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Evaluation of the Refined Decomposition Effect of Reclaimed Asphalt Pavement Materials

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Abstract: To improve the quality of reclaimed asphalt pavement materials (RAPs) and reduce the variability of RAPs, a refined decomposition process was applied to treat RAPs. The change rule and variability of aggregate gradation, asphalt content, aged asphalt properties and aggregate (extracted) properties of RAPs were analyzed with different frequency parameters. In addition, the gradation variability control method and the asphalt content variability control method were used to calculate the maximum addition proportion of RAPs according to the quality control requirements of hot-mixing asphalt mixtures. The results indicate that the variability of aggregate gradation, asphalt content and asphalt properties significantly reduced for the refined decomposition RAP. Compared with the original RAP (0 Hz) of 4.75–9.5 mm and 9.5–19 mm, the "false particle" content of the refined decomposition RAP (50 Hz) reduced by 75.6% and 64.3%, respectively. The refined decomposition process is conducive to the road performance of recycled asphalt mixtures, especially the dynamic stability and the maximum bending tensile strain. Comparing the recycled asphalt mixture with the original RAP (0 Hz), the maximum bending strain of the recycled asphalt mixture with the refined decomposition RAP (50 Hz) increased by 69%, and the immersion residual stability increased to 87.9%. The refined decomposition process improves the quality of the RAP and provides a reference for recycled asphalt mixtures with a high proportion of RAPs. This study contributes to RAP high-level recycling and carbon reduction in the highway maintenance industry.

Keywords: reclaimed asphalt pavement material; recycled asphalt mixture; variability; refined decomposition; gradation

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1. Introduction

In recent years, the concept of green transportation has gradually developed and the shortage of non-renewable resources has become increasingly prominent such as asphalt and aggregate. More researchers have realized that the high-level utilization of reclaimed asphalt pavement materials (RAPs) has huge development potential and have carried out a lot of research work. [1–7]. RAP recycling is an important development direction of green highway transportation, and major countries are making efforts to develop technical specifications for RAP recycling and improve the level of RAP recycling [8–10]. However, due to the complex composition and obvious agglomeration phenomenon of RAPs, the variability (aggregate gradation and asphalt content) of RAPs is large. Therefore, it is difficult to fully utilize the value of RAPs [11–14]. In order to ensure the quality of recycled asphalt mixtures, the addition of RAPs to hot central plant recycled asphalt mixtures is generally required to be no more than 30% [15–17]. When an RAP is directly used to recycle an asphalt mixture without pretreatment, the road performance of the recycled asphalt mixture will decrease with the high addition proportion of RAPs [18,19]. The separation of the aged asphalt and aggregate is beneficial in reducing RAP variability and "false particle" content [15,20]. Therefore, a reasonable RAP decomposition technology is essential to

improve the RAP addition proportion in a recycled asphalt mixture and the quality of the recycled asphalt mixture.

So far, there are three types of RAP decomposition techniques, including the chemical solvent decomposition method [20,21], the microbial decomposition method [22,23] and the physical decomposition method [15,20,24]. The chemical solvent decomposition method uses a chemical solvent to dissolve the asphalt in the RAP, and then the mixed liquid (containing asphalt) is distilled to achieve the separation of the aged asphalt and the aggregate. The use of volatile chemical solvents in the decomposition process can easily have adverse effects on the environment and personnel. Meanwhile, some asphalt components cannot be dissolved in the solvent, reducing the asphalt recovery rate [21]. The microbial decomposition method is a relatively new method. Currently, the microbial decomposition method is in the experimental research stage, and there is a lack of cases and experience of its large-scale application [22]. The physical decomposition method can be further divided into the hot water rubbing method and the refined decomposition method. The hot water rubbing method involves heating the RAP in hot water (80~90 °C) and stirring it with an impeller to achieve separation. This method provides an excellent separation effect of the asphalt and aggregate, but its efficiency is low, and its energy consumption is high [24]. The refined decomposition method is valued by the industry for its high efficiency, low environmental impact and better cost-effectiveness [15].

In the refined decomposition process, the RAP is crushed by collision and friction in the centrifugal impact crusher, and the RAP (after crushing) is divided into coarse RAPs ($\geq$5 mm) and fine RAPs (0–5 mm). The coarse RAP surface contains little asphalt due to the collision and friction, and most aged asphalt enters the fine RAP to realize the separation of the aged asphalt and coarse aggregate. The coarse RAP can be directly used for recycled asphalt mixtures. The fine RAP can be used for recycled asphalt mixtures through cold addition and other methods. The fine RAP can also be used for asphalt mixture components, achieving a high-quality reuse of the RAP. Qiu et al. [25] applied the refined decomposition method of RAPs to a recycled asphalt mixture at a proportion of 80%, and the road performance of the recycled asphalt mixture was equivalent to that of the new asphalt mixture. This study provides a reference for the high addition proportion of RAP to recycled asphalt mixtures based on refined decomposition. Wang et al. [26] applied the refined decomposition method of RAPs to a highway reconstruction project, and the performance of the SMA-13 recycled asphalt mixture was basically the same as that of the new asphalt mixture. Current research pays more attention to the road performance of recycled asphalt mixtures with a refined decomposition of the RAP, but there has been little research on the characteristics of the refined decomposition of RAP.

The quality of the RAP is key component of the recycled asphalt mixture, which directly affects the final road performance and durability of the recycled asphalt mixture. Therefore, in order to ensure the quality of recycled asphalt mixtures, it is necessary to systematically evaluate the RAP's refined decomposition.

This study focuses on the properties of RAPs after refined decomposition and the impact of the refined decomposition of RAPs on recycled asphalt mixtures. The specific research objectives are divided into three parts. Firstly, the influence of the refined decomposition process was studied on the variation of the aggregate gradation, asphalt content, aged asphalt properties and aggregate (extracted) properties for the RAP. Second, the maximum addition proportion of the coarse RAPs to the recycled asphalt mixture was analyzed based on refined decomposition. Thirdly, the influence of refined decomposition on the road performance of recycled asphalt mixtures was studied, including its high-temperature performance, low-temperature performance and water stability. The research results provide a technical basis for the high addition proportion of RAPs in recycled asphalt mixtures and the quality improvement of recycled asphalt mixtures. This research is conducive to improving the utilization level of highway solid waste and providing technical support for the construction of low-carbon and sustainable highways.

2. Experiment

2.1. Test Scheme

The refined decomposition equipment is composed of several subsystems, including a feeding system, a vibrating screen system, a centrifugal impact crusher, a dust removal system, etc. The core subsystem of refined decomposition is the centrifugal impact crusher. When the RAP enters the centrifugal impact crusher, it obtains kinetic energy from the high-speed rotating rotor and is thrown out. The thrown RAP collides and rubs violently with the crusher's baffle and falling RAPs. The "false particles" of the RAP are broken along the asphalt interface between aggregates. The broken RAP is divided into coarse RAP (≥5 mm) and fine RAP (0–5 mm). The coarse RAP surface contains little asphalt due to the collision and friction, and most of the asphalt enters the fine RAP to realize the separation of the asphalt and coarse aggregate. This process is shown in Figure 1.

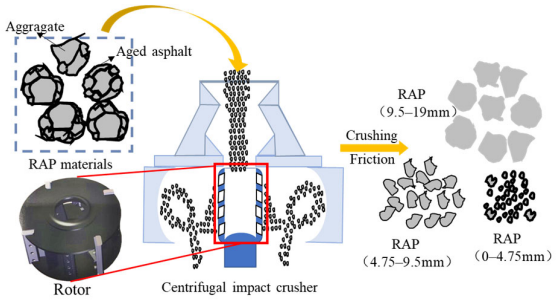

Figure 1. Schematic diagram of refined decomposition technology.

The refined decomposition effect of RAPs is related to many factors, such as the crusher's rotor speed, the RAP's properties and temperature and the crusher's baffle position. The crusher's rotor speed is a key factor. Moreover, since this test was conducted at a project site and the large refined decomposition equipment (120 t/h) was used in the test, it is difficult to change the position of the crusher's baffle as well as the RAP's properties and temperature. Therefore, the collision strength of the RAP was controlled by changing the frequency of the centrifugal impact crusher. The rules and variability of the RAP's aggregate gradation, asphalt content and aggregate performance were analyzed, and the maximum addition proportion of RAPs was calculated by control methods of gradation variability and asphalt content variability. In addition, the influence of the refined decomposition technology on the road performance of recycled asphalt mixtures is discussed. The scheme of this study is shown in Figure 2.

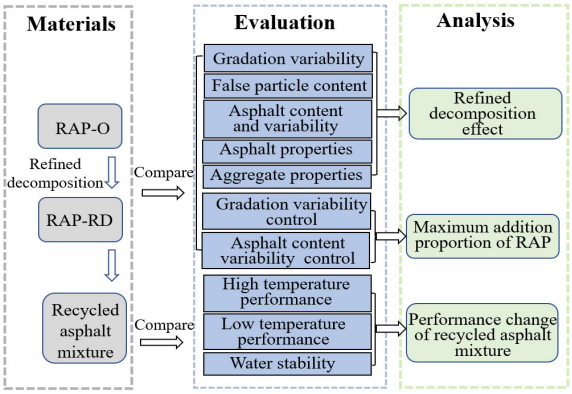

Figure 2. The schemes of this study.

2.2. Test Materials

The RAP used in the experiment was divided into two types: the original RAP without refined decomposition (RAP-O) and the refined decomposition RAP (RAP-RD). The number

of RAP samples used in the test is shown in Table 1. The "0 Hz" represents the RAP without refined decomposition. The "30 Hz", "40 Hz" and "50 Hz" are frequency parameters used by the refined decomposition equipment to control the speed of the centrifugal impact crushers, which are linearly related to the rotor speed. In addition, in order to ensure the representativeness of the sample, the surface part of the stockpile (depth range of 15–20 cm) was removed before sampling, and the material was taken from the quartered positions of the stockpile, which are, respectively, represented by ①②③④.

Table 1. RAP sample numbers in the test.

Size/mm	RAP-O (0 Hz)	RAP-RD (30 Hz)	RAP-RD (40 Hz)	RAP-RD (50 Hz)
9.5–19	A-1 ①②③④	B-1 ①②③④	C-1 ①②③④	D-1 ①②③④
4.75–9.5	A-2 ①②③④	B-2 ①②③④	C-2 ①②③④	D-2 ①②③④
0–4.75	A-3 ①②③④	B-3 ①②③④	C-3 ①②③④	D-3 ①②③④

2.3. Test Methods

2.3.1. Extraction and Screening Result Analysis

In order to evaluate the refined decomposition effect of RAPs, the asphalt content and aggregate gradation of the RAP were tested according to methods T 0722 and T 0725 in the "Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering" (JTG E20) [27].

2.3.2. "False Particle" Content (FPC) Analysis

The FPC analysis is used to analyze the refined decomposition effect of RAPs. The FPC is the ratio of the mass loss of the RAP (below the RAP) after extraction to the mass of the RAP before extraction. The calculation is shown in Equation (1).

$$\mathrm{FPC} = \frac{W_1}{W_2} \times 100 \quad (1)$$

where FPC is the "false particle" content of the RAP, %; W_1 is the mass loss of the RAP after extraction, g; and W_2 is the mass of the RAP before extraction, g.

2.3.3. Evaluation of Asphalt Properties

The aged asphalt from the RAP extraction was tested for properties such as penetration (25 °C), softening point and ductility (15 °C) according to test methods T 0604, T 0606 and T 0604 in the "Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering" (JTG E20), respectively.

2.3.4. Evaluation of Aggregate Properties

The aggregates from the RAP were tested for the elongated and flaky particles' content and crushing values according to test methods T 0312 and T 0316 in the "Test Methods of Aggregate for Highway Engineering" (JTG E42) [28]. The angularity of the aggregate was tested by a coarse aggregate analyzer (sourced from Southern Road Machinery Co., Ltd., Quanzhou, China).

2.3.5. Evaluation of Recycled Asphalt Mixture's Performance

The high-temperature performance, low-temperature performance and water stability were carried out in accordance with the T 0719, T 0715 and T 0709 test methods in the "Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering" (JTG E20), respectively.

3. Results and Discussion

3.1. Refined Decomposition Effect

3.1.1. RAP Aggregate Gradation Variability

The refined decomposition technology reduces RAPs' agglomeration and significantly changes their aggregate gradation. Therefore, it was necessary to analyze the change of the RAP's aggregate gradation. The RAP-O and RAP-RD were extracted, and the aggregate gradation curves are shown in Figure 3.

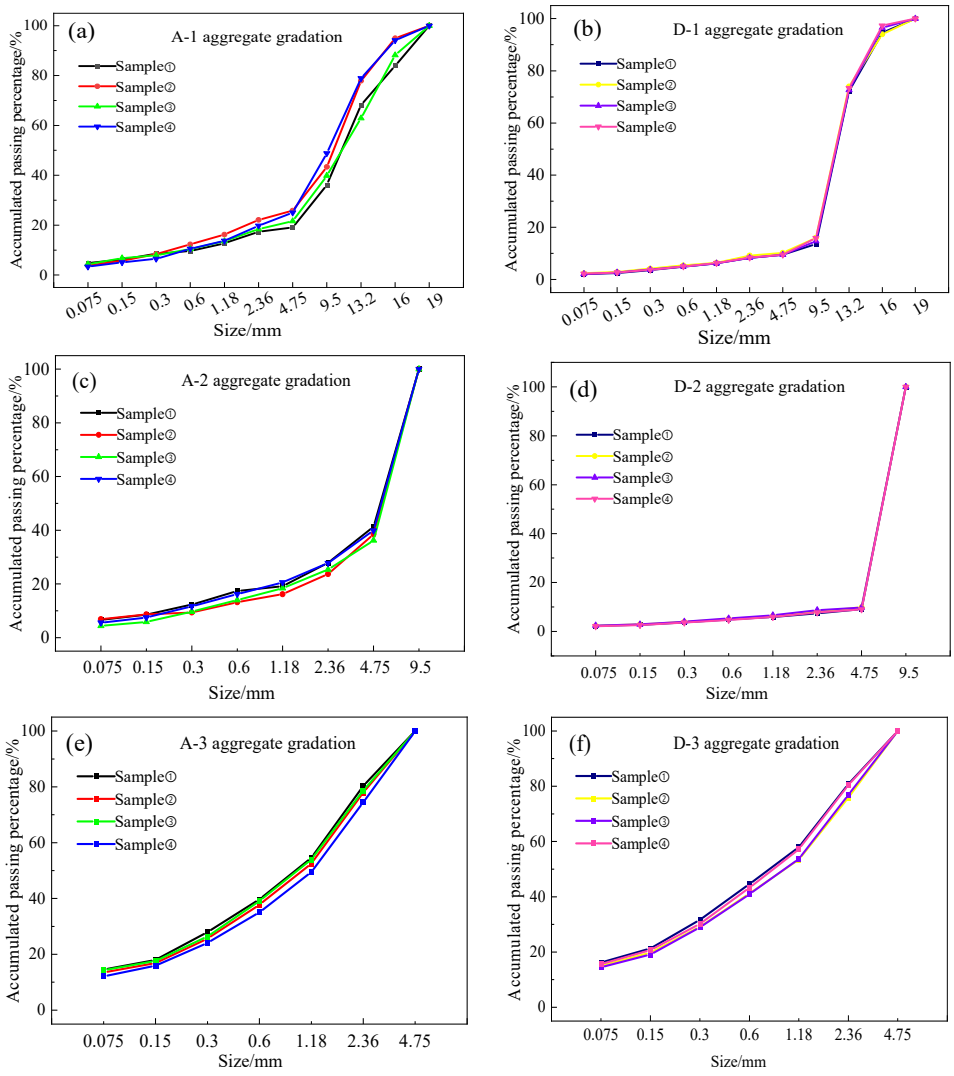

Figure 3. Gradation curves of RAP (extracted). (**a**) A-1 aggregate gradation curves. (**b**) D-1 aggregate gradation curves. (**c**) A-2 aggregate gradation curves. (**d**) D-2 aggregate gradation curves. (**e**) A-3 aggregate gradation curves. (**f**) D-3 aggregate gradation curves.

As shown in Figure 3, for the coarse RAP (>4.75 mm), the aggregate gradation curves of the different original RAP samples have obvious differences. The aggregate gradation curves of the different RAP-RD samples are basically the same. The consistency of the aggregate gradation curves of the refined decomposition RAP-RD (D-1 and D-2) is significantly better than that of the original RAP (A-1 and A-2). The results show that the stability of the RAP's aggregate gradation with refined decomposition is very good. Refined decomposition is beneficial to improve the stability of coarse RAPs' aggregate gradation. For the fine RAP (0–4.75 mm), the consistency of the refined decomposition RAP's (D-3) aggregate gradation curve is slightly better than that of the original RAP's (A-3), and the influence of refined decomposition on the consistency of the coarser RAP's

aggregate gradation curve is greater than that of the fine RAP's. In order to express the variability of the aggregate gradation more clearly, the coefficient of variation (CV) of the RAP's aggregate gradation passing percentage was calculated, and the results are shown in Figure 4.

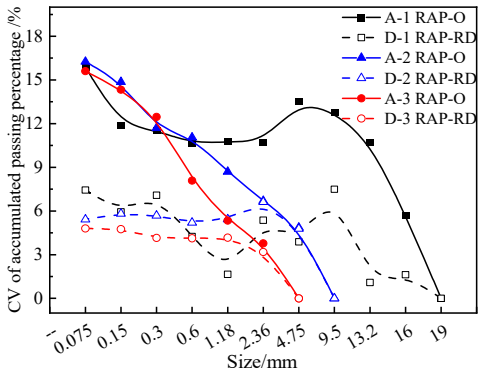

Figure 4. The CV of RAP's (extracted) gradation.

As seen in Figure 4, the aggregate gradation's CV of RAP-O (A-1, A-2 and A-3) is significantly greater than that of the refined decomposition RAP (D-1, D-2 and D-3). For the key size (4.75 mm), the CV of the accumulated passing percentage of A-1 is 13.5% and that of D-1 is 3.88%. Compared with A-1, the CV of the accumulated passing percentage of D-1 decreased by 67.5%. The refined decomposition process was beneficial in improving the stability of the RAP's aggregate gradation. This is mainly due to the existence of many "false particles" in RAP-O, which caused great fluctuation in the aggregate gradation. The refined decomposition made the RAP collide and rub repeatedly in the centrifugal impact crusher. The "false particles" of the RAP were broken along the asphalt interface between aggregates, and most of the asphalt binder entered the fine RAP to realize the separation of the asphalt and coarse aggregate. Refined decomposition reduced the agglomeration phenomenon in the RAP, stabilizing the aggregate gradation. The refined decomposition improved the RAP's aggregate gradation stability and the raw material quality of the recycled asphalt mixture.

3.1.2. "False Particle" Content (FPC)

To explore the effects of the refined decomposition RAP under different frequency parameters, the FPC of the RAP was tested. The test results are shown in Figure 5.

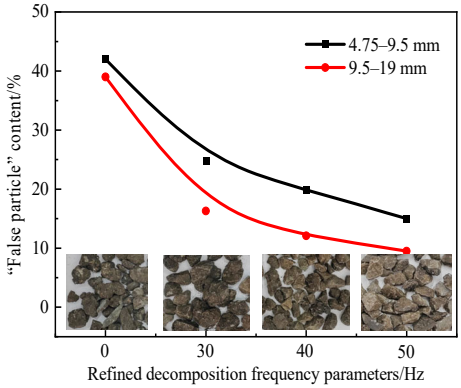

Figure 5. "False particle" content of RAPs.

As shown in Figure 5, the FPC of the RAP gradually decreases with the increase in frequency, and the trend of the FPC in the RAP of 4.75–9.5 mm is basically the same as that in the RAP of 9.5–19 mm. The FPCs of A-1 and A-2 (without refined decomposition, 0 Hz) are 39.0% and 42.0%, respectively. The FPCs of D-1 and D-2 (refined decomposition,

50 Hz) are 9.5% and 15.0%, respectively. Compared with A-1 and A-2 (0 Hz), the FPCs of D-1 and D-2 (50 Hz) reduced by 75.6% and 64.3%, respectively. The FPC of the refined decomposition RAP decreased significantly. This is due to the repeated collision and friction of the coarse RAP in the centrifugal impact crusher, so that the asphalt and asphalt mortar on the coarse RAP's surface were stripped, and the surface contained little asphalt. Coarse RAP can basically be used as an ordinary aggregate. The refined decomposition technology provides a basis for the addition of a large proportion of coarse RAPs in recycled asphalt mixtures.

3.1.3. Asphalt Content and Its Variability of RAPs

The asphalt content of RAPs is an essential indicator of the refined decomposition effect, and the results of the asphalt content and its variability are shown in Figure 6.

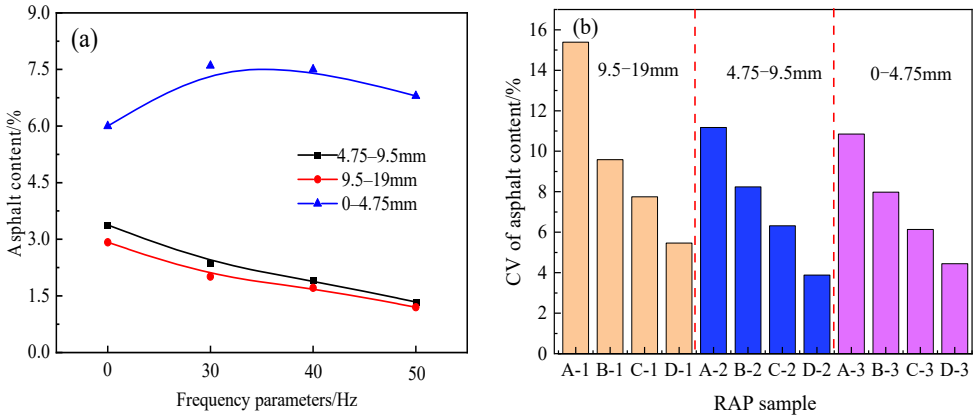

Figure 6. Asphalt content and its variability of RAPs. (**a**) Asphalt content. (**b**) CV of asphalt content.

As shown in Figure 6a, the asphalt content curves of the RAP of 4.75–9.5 mm is generally consistent with those of the RAP of 9.5–19 mm. The asphalt content of RAP-RD (30/40/50 Hz) is significantly lower than that of RAP-O (0 Hz) and gradually decreases as the frequency parameter increases. The refined decomposition process can reduce the asphalt content of coarse RAP (4.75–9.5 and 9.5–19). This is due to the "false particles" of the RAP repeatedly colliding and rubbing, and the asphalt on the surface of the coarse RAP was peeled off to an RAP of 0–4.75 mm. The asphalt content of the coarse RAP-RD decreased. When the frequency of the refined decomposition reaches 50 Hz, the asphalt contents of D-1 and D-2 are lower than 1.5% (1.2% and 1.34%).

In addition, for the RAP of 0–4.75 mm, the asphalt content of RAP-RD (30/40/50 Hz) is higher than that of RAP-O (0 Hz), and the asphalt content of RAP-RD gradually decreases as the frequency increases. This result is mainly due to the "pulverization" of the aggregate during the milling process, resulting in a proportion of the fine aggregate increasing and the asphalt content decreasing in RAP-O (0 Hz). The RAP-RD of 0–4.75 mm comes from the old asphalt mixture (especially the coarse RAP). Since there was no additional "pulverization" aggregate, the asphalt content of the RAP-RD of 0–4.75 mm is higher than that of RAP-O (0 Hz). However, as the frequency of the refined decomposition increased, the kinetic energy of the RAP became larger, and the collision and friction between the RAP became more severe. The collision and friction caused the "pulverization" of the aggregate edges and corners, resulting in a gradual decrease in the asphalt content of the RAP-RD of 0~4.75 mm as the frequency increased.

As shown in Figure 6b, the CV of the RAP-RD (30/40/50 Hz) asphalt content is lower than that of the RAP-O (0 Hz). The refined decomposition reduced the variability of the RAP's asphalt content, which is conducive to improving the quality and stability of the RAP.

3.1.4. Aged Asphalt Properties

Aged asphalt was extracted from the RAP, and the aged asphalt's properties (25 °C penetration, softening point and 15 °C ductility) and their CVs are shown in Figure 7.

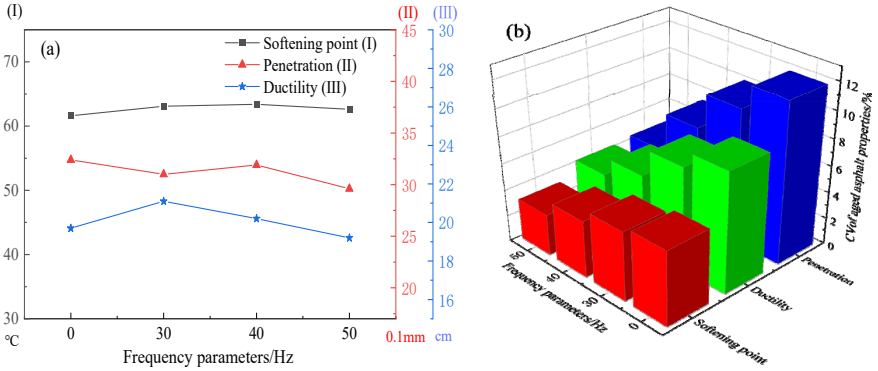

Figure 7. Aged asphalt's properties and their variability. (**a**) Penetration, softening point and ductility of aged asphalt. (**b**) CVs of aged asphalt's properties.

As shown in Figure 7, the change of the aged asphalt's properties (penetration, softening point and ductility) is not obvious with the increase in frequency. However, the variability of the aged asphalt's properties (penetration, softening point and ductility) gradually decreases with the increase in frequency. The results show that the refined decomposition process can not change the properties of aging asphalt but can improve the stability of the asphalt's properties. This is mainly due to the further mixing of the RAP during the collision and friction in the refined decomposition process, which reduces the variability of the RAP's asphalt properties. In addition, refined decomposition is a physical process (collision and friction between the RAP), which has relatively little influence on the asphalt's properties.

3.1.5. Aggregate Properties

The test aggregates were obtained by extracting the RAP (different frequency parameters). The test results (angularity, elongated and flaky particles' content and crushing values) of the aggregates are shown in Figure 8.

As shown in Figure 8a, the angularity of the coarse aggregates (4.75–9.5 mm and 9.5–19 mm) gradually decreases as the frequency of the refined decomposition increases. The refined decomposition process can reduce the angularity of the coarse aggregates. This is mainly because the collision and friction of the RAP in the centrifugal impact crusher became more intense as the frequency increased. The shape of the aggregates tends to be "spherical", resulting in the angularity of the aggregates to decrease. The angularity of the aggregates has a significant impact on the performance of the asphalt mixture, especially at a high-temperature performance. Therefore, refined decomposition cannot excessively increase the frequency to improve the refined decomposition effect. Otherwise, it may cause a significant decline in the angularity of the coarse aggregates, thereby reducing the high-temperature performance of the recycled asphalt mixture.

As shown in Figure 8b, the elongated and flaky particles' content of the aggregates obtained from RAP-RD is lower than that of the aggregates obtained from RAP-O, and as the frequency increases, the elongated and flaky particles' content of the aggregates gradually decreases. The refined decomposition process is beneficial to reducing the elongated and flaky particles' content of the coarse aggregates. When the frequency reaches 50 Hz, the elongated and flaky particle contents of the aggregates (50 Hz) of 4.75–9.5 mm and 9.5–19 mm are 4.2% and 4.0%, respectively. Compared to the aggregates obtained from RAP-O (0 Hz), the elongated and flaky particles' content decreased by 37.3% and 37.5%, respectively. The elongated and flaky particles were easily broken, resulting in a decrease in the elongated and flaky particles' content of the aggregates obtained from RAP-RD.

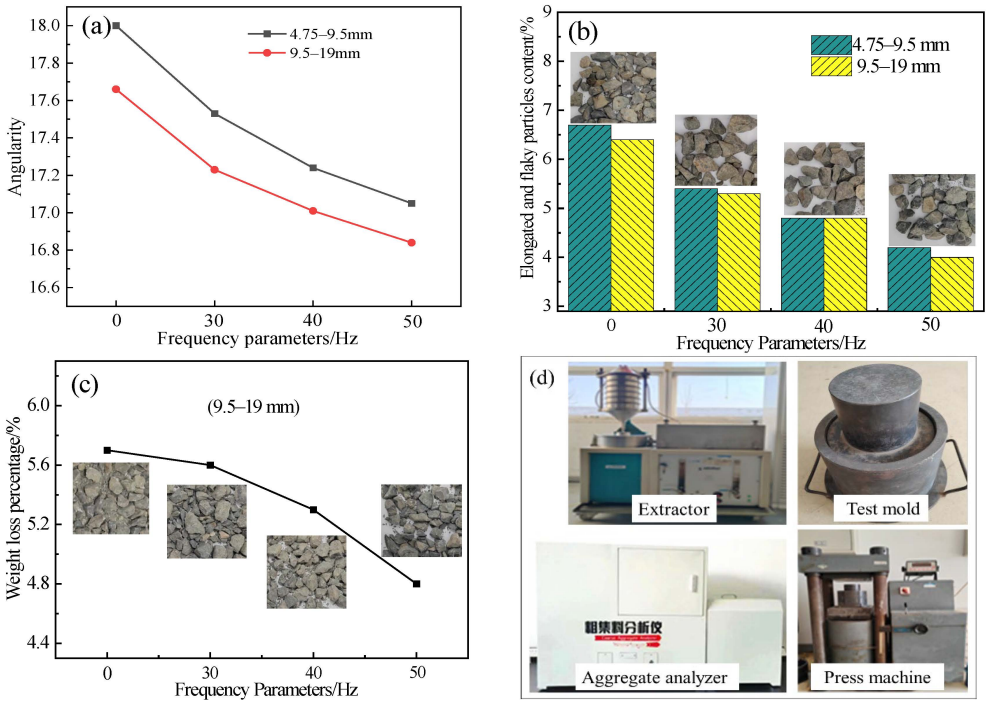

Figure 8. Aggregate properties of RAP (extracted). (**a**) Angularity. (**b**) elongated and flaky particles' content. (**c**) crushing values. (**d**) test equipment.

As shown in Figure 8c, the crushing values of the aggregates obtained from RAP-RD are lower than that of the aggregates obtained from RAP-O. The refined decomposition process is conducive to reducing the crushing values of the coarse aggregates. The crushing values of the aggregates gradually decreases as the frequency increases. This is because the refined decomposition reduces the elongated and flaky particles' content and the angularity of the aggregates, and the aggregates tend to be more "spherical", which in turn reduces the crushing of the aggregates.

3.2. Maximum Addition Proportion of RAPs

The aggregate gradation of the mixture has a significant influence on the quality of the asphalt mixture. To keep the quality of the recycled asphalt mixture within a controllable range, it is necessary to adopt the refined decomposition process to reduce the aggregate gradation variability of the RAP. The CV of the RAP is larger than that of new aggregates. When the RAP addition proportion is large, the recycled asphalt mixture will not meet the specification requirements. The refined decomposition can reduce the CV of the RAP, which is conducive to improving the addition proportion of the RAP and ensuring the quality of the recycled asphalt mixture.

Assuming that the addition proportion of RAP is X, the RAP's aggregate gradation variability should meet the requirement of Equation (2) [29].

$$VX \leq V' \tag{2}$$

where V is the standard deviation of the RAP's aggregate gradation (passing percentage), %; X refers to the addition proportion of the RAP; and V' is the requirement of the hot central plant recycled asphalt mixture (passing percentage), %.

Since the variability of the new aggregate gradation was not considered, the requirements for the aggregate gradation variability of the recycled asphalt mixture should be slightly more stringent than that of the hot central plant recycled asphalt mixture. Therefore, it is recommended that the deviation from the passing rate (0.075 mm) should not be greater than 1% in the hot central plant recycled asphalt mixture for highways, and the deviation

of the percent passing (4.75 mm) should not be greater than 4%, and the deviation of the percent passing (0.15 mm, 0.3 mm, 0.6 mm, 1.18 mm and 2.36 mm) should not be greater than 3%. According to Equation (2), when the RAP variability is large, the requirements can be met by reducing the addition proportion of the RAP. When the RAP variability is small, it is beneficial to improve the addition proportion of the RAP. Therefore, it is necessary to consider the RAP variability to determine the maximum addition proportion of the RAP.

Relevant studies have shown that the passing percentage exhibits a normal distribution characteristic [30,31]. According to mathematical statistical methods, the overall standard deviation can be estimated from samples. According to the confidence interval theory, the population standard deviation was calculated by Equation (3).

$$S = \frac{\sigma}{\sqrt{n}} t_{\frac{\alpha}{2}} \tag{3}$$

where S is the overall standard deviation of the RAP (passing percentage), %; σ is the standard deviation of the RAP samples (passing percentage), %; n represents the number of samples, and α is the confidence level; and $t_{\alpha/2}$ is from the t-distribution table.

When the confidence level α is 0.05 and the degree of freedom $(n - 1)$ is 3, the table is checked to obtain $t_{\alpha/2}$ = 3.182. The S of A-1 and D-1 are listed in Tables 2 and 3.

Table 2. The S of A-1 and D-1's passing percentage (9.5–19 mm).

Size/mm	S/%		Requirements
	A-1	D-1	
19	0.0	0.0	SX ≤ 4%
16	8.2	2.5	SX ≤ 4%
13.2	12.3	1.3	SX ≤ 4%
9.5	8.6	1.8	SX ≤ 4%
4.75	4.9	0.6	SX ≤ 4%
2.36	3.3	0.7	SX ≤ 3%
1.18	2.4	0.2	SX ≤ 3%
0.6	1.8	0.3	SX ≤ 3%
0.3	1.4	0.4	SX ≤ 3%
0.15	1.1	0.3	SX ≤ 3%
0.075	1.0	0.3	SX ≤ 1%

Table 3. The S of A-2 and D-2's passing percentage (4.75–9.5 mm).

Size/mm	S/%		Requirements
	A-2	D-2	
9.5	0.0	0.0	SX ≤ 4%
4.75	3.5	0.7	SX ≤ 4%
2.36	3.2	0.8	SX ≤ 3%
1.18	3.0	0.5	SX ≤ 3%
0.6	3.1	0.4	SX ≤ 3%
0.3	2.3	0.3	SX ≤ 3%
0.15	2.1	0.3	SX ≤ 3%
0.075	1.8	0.2	SX ≤ 1%

There is a maximum addition proportion of the RAP according to the gradation variability of the recycled asphalt mixture, which is calculated according to Equation (4) [14]:

$$X_{\max} = \min\{4\%/S_{\geq 4.75}, 3\%/S_{\leq 2.36}, 1\%/S_{0.075}\} \tag{4}$$

where $X_{\max}$ is the maximum addition proportion of the RAP; $S_{\geq 4.75}$ refers to the S of the passing percentage (≥4.75 mm), %; $S_{\leq 2.36}$ is the S of the passing percentage (≤2.36 mm), %; and $S_{0.075}$ is the S of the passing percentage (0.075 mm), %.

The asphalt and aggregate ratio should not exceed ±0.3%, according to the requirements of the "Technical Specification for Construction of Highway Asphalt Pavements" (JTG F40) [32]. Considering the variability of new asphalt, the variability of the RAP's asphalt content should be controlled to ±0.2%. From Figure 7b, the variability of RAP-RD's (50 Hz) asphalt content was significantly lower than that of RAP-O (0 Hz), and the refined decomposition process reduced the variability of the RAP's asphalt content. Based on the requirements for the asphalt content variability of recycled asphalt mixtures, the maximum addition proportion was calculated with reference to the gradation variability control method.

The maximum addition proportion of the RAP was calculated following the gradation variability control method and the asphalt content variability control method, respectively. The results are shown in Figure 9.

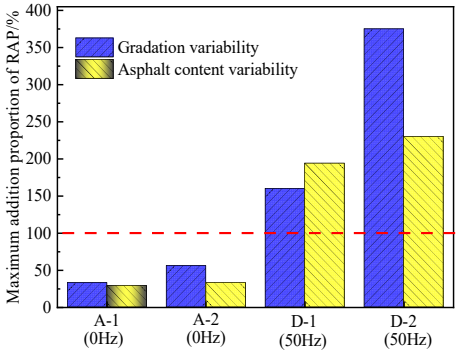

Figure 9. Maximum addition proportion of RAPs with different control methods.

As shown in Figure 9, based on the gradation variability control method and the asphalt content variability control method, the maximum addition proportion of RAP-RD (D-1 and D-2) is much higher than that of RAP-O (A-1 and A-2). According to the gradation and the asphalt content variability control method, the maximum addition proportion of A-1 (RAP-O) shall not exceed 33% and 29%, respectively. When the addition proportion exceeds the calculated value, the mixture's gradation or asphalt content of the recycled asphalt mixture may easily exceed the control range. This calculation result meets the requirement that the RAP's addition proportion should not exceed 30% in the current specification. For RAP-RD (D-1 and D-2), the maximum addition proportion calculated by the gradation and the asphalt content variability control method significantly exceedes 100%. This calculation result shows that the addition proportion of D-1 and D-2 (≥4.75 mm) can achieve 100% replacement of new coarse aggregates. The results prove that the refined decomposition can improve the addition proportion of coarse RAPs. The refined decomposition process provides a reference for achieving a large addition proportion of RAPs.

3.3. Road Performance of Recycled Asphalt Mixture

3.3.1. Mix Design of Recycled Mixture

Three kinds of RAPs (0 Hz, 30 Hz and 50 Hz) were selected to prepare the recycled asphalt mixture, and the addition proportion of the RAPs was 50%. SBS-modified asphalt (I-C) was selected as the asphalt binder, and the asphalt aggregate ratio of the recycled asphalt mixture was 4.8%. The aggregate gradation curve of the recycled asphalt mixture and the new asphalt mixture is shown in Figure 10. The formation of the recycled asphalt mixture was carried out according to T 0702 and T 0703 methods in the "Standard Test Methods of Asphalt and Bituminous Mixtures for Highway Engineering" (JTG E20).

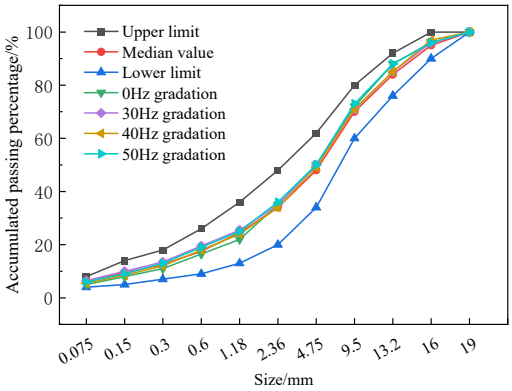

Figure 10. Aggregate gradation curve of asphalt mixture.

3.3.2. Road Performance Analysis of Recycled Asphalt Mixture

Three kinds of recycled asphalt mixtures were prepared from the refined decomposition RAP with different frequency parameters (new asphalt mixture use for comparative tests). The Marshall stability, dynamic stability, maximum bending tensile strain and immersion residual stability of the recycled asphalt mixture were tested to evaluate its high-temperature performance, low-temperature performance and water stability. The test results are shown in Figure 11.

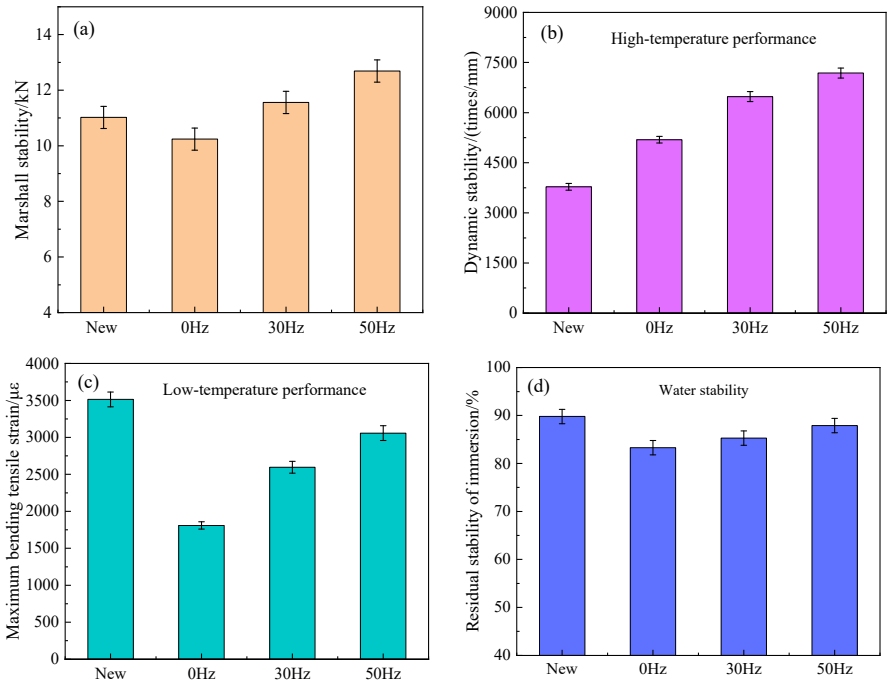

Figure 11. Road performance of recycled asphalt mixture. (**a**) Marshall stability. (**b**) Dynamic stability. (**c**) maximum bending tensile strain. (**d**) immersion residual stability.

As shown in Figure 11, compared with the new asphalt mixture, the Marshall stability and dynamic stability of the recycled asphalt mixture with the refined decomposition RAP improved, but the maximum bending tensile strain and immersion residual stability slightly decreased. The road performance of the recycled asphalt mixture under 30 Hz and 50 Hz frequency parameters meets the specification requirements. By analyzing the recycled asphalt mixture with different frequency parameters (0/30/50 Hz), the Marshall stability, dynamic stability, maximum bending tensile strain and immersion residual stability of the asphalt mixture are improved, with an increase in frequency. Comparing the recycled asphalt mixture with the original RAP, the maximum bending strain of the recycled asphalt

mixture with the refined decomposition RAP (50 Hz) increased by 69%, and the immersion residual stability increased to 87.9%. This is mainly because the refined decomposition breaks the RAP "false particles", and the coarse RAP (>4.75 mm) is close to the ordinary aggregate. The fine RAP (0–4.75 mm) is easier to be evenly mixed with the regenerant and new asphalt, which improves the homogeneity of the recycled asphalt mixture. Refined decomposition is conducive to improving the road performance of recycled mixtures and realizing the high-value and high-level recycling of RAPs.

4. Conclusions

RAP-O and RAP-RD with different frequency parameters (30/40/50 Hz) were evaluated for the RAP refined decomposition effect. The change rule and variability of the aggregate gradation, asphalt content, aged asphalt properties and aggregate properties were discussed. The main findings are as follows:

- The variability of the aggregate gradation (extracted), asphalt content and asphalt properties of RAP-O (original) is large.
- The refined decomposition process reduces the variability of the RAP's aggregate gradation (extracted), asphalt content and asphalt properties.
- The maximum addition proportion of the RAP was calculated using the gradation variability control method and the asphalt content variability control method, respectively. The maximum addition proportion of RAP-RD is significantly higher than that of RAP-O (original).
- The refined decomposition process is conducive to the road performance of recycled asphalt mixtures, especially the dynamic stability and the maximum bending tensile strain.
- The refined decomposition process can improve the quality of RAPs and can achieve the high-value and high-level recycling of RAPs.
- Future research should focus on the application of fine RAPs ($\leq$4.75 mm) after refined decomposition to further improve the high-value utilization level of RAPs.

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