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Identification and analysis of mixing-induced homogeneity in reclaimed asphalt pavement materials

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Abstract: Asphalt mixtures were prepared in the laboratory using reclaimed asphalt pavement (RAP) at a 40% mass concentration to investigate the homogeneity characteristics of RAP during the mixing process, taking into account the mixing duration and aging rate. Specifically, titanium dioxide powder was incorporated into RAP binders as an identification tracer. Homogeneity indices were subsequently established to evaluate the homogeneity characteristics of asphalt mixtures. Computed tomography (CT) was used to create digital images of asphalt mixtures, and Mimics software was used to identify the components. Finally, a homogeneity evaluation system was established to assess the uniformity of both the components and RAP agglomerates. The results indicate that homogeneity is mostly influenced by the distribution of coarse aggregates, followed by asphalt binders and air voids. Homogeneity improvement is hindered by the formation of new agglomerates during the mixing process, whereas it is increased by prolonging the mixing time. A homogeneity evaluation system based on components and agglomerates can effectively reveal the principles governing homogeneity characteristics and provide a reference for the construction of high-quality recycled asphalt pavement.

Key words: reclaimed asphalt pavement (RAP); mixing-induced homogeneity; image segmentation; homogeneity index

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Asphalt pavement recycling technology has attracted global interest owing to its ability to conserve resources, reduce construction costs, and improve the environment. However, the incorporation of reclaimed asphalt pavement (RAP) materials in the production of asphalt mixtures results in superior quality owing to their intricate composition and status[1]. The inclusion of RAP materials in an asphalt mixture leads to the formation of aggregates, new asphalt/asphalt rejuvenators, aged asphalt, and other components[2–3]. In particular, owing to the presence of clusters caused by insufficient milling and crushing, the blending efficiency between the newly added materials and RAP materials plays a critical role in high-quality recycled pavement construction[4–7].

Previous studies have focused on visualizing the components within asphalt mixtures to effectively investigate the homogeneity of asphalt mixtures[8]. Hassan et al.[9] successfully characterized the air void distribution with the aid of X-ray computed tomography (CT). Furthermore, Gao et al.[10] and Chen et al.[11] constructed a three-dimensional pore structure using CT technology. Vassaux et al.[12–13] defined the homogeneity of recycled asphalt mixtures by considering the distribution of carbonyl functions and accordingly proposed a model for recycled mixture using an infrared imaging microscope, where TiO_2 particles (0.15 μm) were used as a tracer for the new asphalt. Castorena et al.[14] utilized scanning electron microscopy and energy dispersive spectroscopy to feature a miscible map depicting new and aged asphalt.

To understand the evolution of homogeneity in recycled asphalt mixtures, it is necessary to acknowledge the existence of RAP agglomeration, which is a basic characteristic of pavement recycling[15–17]. Ferreira et al.[18] proposed that there was a significant impact on the partial cluster dissociation due to the activation of the RAP-binder, which ranged between 40% and 70%. Xu et al.[19] classified RAP materials into three categories, including weak structural agglomerates, strong structural agglomerates, and coarse aggregates, to quantify their aging degree. They also proposed the loss rate and stability index (w) as quantitative indicators for estimating the degree of RAP agglomeration. Adbelaziz et al.[20] expressed interest in the quantification of RAP activity in the recycled binder and provided a viable framework for investigating the application of RAP. Navaro et al.[21] also defined an

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index to evaluate the degree of RAP agglomeration based on microscopic observation techniques and chromatographic analysis. Bressi et al.[22-23] innovatively characterized RAP agglomeration by calculating the complex modulus of asphalt binders under ideal and actual mixing situations. Besides, Wu et al.[24] established an evaluation method for a graded cluster of hot-recycled asphalt mixture by considering the graded cluster quality and overall asphalt rotational viscosity. Zhu et al.[25] and Li et al.[26] discovered that the use of high viscosity modifiers and foaming agents for RAP applications could improve the mechanical strength of the recycled asphalt mixture while also improving the compatibility of matrix asphalt and aged asphalt. Additionally, Wu et al.[27] stated that pretreatment using binder extraction or hot-mix treatment methods was necessary for the application of polyurethane recycled asphalt in road engineering. It is crucial to understand the evolution of homogeneity and clusters in recycled asphalt mixtures during the mixing process due to the intricate nature of RAP materials in the production of high-quality recycled asphalt mixtures. This study utilizes CT scanning combined with titanium dioxide as a tracer to investigate the component distribution through digital images generated by Mimic software. Accordingly, two homogeneity indicators were proposed based on component distribution and agglomeration.

1 Material and Experimental Design

1.1 Raw materials

1.1.1 Asphalt

The laboratory utilized new asphalt with a penetration grade of 60/80 to produce RAP materials, which also served as new asphalt in this study. The primary indicators of the base asphalt, along with the aged asphalt subjected to the rolling thin-film oven test (RTFOT) method, were measured according to the specification requirements outlined in Table 1.

Table 1 Properties of asphalt before and after RTFOT

Asphalt	Test items	Reference value
Base asphalt	Penetration (25 ℃, 100 g, 5 s)/0.1 mm	66
	Ductility (15 ℃)/cm	>100
	Softening point/℃	48.7
Asphalt after RTFOT (163 ℃, 5 h)	Mass loss/%	-0.2
	Penetration ratio/%	63
	Ductility ratio (15 ℃)/%	179

1.1.2 Aggregates

Basalt was used as the coarse and fine aggregates for the experimental investigation, while limestone was used as the mineral powder. The primary indicators were measured using a test procedure for aggregates in highway engineering (JTG E42—2005), and the results are illustrated in Table 2.

Table 2 Properties of aggregates g/cm³

Aggregate	Apparent density	Bulk density
1#	3.007	2.916
2#	2.988	2.897
3#	3.001	2.912
4#	2.920	

1.1.3 Titanium dioxide

Titanium dioxide powder was intentionally introduced into aged asphalt as a tracer for asphalt binders, replacing the mineral powder of equivalent quality derived from RAP materials. Consequently, it is feasible to distinguish between new and aged asphalt samples via CT scanning. The basic properties of the used titanium dioxide powder are illustrated in Table 3.

Table 3 Properties of titanium dioxide powder

Test items	Measured values
Purity of TiO_2/%	98
Volatiles in 105 ℃/%	0.5
Crystal size/μm	0.23
Oil absorption capacity per 100 g/g	≤22.0
Density/($g \cdot cm^{-3}$)	4.1
pH	6.0-8.5

1.2 Laboratory production of RAP materials

The RAP materials utilized in this study were produced in the laboratory by replacing in-field RAP conducted under controlled conditions. Specifically, the new asphalt was subjected to RTFOT at 130 ℃ for 48 and 96 h to fabricate a RAP-binder with varying aging degrees. Subsequently, RAP materials were prepared by mixing aged asphalt with aggregates. A type of AC-13 asphalt mixture was adopted, as illustrated in Table 4. The asphalt mixtures were manually crushed into loose RAP materials using a hammer following mixing and compaction, as depicted in Fig. 1. Furthermore, the gradation of loose RAP materials was measured (see Table 4). It is evident that three parallel measurements demonstrated the consistency

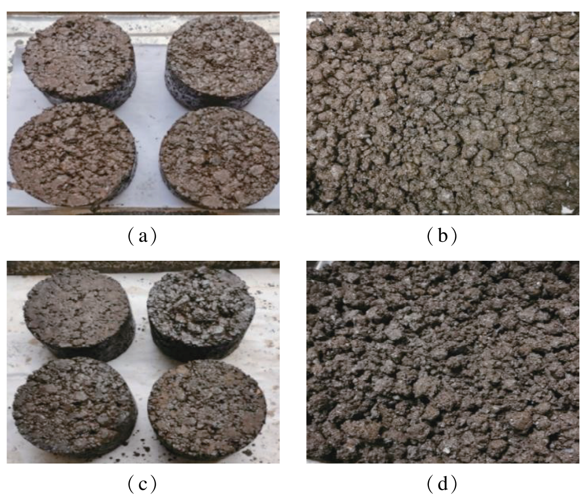


Fig. 1 Preparation of RAP materials. (a) Samples for aging 48 h; (b) Crushed sample for aging 48 h; (c) Samples for aging 96 h; (d) Crushed sample for aging 96 h

Table 4 Gradation curves of designed asphalt mixtures and crushed RAP materials

Sieve size/mm	Passing ratio/%			
	Composite gradation	First breakdown	Second breakdown	Third breakdown
26.5	100	100	100	100
19.0	100	95.87	95.92	95.97
16.0	100	85.05	87.96	86.22
13.2	90.41	68.59	65.11	72.18
9.50	73.22	39.95	37.80	34.77
4.75	56.42	10.21	10.12	9.94
2.36	30.58	4.41	4.48	4.25
1.18	18.42	0.56	0.45	0.78
0.60	11.69	0	0	0
0.30	7.71	0	0	0
0.15	6.63	0	0	0
0.075	5.43	0	0	0

of the laboratory-prepared RAP materials in terms of the gradation curve.

1.3 Design of experimental protocols

It is important to emphasize that the aim of this study was to determine the effects of various blending conditions on the homogeneity of recycled asphalt mixtures. In contrast, determining whether the mechanical performance of the samples meets the specified standards is beyond the scope of this study. Additionally, a simplified option such as the Marshall compaction method was employed instead of considering the utilization of rejuvenator in recycled asphalt mixtures or the influence of compaction methods on specimen preparation.

Two reference samples, including asphalt mixtures, prepared primarily with new asphalt and asphalt aged for 4 d, were used to calibrate the CT value for subsequent component identification. The resulting recycled asphalt mixtures were manufactured with 40% RAP content. The loose RAP materials are specifically heated to 80 ℃ for 4 h and then mixed for 30 s as part of the pretreatment process. The pretreated RAP materials are then mixed with new aggregates and new asphalt to determine the setting time (30, 60, 120, 180, and 240 s). Consequently, the study determined various combinations of mixing time (30, 60, 120, 180, and 240 s) and aging degrees (2 and 4 d) for the RAP binders. The mixing temperature was fixed at 150 ℃ in the thermal-equilibrium state for each mixing condition, and two parallel Marshall specimens were prepared for the experimental investigation.

2 Methodologies

2.1 Component identification of recycled asphalt mixtures

This study implemented the CT method to identify the components of recycled asphalt mixtures using a Discovery CT750 HD medical CT scanner manufactured by GE. Specifically, the cylindrical samples underwent CT scanning to obtain a series of axial and radial images. Subsequently, Mimics software was implemented with the 3D-Reconstruction function to assemble these images and differentiate the varying CT values of components[28].

First, each standard Marshall specimen was subjected to CT scanning at fixed intervals of 0.625 mm along the axial and radial directions. Consequently, each specimen consisting of 100 axial cross-sectional images and 155 radial cross-sectional images was imported into the Mimics software to generate a 3D reconstruction of each individual specimen using the 3D-Reconstruction function. The CT value of each component was determined using images of two of the reference samples mentioned in Section 1.3 during the identification process, and the obtained criteria were applied to the experimental samples. The histogram bimodal threshold method was used to determine the threshold values of new asphalt, aged asphalt, and their blended mix to differentiate between aggregates and voids[29]. This method involved repeatedly adjusting the interval boundary of CT values in the CT value histogram of the components. The differentiation between aged and new asphalt was determined based on Fig. 2. The image segmentation criteria for different components based on CT scanning of cross-section samples can be implemented as follows: 2546-3071 HU for coarse aggregates, 2209-2296 HU for aged asphalt, 1638-2209 HU for new asphalt, and 1024-1200 HU for voids. A colored 3D construction can be generated using the Marks function by obtaining images of experimental samples and CT values for different components, as depicted in Fig. 3. This also facilitates subsequent area division methods with known thresholds for each component and the cross-section images shown in Fig. 4.

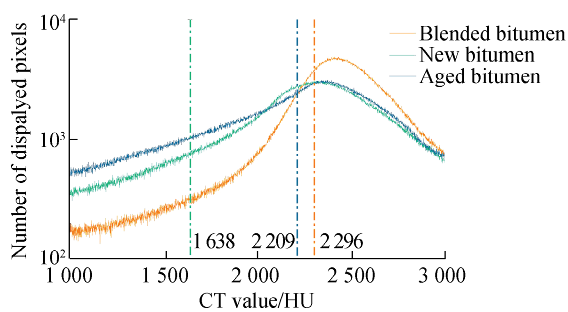


Fig. 2 Differentiation of aged and base asphalt in CT-scan images

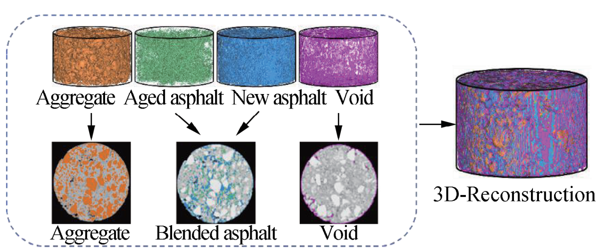
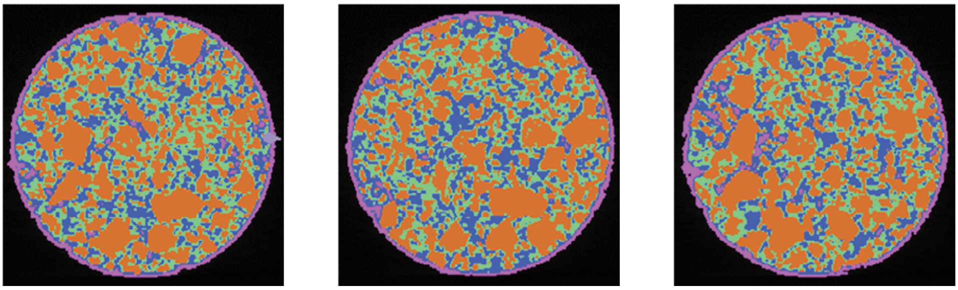


Fig. 3 Components identification of the recycled asphalt mixture



(a) (b) (c)

Fig. 4 Samples of images for aging 4 d. (a) Mixing 30 s; (b) Mixing 60 s; (c) Mixing 120 s

2.2 Homogeneity estimation of recycled asphalt mixtures

This study employed equal-area segmentation of images for homogeneity estimation of recycled asphalt mixtures[29]. The segmentation is based solely on 100 axial cross-section images of each individual experimental specimen. The cross-section image was divided into 36 equal parts using a combination of annular and fan area division methods to ensure homogeneity in both radial and annular directions, as illustrated in Fig. 5. The following two homogeneity indexes from varying perspectives were proposed based on the above equal-area segmentation[30-31].

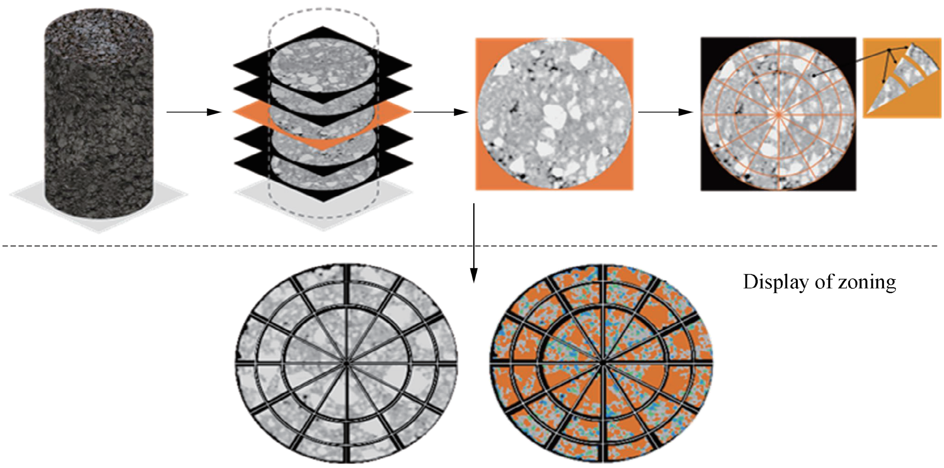


Fig. 5 Illustration of the homogeneity evaluation

2.2.1 Distribution-based homogeneity index

The area ratios of components, including air voids, coarse aggregates, and asphalt mastics, were all ensured by the following method. Accordingly, the distribution-based homogeneity index, D, was calculated, as shown in Eqs. (1)-(5). As the value of D increases, the degree of homogeneity decreases.

$$K_{ij} = \frac{A_{ij}}{A_0} \tag{1}$$

where A_{ij} is the area occupied by a component in the i-th region of the j-th layer cross-section; A_0 is the area of a single segmented region. K_{ij} specifies the area ratio of a specific component.

$$\overline{K}_j = \frac{1}{2mt}\sum_{i=1}^{2mt} K_{ij} \tag{2}$$

where m is the number of segmenting diameters; t is the number of segmenting concentric circles; and $\overline{K}_j$ is the mean value of K_{ij} within a single cross-section.

$$D_j = S_j = \sqrt{\frac{1}{2mt-1}\sum_{i=1}^{2mt}(K_{ij} - \overline{K}_j)^2} \tag{3}$$

The standard deviation D_j along the cross-section of each layer is calculated for all K_{ij} in a single cross-section.

$$D = \frac{1}{n}\sum_{j=1}^{n} S_j \tag{4}$$

where n is the number of layers of each specimen. The mean value D of the standard deviation D_j of all the cross-sectional images of a single specimen is calculated to obtain the homogeneity index of a component within the specific specimen.

$$D = \sum D_t \tag{5}$$

where t represents different components, including coarse aggregates, asphalt mastics, and air voids.

2.2.2 Agglomeration-based homogeneity index

The presence of aged asphalt induces more agglomerations inside the asphalt mixtures. Accordingly, the area ratio of aged asphalt to total binders can be used as an indirect parameter to evaluate the agglomeration-based homogeneity of recycled asphalt mixtures. Hence, the agglomeration-based homogeneity index, H, was calculated to estimate the homogeneity degree, as illustrated in Eqs. (6)-(9). As the value of H increases, the degree of homogeneity decreases.

$$M_{ij} = \frac{A_{Rij}}{A_{Vij} + A_{Rij}} \tag{6}$$

where A_{Rij} is the area occupied by aged asphalt in the i-th region of the j-th layer cross-section; A_{Vij} is the area occupied by new asphalt in the i-th region of the j-th layer cross-section. M_{ij} specifies the area ratio of a specific component.

$$\overline{M} = \frac{1}{2nmt}\sum_{j=1}^{n}\sum_{i=1}^{2mt} M_{ij} \tag{7}$$

where $\overline{M}$ is the mean value of M_{ij} within a single sample.

$$H_d = \sqrt{\frac{1}{2mt}\sum_{i=1}^{2mt}(M_{ij} - \overline{M})^2} \tag{8}$$

where the standard deviation H_d along the cross-section of each layer is calculated for all M_{ij} in a single cross-section.

$$H = \sqrt{\frac{1}{2nmt}\sum_{j=1}^{n}\sum_{i=1}^{2mt}(M_{ij} - \overline{M})^2} \tag{9}$$

where H is the mean value of the standard deviation H_d of all the cross-sectional images of a single specimen.

3 Results and Discussion

3.1 Cross-section homogeneity using distribution-based index

Fig. 6 illustrates the calculated D-values for various components of the recycled asphalt mixtures, with red dots representing the average of the two parallel specimens within each experimental group, thereby capturing the overall trend during the mixing process. The specimen containing coarse aggregates exhibited a maximum D-value of 0.143, which was achieved using asphalt that had been aged for 2 d and mixed for 120 s. In contrast, the minimum D-value (0.113 9) was obtained using asphalt aged for 4 d and mixed for 60 s. Although the increase in the mixing time did not induce an explicit decreasing tendency for coarse aggregates, the large variation in the D-value indicated that the mixing time contributed to the homogeneity of the recycled asphalt mixtures.

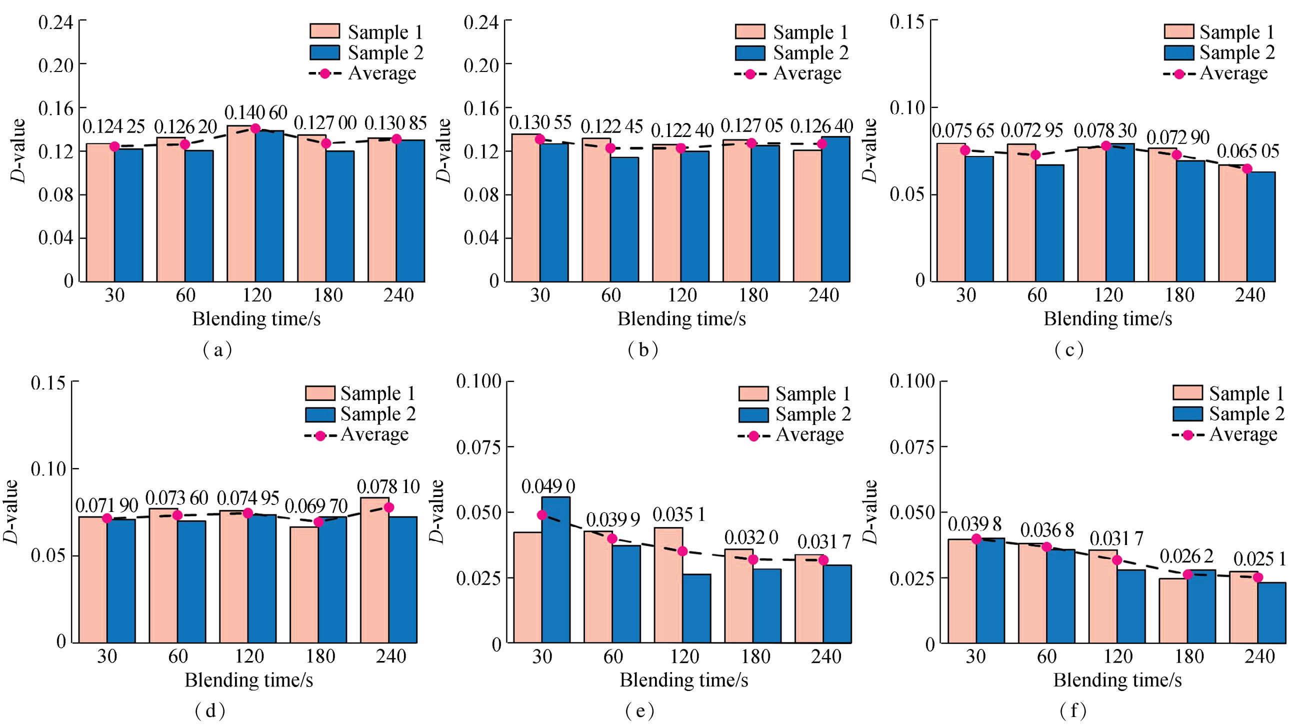


Fig. 6 D-values of components. (a) Aggregate for 2-d aging; (b) Aggregate for 4-d aging; (c) Asphalt mastics for 2-d aging; (d) Asphalt mastics for 4-d aging; (e) Air voids for 2-d aging; (f) Air voids for 4-d aging

The D-value of the asphalt mastics was significantly smaller than that of coarse aggregates, as observed in the maximum and minimum D-values of 0.083 5 and 0.063 0, respectively. Nevertheless, it can be inferred that the distribution of asphalt mastics was significantly influenced by the mixing time when preparing recycled asphalt mixtures.

The homogeneity of air voids was superior to that of the other two components in terms of distribution, indicating that its value was significantly lower than that of the others. A decreasing trend can be observed, with the maximum and minimum D-values being 0.055 8 and 0.022 9, respectively. Therefore, the extension of the mixing time induced a slight decrease in the D-value of air voids.

Unfortunately, the aforementioned homogeneity evaluation based on individual components failed to adequately describe the evolution of homogeneity with mixing time, as expected. Hence, the overall homogeneity D-value, which takes into account all components, was introduced and is displayed in Fig. 7.

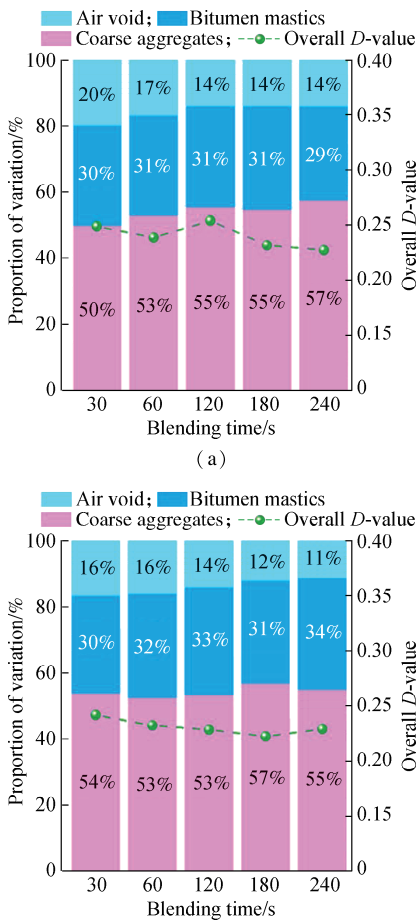


Fig. 7 Overall D-value for all components. (a) Samples prepared with a 2-d aged binder; (b) Samples prepared with a 4-d aged binder

It was explicitly evident that the predominant factor causing inhomogeneity was the coarse aggregates, followed by asphalt mastics and air voids. The contribution of air voids to the inhomogeneity of recycled asphalt mixtures decreased with increasing mixing time, ranging from 20% to 14% in the case of samples prepared with 2-d aged asphalt and from 16% to 11% for samples prepared with 4-d aged asphalt. The contribution to the inhomogeneity of recycled asphalt mixtures fluctuated without a clear tendency in the case of asphalt mastics. Nonetheless, the contribution ranged from 30% to 34% when the samples were prepared with a 4-d aged binder, which was significantly greater than that when the samples were prepared with a 2-d aged binder.

An increased tendency was observed for the proportion of coarse aggregates when the recycled asphalt mixtures were prepared with the 2-d aged binder. However, this rule was not applicable in the case of 4-d aged binders. The green dotted line on the right axis presents the evolution of homogeneity with the mixing time indicated by the overall D-value.

Fig. 8 highlights the trend line of the overall D-value for the 2-d and 4-d aged asphalt. The overall D-value decreased at the initial stage (from 30 to 60 s), which indicated a progressive improvement in the sample homogeneity. At this stage, the added components were dispersed predominantly via mechanical mixing, thereby decreasing the overall D-value. However, during the stage from 60 to 120 s, the utilization of the 2-d aged binder resulted in an increase in the overall D-value. From Fig. 7, it can be deduced that the increase in the overall D-value was ascribed to the distribution of coarse aggregates. This finding can be attributed to the formation of new clusters during the mixing process as the primary dispersion of the original clusters, which is a result of 2-d aging, ended. The 4-d aged binder continued to decline, indicating that primary dispersion was still dominant despite the fact that the formation of new clusters slowed the dispersion rate. The formed clusters were further crushed when the mixing time exceeded 120 s, and the sample homogeneity conformed to the expected declining tendency. Another abnormal phenomenon occurred in the case of 4-d aged binders when the mixing time increased from 120 to 240 s. At this stage, the extension of the mixing time induced more aged binders to participate in the new and aged binder blends. Therefore, the sudden increase was caused by an increased contribution percentage of asphalt mastics, as depicted in Fig. 7, resulting from a more significant RAP aging degree. Primarily, this suggests that there exists an ideal aging-state line that indicates the transition from the RAP of 2-d aging to 4-d aging.

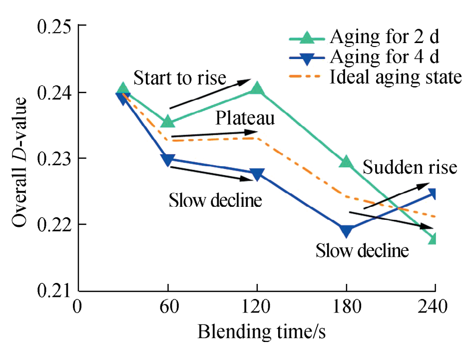


Fig. 8 Trend line of the overall D-value

3.2 Cross-section homogeneity using agglomeration-based index

In addition to the homogeneity evaluation based on the distribution-based homogeneity index (D), the agglomeration-based homogeneity index H-value was applied to characterize the homogeneity. Accordingly, the overall H-values were calculated as the mean value within each experimental group, considering the varying mixing times and aging degrees. The error bar in Fig. 9 represents the deviation between a specific H-value and its average value. There was no significant variation in the initial blending period (30-60 s) in the overall H-value for the 2-d aged asphalt. Nevertheless, when the mixing time increased from 60 to 120 s, a sudden increase in the overall H-value was observed, which was in line with the overall D-value. However, during the subsequent blending period of 120-180 s, a more pronounced decrease occurred compared to the previous increase. As indicated before, the sudden rise was ascribed to the newly formed clusters, and the decline was attributed to the deformation of clusters. This explanation was also applicable to the overall H-value.

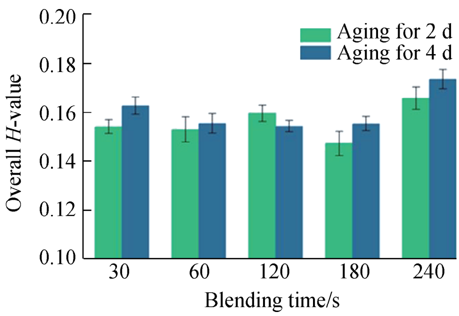


Fig. 9 Overall H-values for varying mixing times and aging degrees

The overall H-values for the samples prepared with the 4-d aged asphalt decreased and then remained stable during the blending time from 30 to 180 s. The high aging degree weakened the flowability of loose asphalt mixtures, resulting in dispersion dominating over cluster agglomeration during blending, while binder agglomeration remained largely unchanged. However, regardless of whether the binder was aged for 2 or 4 d, the continuous extension of blending time induced progressive aging of the binder after mixing for 180 s. As a result, binder agglomeration reoccurred owing to the alteration of binder viscosity.

In conclusion, the homogeneity of asphalt mixtures can be intuitively characterized by the overall D-value. However, when RAP materials were employed as binders, comprising aged asphalt and newly added asphalt, the feasibility of solely employing the D-value was not satisfactory because of its inability to account for nonhomogeneous components. Therefore, acknowledging that the H-value is more sensitive to cluster formation, a more comprehensive homogeneity evaluation of recycled asphalt mixtures can be obtained by combining the D and H-values.

3.3 Axial-direction homogeneity using proposed indexes

A distribution-based index was utilized to characterize the homogeneity of the recycled asphalt mixtures in the axial direction. It is important to identify weak spots located in areas where the distribution-based index varies dramatically and forms peaks.

Fig. 10 presents the overall D-values of the 100 cross-sectional images that were uniformly selected. It can be observed that the D-value is relatively higher at the top/bottom portions of specimen, regardless of whether the material is aged for 2 or 4 d. This indicates that the top/bottom part withstands increased compaction without losing homogeneity. When the sample was prepared with the 2-d aged asphalt, the sample with a blending time of 240 s exhibited the highest degree of homogeneity, while the sample with a blending time of 120 s exhibited the lowest degree of homogeneity. This conclusion was consistent with the findings obtained from the cross-sectional overall D index. When the specimen was prepared with the 4-d aged asphalt, the homogeneity in the axial direction was better than that of the 2-d aged asphalt. However, it should be noted that there was still a high degree of cross-sectional inhomogeneity. In addition, the most favorable

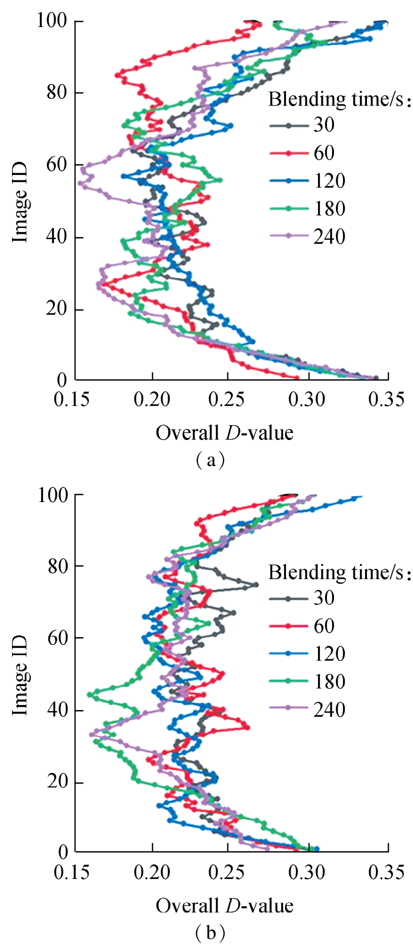


Fig. 10 Overall D-value in the axial direction. (a) 2-d aging; (b) 4-d aging

blending time was determined to be 180 s, which was in line with the findings obtained from the cross-sectional overall D index. The above analysis indicated that the distribution of components in the cross-sectional and axial directions essentially followed a similar rule. However, the use of RAP materials with a relatively high degree of aging did not result in a lower degree of homogeneity. This interesting observation revealed that the evolution of the homogeneity of recycled asphalt mixtures not only relies on the properties of the RAP materials but also depends on the appropriate production methods that correspond to the component properties.

The fluctuation of aged binders over a 2-d period is more extensive and dramatic compared with binders aged for 4 d, making it easier to identify weak spots. It also formed more peaks, representing more weak spots. The peaks were consistently visible at image IDs 25-45 and 60-85, regardless of the mixing conditions. In conclusion, weak spots appear consecutively along the axial direction in the 2-d aged asphalt mixture and intermittently along the axial direction in the 4-d aged asphalt mixture. These weak spots were mainly distributed at the upper one-third of the height position.

Fig. 11 shows the homogeneity of the recycled asphalt

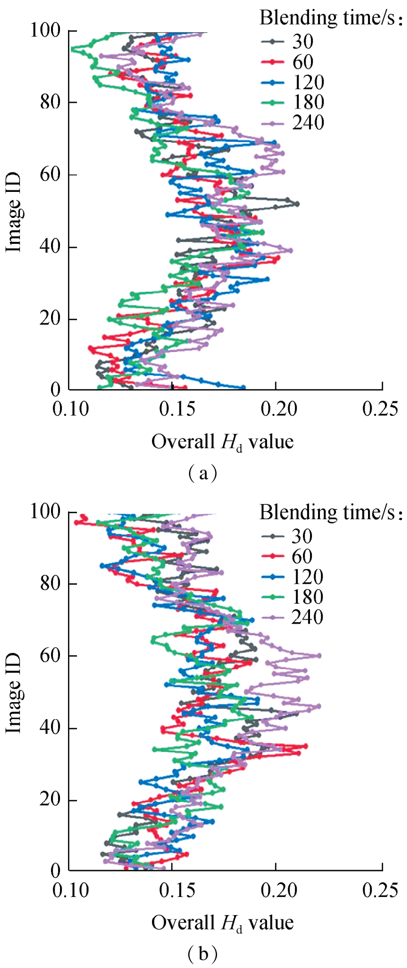


Fig. 11 Overall H_d value in the axial direction. (a) 2-d aging; (b) 4-d aging

mixtures in the axial direction using the agglomeration-based index. The distribution of H_d values along the axial direction demonstrated that the region with the highest degree of inhomogeneity was located near the center of the sample, while the top/bottom parts were the most homogeneous. This occurrence can be attributed to the increased compaction at the top/bottom, resulting in cluster deformation.

The agglomeration-based index induced a relatively low degree of inhomogeneity in the sample in the axial direction when comparing the distributions of D and H_d values. In the case of the 2-d aged asphalt, the most favorable mixing condition occurred at a blending time of 180 s, which was contrary to that obtained based on the distribution-based index. However, when the sample was prepared with 4-d aged asphalt, the blending time of 180 s still seemed superior to others, which is consistent with the rules obtained from the distribution-based index. In conclusion, the homogeneity evaluation system was indicator-dependent, and a comprehensive homogeneity evaluation should simultaneously consider the distribution and agglomeration situations, particularly for RAP materials with a relatively high degree of aging.

3.4 Summary of homogeneity indexes

In terms of evaluating homogeneity using a distribution-based index, coarse aggregates were more influential than asphalt mastics and air voids, and each component exhibited different trends as the mixing time increased. Moreover, the overall D-value indicated the presence of both new cluster formation and the deformation of existing clusters during the mixing process. The comparison between these two parameters determined the fluctuations in the distribution-based index. Regarding the agglomeration-based index, the formation of new clusters occurs after the initial deformation of the old clusters, which results in a reduction in the H-value. Despite the high levels of aging impeding the flowability of asphalt mixture and hindering cluster formation, both aging levels experienced a significant increase toward the end of aggressive long-term aging. The conclusions drawn from the distribution-based index and agglomeration-based index were occasionally contradictory when considering the axial direction. This indicated that a comprehensive evaluation system should consider the component distribution and agglomeration situations. Furthermore, varying degrees of aging revealed distinct weak spot patterns.

4 Conclusions

1) The homogeneity of the recycled asphalt mixtures was closely linked to the distribution of aggregates, asphalt mastics, and air voids. Among these factors, the distribution of aggregates played the most significant role in determining homogeneity, followed by the contribution

of asphalt mastics.

2) An increase in mixing time generally leads to a decrease in the homogeneity of the samples. However, it is important to note that the mixing process can also result in the formation of new clusters, which may further deteriorate overall homogeneity. The occurrence of these new clusters was closely linked to the flowability characteristics of the asphalt binder.

3) The component-based index illustrated that the center part of the cylinder specimen exhibited greater homogeneity than the bottom/top parts, while the agglomeration-based index revealed comprehensive deformation of clusters in the bottom/top parts. The weak spots were mainly distributed in the upper one-third of the height of the cylindrical specimen. It can be observed that the evolution of homogeneity relies on the properties of the RAP materials and appropriate production methods to match the component properties.

4) The homogeneity of recycled asphalt mixtures cannot be sufficiently represented by the distribution-based index owing to the presence of clusters in the RAP materials. For efficient compensation, the agglomeration-based homogeneity index can be used as an additional index for homogeneity estimation.

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再生沥青混合料拌和均匀性识别与机理分析

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摘要:为探究再生沥青混合料(RAP)拌和过程中的均匀性特征变化规律,考虑拌和时间和 RAP 料老化程度因素,选择二氧化钛粉末作为 RAP 料示踪剂,在实验室内制备掺有质量分数 40% RAP 料的再生沥青混合料,并建立均匀性指标评价再生沥青混合料均匀性特征. 通过计算机断层扫描技术(CT)获取沥青混合料数字图像,并对图像进行基于 Mimics 软件的组分识别,最终建立关于组分和结团的均匀性评价体系. 结果表明:粗集料分布情况对混合料拌和均匀性的影响最大,其次是沥青和孔隙分布情况;延长搅拌时间有利于提高再生沥青混合料的拌和均匀性,然而拌和过程中形成的新结团又会阻碍拌和均匀性的改善. 考虑组分和结团的均匀性评价体系可以有效揭示再生沥青混合料拌和均匀性特征变化规律,为建设高质量再生沥青路面提供参考.

关键词:再生沥青混合料;拌和均匀性;图像分割;均匀性指标

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