slip-bands, the average length of slip-bands, and the D value each have an $R^2 \geq 0.8$ with RD, and all are crack-related evaluation indices for recycled asphalt mixtures. This study recommends them as primary indices for mesostructural evaluation. For threshold standards of the mesoscopic indices, based on a RAP content of 45 %, this study proposes that the number of slip-bands ≤ 8 , average length of slip-bands ≤ 48 mm, and $D \leq 7.5$ %.
- (3) Increasing RAP content improves rutting resistance but simultaneously reduces the uniformity of mesostructural component distribution and the crack resistance of the mixture. Especially when RAP content exceeds 45 %, the distribution of aged asphalt and RAP becomes significantly non-uniform, leading to an increase in weak interfaces. The number of slip-bands increases markedly, and multiple penetrating cracks interconnect to form a crack network, causing a significant rise in the cracking risk of the recycled asphalt mixture. Considering rutting resistance, crack resistance, and resource utilization efficiency comprehensively, the recommended suitable RAP content range is 30 % - 45 %.

4. Conclusions

- (1) The distributions of aged asphalt, RAP, and new aggregates in recycled asphalt mixtures exhibit considerable randomness. Increasing RAP content reduces the homogeneity of the mixture. When the RAP content exceeds 45 %, aged asphalt and RAP display particularly pronounced non-uniform distributions, and the increased presence of weak RAP-aged asphalt interfaces leads to a decline in mechanical performance.
- (2) Distinct differences in normal stress and shear stress are observed across different regions of the recycled asphalt mixture. The maximum normal stress occurs at the center of the loading zone, while the maximum shear stress is located at the bottom sides of the loading center. At the bottom of the loading zone, the normal stress attenuates to 20 %–50 % of that at the loading plate, whereas the shear stress remains relatively high.
- (3) Considerable differences in normal stress and shear stress exist among different mesostructural components of the recycled

asphalt mixture. The capacity to transfer normal stress among mesostructural components follows the order: RAP > new aggregates > asphalt mortar. Regions enriched with new aggregates experience relatively higher shear stress, while regions rich in RAP show comparatively lower shear stress.

- (4) RAP content significantly influences the maximum microcrack length, the numbers of SS and TS microcracks, and the numbers of effective and other microcracks. Increasing the RAP content substantially elevates the cracking risk of the recycled asphalt mixture. As RAP content increases from 15 % to 60 %, the number of TS microcracks grows slowly, the number of SS microcracks stabilizes when RAP content exceeds 30 %, the number of effective microcracks increases by 2.04 times, and the number of other microcracks decreases by 47.61 %.
- (5) RAP content significantly influences the distribution regions, morphological characteristics, and development trends of slip-bands. As RAP content increases, the number of slip-bands increases notably, and multiple penetrated cracks interconnect to form a network of cracks, with the crack damage index D exhibits an exponential upward trend. The relationship between RAP content and aggregate breakage rate exhibits an exponential growth trend. At 60 % RAP content, the aggregate breakage rate in the loading zone is about seven times that at 15 % RAP content, while in the side regions, it is approximately 3.78 times higher.
- (6) Considering rutting resistance, crack resistance, and resource utilization efficiency comprehensively, the recommended suitable RAP content range is 30 % - 45 %. The designed recycled asphalt mixture was simulated and validated using the DEM method, with the following threshold values for the mesoscopic indices: number of slip-bands ≤ 8 , average length of slip-bands ≤ 48 mm, and $D \leq 7.5$ %. Material optimization measures to inhibit crack development include the use of high viscosity modified asphalt or rejuvenators to enhance the adhesion of aged asphalt and reduce the risk of crack initiation.

CRediT authorship contribution statement

Liwan Shi: Writing – review & editing, Writing – original draft, Software, Methodology, Conceptualization. **Zhiyong Hu:** Writing – review & editing, Supervision. **Hao Li:** Resources. **Bohuang Lin:** Writing – review & editing. **Youwei Tan:** Formal analysis. **Yi Deng:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.partic.2026.05.019>.

References

- Alae, M., Xu, L., Cao, Z. L., Xu, X. Y., & Xiao, F. P. (2023). Fatigue and intermediate-temperature cracking performance of rejuvenated recycled asphalt binders and mixtures: A review. *Journal of Cleaner Production*, 384, Article 135587.
- Cheng, L., Yuan, W. S., Zhang, L., Zhou, S., Zhang, Z. J., Ma, Y., Yuan, F., & Liu, Z. Q. (2024). Investigation of damage and crack characteristics of epoxy modified recycled asphalt mixtures based on a three-dimensional meso-heterogeneous model. *Construction and Building Materials*, 438, Article 137144.
- Cui, Y. N., Geng, K., Zhou, Q. Y., & Zhang, S. Y. (2024). Research on the adhesion between warm mix recycled asphalt and aggregates at macro and micro scales. *Construction and Building Materials*, 455, Article 139076.
- Daniel, A. Z. A., Hugo, A. R. Q., & Carlos, A. Z. M. (2021). Mechanical performance of gilsonite modified asphalt mixture containing recycled concrete aggregate. *Applied Sciences*, 11(10), 4409.
- Dong, J., Ding, Y. X., Liu, Y. H., Ning, Z. Y., & Qi, Y. J. (2024). Tensile test and discrete element study on recycled aggregate hydraulic asphalt concrete. *Construction and Building Materials*, 450, Article 138538.
- Fan, X. Z., Qiao, Y. H., Zhang, J. Z., Xiong, Y. S., Cao, W. D., Yang, K., & Yao, Z. Y. (2024). Towards the high RAP dosage obtained by refined processing influence on comprehensive performance of recycled asphalt mixture. *Construction and Building Materials*, 452, Article 138885.
- Gao, L., Li, H., Xie, J. G., & Yang, X. (2017). Mixed-mode fracture modeling of cold recycled mixture using discrete element method. *Construction and Building Materials*, 151, 625–635.
- Jiang, J. W., Leng, Z., Yang, B., Lu, G. Y., Tan, Z. F., Han, M. Z., & Dong, Z. J. (2022). Penetration mechanism of the emulsion-based rejuvenator in damaged porous asphalt mixture: Microstructure characterization and 3D reconstruction. *Materials & Design*, 221, Article 111014.
- Jin, D. Z., Ge, D. D., Zhou, X. D., & You, Z. P. (2022). Asphalt mixture with scrap tire rubber and nylon fiber from waste tires: Laboratory performance and preliminary M-E design analysis. *Building*, 2(12), 160.
- Jin, D. Z., Yin, L., Malburg, L., & You, Z. P. (2024). Laboratory evaluation and field demonstration of cold in-place recycling asphalt mixture in Michigan low-volume road. *Case Studies in Construction Materials*, 20, Article e02923.
- Jin, D. Z., Yin, L., Nedrich, S., Boateng, K. A., & You, Z. P. (2024). Resurface of rubber modified asphalt mixture with stress absorbing membrane interlayer: From laboratory to field application. *Construction and Building Materials*, 441, Article 137452.
- Kou, C. J., Fan, R. X., Zhang, M. Y., Zhu, Z. H., Kang, A. H., & Baaj, H. (2025). Investigation into the crack propagation behaviors of asphalt mixture containing recycled concrete aggregates using digital image correlation. *Construction and Building Materials*, 470, Article 140636.
- Li, H., Shi, L. W., Li, J. Q., Ma, T., Tan, Y. W., Chen, W. Z., & Lin, Y. K. (2026). Durability influencing factors and attenuation characteristics of composite modified asphalt anti-skid surface layer. *Construction and Building Materials*, 516, Article 145631.
- Liang, H. H., Guo, H. J., Zhang, J. J., Li, H., Shi, L. W., & Deng, K. L. (2025). Influence of gradation composition on crack evolution of stone mastic asphalt based on digital image processing. *Theoretical and Applied Fracture Mechanics*, 136, Article 104848.
- Liang, H. H., Shi, L. W., Wang, Y. C., Li, P. X., & Huang, J. J. (2025). A study on the mechanical properties of an asphalt mixture skeleton meso-structure based on computed tomography images and the discrete element method. *Applied Sciences*, 15, Article 10799.
- Lin, B. H., Shi, L. W., Zhang, X., Liang, H. H., & Wang, D. Y. (2022). Study on meso-structural characteristics and homogeneity of asphalt mixture skeleton contacts. *Case Studies in Construction Materials*, 17, Article e01277.
- Ling, M., Zhang, Y., Kaseer, F., Martin, A. E., & Lytton, R. L. (2020). Investigation of fracture behavior of asphalt mixture composite using energy-based approach. *Composites Part B: Engineering*, 181, Article 107324.
- Liu, Q., Liu, J. Y., Wu, J. T., Jiao, Y., Fang, R. Y., & Zhu, J. L. (2024). Investigating agglomeration behavior of recycled asphalt mixtures in mixing stage using discrete element method. *Construction and Building Materials*, 440, Article 137504.
- Liu, J. Y., Liu, Q., Yin, L., & Wu, J. T. (2025). Temperature and contact states of hot-recycled asphalt mixing at a non-thermal equilibrium condition based on discrete element method. *Construction and Building Materials*, 469, Article 140526.
- Liu, Q., & Oeser, M. (2021). The influence of mixing conditions on the macro-scale homogeneity of asphalt mixtures blended with reclaimed asphalt pavement (RAP). *Materials*, 14(15), 4137.
- Nian, T. F., Ge, J. G., Li, P., Guo, R., Li, J. G., & Wang, M. (2022). Improved three-dimensional discrete modeling method and anti-cracking properties of asphalt mixture. *Construction and Building Materials*, 321, Article 126405.
- Nian, T. F., Wang, M. M., Ge, J. G., Guo, R., Li, P. Y., & Song, J. Q. (2024). Enhancing low-temperature crack resistance: A method for establishing meso-models and evaluating steel fiber-reinforced hot recycled asphalt mixtures. *Construction and Building Materials*, 438, Article 137026.
- Nian, T. F., Wang, M. M., Huang, X. M., Ge, J. G., Song, J. Q., & Li, P. Y. (2024). Investigating crack resistance and mechanisms of crack extension in high-content steel fibers reinforced hot recycled asphalt mixtures. *Construction and Building Materials*, 450, Article 138717.
- Sheng, Y. P., Jia, H. C., Lv, H. L., Chen, H. X., Zhao, X. R., Wang, R. Z., & Meng, J. D. (2020). Study on mesoscopic mechanics of recycled asphalt mixture in the indirect tensile test. *Mathematical Problems in Engineering*, 1–12.
- Shi, L. W., Liang, H. H., Wang, D. Y., & Liu, T. (2022). Mesogenetic evaluation and design of coarse aggregate contact within asphalt mixture. *Journal of Materials in Civil Engineering*, 34(8), Article 04022187.
- Shi, L. W., Wang, Y. C., Li, H., Liang, H. H., Lin, B. H., & Wang, D. Y. (2023). Recycled asphalt mixture's discrete element model-based composite structure and mesoscale-mechanical properties. *Case Studies in Construction Materials*, 18, Article e01987.
- Sivilevičius, H., & Vislavičius, K. (2019). Simulation of composition of recycled hot-mix asphalt mixture produced in asphalt mixing plant. *Construction and Building Materials*, 214, 17–27.
- Sun, X. L., Qin, X., Liu, Z. S., & Yin, Y. M. (2025). Damaging effect of fine grinding treatment on the microstructure of polyurea elastomer modifier used in asphalt binder. *Measurement*, 242, Article 115984.
- Sun, D. Q., Tian, Y., Sun, G. Q., Pang, Q., Yu, F., & Zhu, X. Y. (2018). Performance evaluation of asphalt mixtures containing recycled concrete aggregates. *International Journal of Pavement Engineering*, 19(5), 422–428.
- Sun, X. L., Ye, Y. C., Qin, X., Liu, Z. S., Zhao, W. S., & Wang, Z. M. (2026). Deterioration behavior and mechanism of heavy metal leaching inhibition efficiency of MSWI fly ash - Asphalt mastic under ultraviolet irradiation. *Waste Management*, 215, Article 115428.
- Tan, Y. Q., Wang, W., Xu, Y. J., Xing, C., Hu, J. Y., Li, S., & Dai, M. X. (2024). Investigation into the force chain transmission mechanism of asphalt mixture under indirect tensile mode. *Construction and Building Materials*, 411, Article 134500.
- Wang, H. T., Cheng, Y. C., Liang, J. X., Zhao, W. S., & Li, A. P. (2024). Evaluating the fracture characterization of asphalt mixtures under freeze-thaw damage based on full-field measurements. *Measurement*, 228, Article 114393.
- Wang, L., & Yang, X. C. (2022). Analysis of optimal RAP content based on discrete element method. *Advances in Materials Science and Engineering*, 1–7.
- Xue, B., Que, Y., Pei, J. Z., Ma, X. Y., Wang, D., Yuan, Y., & Zhang, H. (2024). A state-of-the-art review of discrete element method for asphalt mixtures: Model generation methods, contact constitutive models and application directions. *Construction and Building Materials*, 414, Article 134842.
- Yang, Y. H., Chen, Y. M., Li, B. C., & Yang, Y. (2024). Micro-scale Fracture characteristics of emulsified asphalt cold recycled mixture based on discrete element method. *Coatings*, 14(11), 1436.
- Yang, X. C., Tang, H. Z., Cai, X., Wu, K. H., Huang, W. K., Zhang, Q. R., & Li, H. (2023). Evaluating reclaimed asphalt mixture homogeneity using force chain transferring stress efficiency. *Construction and Building Materials*, 365, Article 130050.
- Yang, Y. H., Wang, H. B., Yang, Y., & Zhang, H. Z. (2021). Evaluation of the evolution of the structure of cold recycled mixture subjected to wheel tracking using digital image processing. *Construction and Building Materials*, 304, Article 124680.
- Yao, X. G., & Xu, T. (2023). Fatigue fracture and self-healing behaviors of cold recycled emulsified asphalt mixture containing microcapsules based on semicircular bending test. *Journal of Cleaner Production*, 410, Article 137171.
- Yousefi, A. A., Sobhi, S., Aliha, M. R. M., Pirmohammad, S., & Hagushenas, H. F. (2021). Cracking properties of warm mix asphalts containing reclaimed asphalt pavement and recycling agents under different loading modes. *Construction and Building Materials*, 300, Article 124130.
- Yu, J. M., Lin, Z. Y., Zou, G. L., Yu, H. Y., Leng, Z., & Zhang, Y. (2024). Long-term performance of recycled asphalt mixtures containing high RAP and RAS. *Journal of Road Engineering*, 4(1), 36–53.
- Zhan, Y. Q., Wu, H., Song, W. M., Chen, X. B., & Liao, H. B. (2024). A novel approach to investigate the crack resistance of recycled asphalt mixture based on energy evolution. *Engineering Fracture Mechanics*, 307, Article 110284.
- Zhang, Q. R., Cai, X., Wu, K. H., Chen, L., Zhang, R. D., Xiao, H., & Hanssian, H. M. Z. (2021). Shear performance of recycled asphalt mixture based on contact interface parameter analysis. *Construction and Building Materials*, 300, Article 124049.
- Zhang, J. Z., Guo, C. C., Chen, T. T., Zhang, W. W., Yao, K., Fan, C., Liang, M., Guo, C. H., & Yao, Z. Y. (2021). Evaluation on the mechanical performance of recycled asphalt mixtures incorporated with high percentage of RAP and self-developed rejuvenators. *Construction and Building Materials*, 269, Article 121337.
- Zhao, X. K., Dong, Q., Chen, X. Q., & Ni, N. J. (2021). Meso-cracking characteristics of rubberized cement-stabilized aggregate by discrete element method. *Journal of Cleaner Production*, 316, Article 128374.
- Zhao, W. T., Qian, G. P., & Yang, Q. (2025). Sustainable pavement design: A comprehensive study on incorporating 100% recycled asphalt pavement and utilizing 100% industrial solid waste. *Construction and Building Materials*, 462, Article 139972.
- Zhou, Y. X., Fan, Y. L., Chen, B. S., Shi, C. G., Cai, X., Yang, J., & Huang, W. (2025). Study on cracking damage behavior of epoxy asphalt recycled pavement with high RAP content based on acoustic emission and digital image correlation methods. *Journal of Cleaner Production*, 501, Article 145288.