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Effect of Fractionation Process and Addition of Composite Crumb Rubber-Modified Asphalt on Road Performance Variability of Recycled Asphalt Mixtures with High Reclaimed Asphalt Pavement (RAP) Content

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Abstract: The application of reclaimed asphalt pavement (RAP) can help reduce resource waste and environmental pollution in road construction. However, so far, only a small percentage of RAP materials can be used in road construction. The key obstacles to the application of a recycled asphalt mixture (RAM) with high RAP content are the variability of RAP materials and the difficulty of fully rejuvenating aged asphalt. However, there is still a lack of research on the effect of the variability of RAP materials and recycled asphalt on the quality control of a RAM. Therefore, this study investigates the effects of sieve pretreatment of RAP material using 4.75 mm sieve mesh and the use of composite crumb rubber-modified asphalt (CCRMA) to reclaim aged asphalt on the road performance and frame variability of reclaimed asphalt mixtures. Therefore, this study investigates the effects of the fractionation process of RAP material using 4.75 mm sieve mesh and the use of CCRMA to reclaim aged asphalt on the road performance of a RAM. The results show that the fractionation process can effectively reduce the mitigation of RAP agglomeration and reduce the variability of gradation, which in turn reduces the variability of road performance. The incorporation of CCRMA can effectively improve the high-temperature stability performance and low-temperature cracking resistance. The dynamic stability and the fracture energy of the CRAM (RAM prepared using CCRMA) were four and one and a half times as large as that of the NAM (RAM prepared using base asphalt), respectively. The fractionation process of RAP material and the utilization of CCRMA could help reduce the variability of the RAM while improving the road performance of the RAM.

Keywords: recycled asphalt mixture; variability; reliability design; fractionation process; road performance

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1. Introduction

Utilizing recycled materials instead of virgin materials in the production of hot-mix asphalt mixtures helps to reduce construction costs, lessen the reliance on natural aggregates, and reduce greenhouse gas emissions [1–3]. When considering the performance of a recycled asphalt mixture (RAM), the reclaimed asphalt pavement (RAP) content in the actual projects is generally controlled within 30% (“RAP” is a mixture of old asphalt pavement that has been excavated, recycled, crushed, and screened, and “RAM” is a mixture made by remixing RAP with new asphalt material, new aggregate, etc. in a certain proportion) [4,5]. However, the continuous growth of RAP materials in recent years has caused unpredictable environmental pollution. The use of a RAM with low RAP content cannot solve the growing RAP problem [6,7]. Therefore, the RAM with a high content of RAP has received more and more attention in practical applications.

When the RAP content exceeds 25%, the road performance of the RAM gradually decreases as the RAP content increases [8–10]. Barros et al. [11] found that the cleavage expansion rate increased when the RAP content in the mixture increased. Zhu et al. [12] stated that mixtures with high RAP content suffered from weak cracking resistance. The variability of RAP and the low performance of recycled asphalt are the main reasons for limiting the maximum RAP blending. Al-Qadi et al. [13] noted that the lack of understanding of aggregate and binder properties and the uncertainty of RAP grades resulted in the RAP content remaining at a low level. To keep RAP variability within acceptable limits, some studies have pretreated RAP material by fragmentation and fractionation, etc. Previous research has shown that fractionation treatments provide better retention of rutting potential, improved fatigue performance (higher fracture energy), and better control of the volumetric properties of asphalt mixtures [14]. Zaumanis et al. [15] found that pretreating RAP by fragmentation and fractionation reduced the variability of RAP and increased the RAP content in the RAM. Pan et al. [16] proposed an optimized gradation design method after RAP fractionation and found that the fractionation process reduced the effect of RAP variability on the RAM. Most of the current research focuses on the effect of the RAP fractionation process on the road performance of the RAM [17]. However, there is a lack of research on the effect of the RAP fractionation process on the variability of RAM road performance.

Another major factor affecting the performance of a RAM with high RAP content is the method of reclaiming asphalt in the RAM. Various methods have been used to effectively rejuvenate aged asphalt, including the incorporation of rejuvenators and soft binders into RAP mixtures [18–20]. Many studies have been conducted on the utilization of recycling agents to regenerate asphalt mixtures [21–23]. Wang et al. [18] investigated the impact of the HRA-2 rejuvenator on a RAM containing high RAP content and found that the addition of the HRA-2 rejuvenator reduced the high-temperature performance of the RAM and improved its water stability and low-temperature crack resistance. Yousefi et al. [24] investigated the effect of two types of rejuvenators (one was aromatic extracts and one was triglycerides/fatty acids) on the cracking properties of asphalt mixtures containing 25% RAP and found that recycling agents improved the low-temperature cracking resistance of asphalt mixtures. In addition, the other method is to use a softer asphaltene blend and rejuvenate aged asphalt by adding virgin asphalt [25]. Recent research showed that composite crumb rubber-modified asphalt (CCRMA) was significantly more effective than virgin asphalt in blending aged asphalt containing high RAP content [26,27]. Therefore, CCRMA has great potential for enhancing the road performance of the RAM with high RAP content. In recent years, many studies have been conducted on the effect of CCRMA on the properties of aged asphalt. Liu et al. [27] found that the high-temperature and fatigue resistance performances of aged asphalt were improved by adding CCRMA. Chen et al. [28] concluded that CCRMA had a significant effect on the chemical, microscopic, and rheological properties of aged asphalt binders. However, compared to aged asphalt, the effect of CCRMA on the performance of the RAM has been less studied, especially on the performance of the RAM with high RAP content.

Therefore, the objectives of this study were (1) to evaluate the effect of the fractionation process on controlling the variability of the road properties for the RAM and (2) to evaluate the effect of the combined use of CCRMA as a blending asphalt and fractionation process on the road properties for the RAM and their variability.

2. Materials and Methods

2.1. Materials

2.1.1. RAP Characterization

RAP was obtained from Wuxi Road and Bridge Municipal Co., Ltd. (Xihu Middle Road, Xishan District, Wuxi City), as shown in Figure 1. The RAP material was fractionated using a 4.75 mm sieve and divided into two portions based on the aggregate size. The aggregate gradation for the two portions of the fractionated RAP material is displayed in Figure 2. The old asphalt content (by mass of mixture) in the RAP was 5.57%.

Figure 1. RAP material.

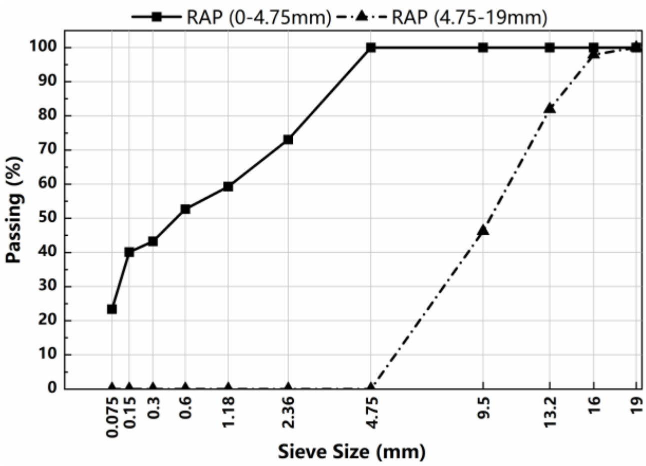

Figure 2. The aggregate gradation of RAP material.

2.1.2. Properties of Virgin Binders

The base asphalt was chosen as the virgin binder to prepare the RAM in this study. According to our previous tests [27], CCRMA can effectively improve the high-temperature performance and fatigue resistance of aged asphalt, so CCRMA was also chosen to prepare recycled asphalt mixtures. Table 1 lists the technical indicators of the asphalt, where G* is the complex modulus and δ is the phase angle.

Table 1. Technical indicators of base asphalt and CCRMA.

Technical Indicators		Base Asphalt	CCRMA	Test Method
Penetration (25 °C, 5 s, 100 g) (0.1 mm)		70	83	T0604-2011
Ductility (5 °C, 5 cm/min) (cm)		-	59	T0605-2011
Ductility (10 °C, 5 cm/min) (cm)		25	-	T0605-2011
Softening point (°C)		48.5	87	T0606-2011
G*/sinδ@64 °C	Virgin asphalt	1.24	-	T0628-2011
	RTFOT aged asphalt	3.01	-	T0628-2011
G*/sinδ@70 °C	Virgin asphalt	0.63	-	T0628-2011
	RTFOT aged asphalt	2.94	-	T0628-2011
G*/sinδ@94 °C	Virgin asphalt	-	1.35	T0628-2011
	RTFOT aged asphalt	-	2.26	T0628-2011
G*/sinδ@100 °C	Virgin asphalt	-	0.83	T0628-2011
	RTFOT aged asphalt	-	1.54	T0628-2011

2.1.3. Design and Preparation of RAP Mixtures

For the preparation of RAM, basalt was selected as coarse and fine aggregates, and limestone mineral powder with a particle size of less than 0.075 mm was selected as filler. Table 2 shows the technical specifications of the aggregate.

Table 2. Technical specifications of the aggregates.

Technical Specifications	Unit	Coarse Aggregate	Fine Aggregate	Fillers	Test Method
Apparent relative density	g/cm^3	2.78	2.66	2.61	T0328-2005
Crushing value	%	11.4	-	-	T0316-2005
Los Angeles abrasion loss	%	18.2	-	-	T0317-2005
Needle flake particle content	%	11.7	-	-	T0312-2005
Water absorption rate	%	1.3	-	-	T0307-2005
Firmness	%	10.4	-	-	T0314-2000
Sand equivalent	%	-	86	-	T0334-2005
Angularity	%	-	51	-	T0345-2005
Hydrophilic coefficient	-	-	-	0.4	T0353-2000
Plasticity coefficient	-	-	-	3.1	T0354-2000

The RAM was designed as a dense-graded mixture with a nominal maximum aggregate size of 13 mm and 50% RAP content. Referring to the grading control range of AC-13, three gradation curves were determined and named AC-13a, AC-13b, and AC-13c, as shown in Figure 3. The asphalt content was selected as 5.57%, which is the same as the old asphalt content in RAP. To investigate the effect of the fractionation process on the performance of the RAM, RAM with fractionated RAP materials (RAM-FR) and unfractionated RAP materials (RAM-UR) was prepared.

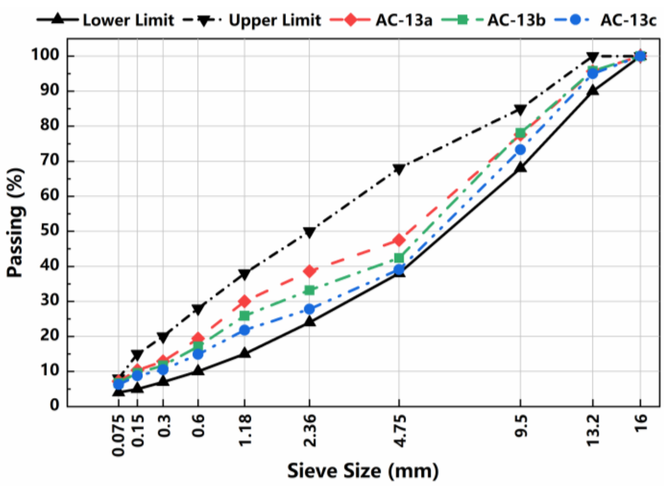

Figure 3. Gradation curves of RAM.

For the preparation of RAM, asphalt, new aggregates, and RAP material were first placed in ovens at different temperatures for insulation. Among them, the asphalt was kept at 150 °C for 2 h, the new aggregates were insulated at 180 °C for 4 h, and the RAP material was insulated at 120 °C for 2 h [29]. After insulation, the RAP material was mixed in a mixing pot at a temperature of 180 °C for 90 s. After adding the new aggregates to the RAP material, the mixture was mixed for 90 s to ensure a uniform mixture. Subsequently, the new asphalt (base asphalt) was added and mixed for 90 s to obtain a loose asphalt mixture. The asphalt mixture specimens of target heights were obtained using a Superpave gyratory compactor (SGC) by controlling the number of gyrations to 100 times and adjusting the quality of the asphalt mixture [30]. Finally, the specimens were placed at room temperature for 48 h for further testing.

2.2. Experimental Design

2.2.1. Rutting Test

The rutting test was used to evaluate the rutting resistance of RAM [31]. According to the JTG E20-2011 [12], the RAM was formed into plate specimens measuring 300 mm × 300 mm × 50 mm in size and repeatedly rolled on the same track with a solid rubber wheel with a wheel pressure of 0.7 MPa at a temperature of 60 °C to form rutting grooves. The rutting resistance of RAM was evaluated in terms of the rutting depth (*RD*) and the dynamic stability (*DS*) of the asphalt mixture specimens, as calculated by Equation (1):

$$DS = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \times C_1 \times C_2 \quad (1)$$

where d_1 and d_2 correspond to the rut depths at t_1 and t_2, respectively; N is the crushing speed of the round-trip process of the test wheel; and C_1 and C_2 are the correction factors of the testing machine and specimen factor, respectively.

2.2.2. Indirect Tensile Test

The cylindrical specimens with a diameter of 100 mm and a height of 63.5 mm were prepared for the indirect tensile (IDT) test. Considering that the actual load acting on the pavement is constant and the deformation of the pavement grows with the growth of the constant load, the stress-controlled mode was used to perform the IDT test at 25 °C. To obtain the fatigue life of RAM, the average indirect tensile strengths of the different types of mixtures under dry conditions were first obtained from the IDT test, and then the stress ratio (0.25) for the fatigue test was determined [32,33]. Finally, the fatigue life was obtained based on the vertical permanent strain curve of the asphalt mixture, which was used to evaluate the medium-temperature fatigue performance of RAM.

2.2.3. Semi-Circular Bending Test

To investigate the low-temperature performance of RAM, a single-load semi-circular bending (SCB) test was performed at −12 °C using a 50 mm/min displacement loading rate [34,35]. Based on the obtained vertical load–displacement curves, the fracture energy (G_f) was calculated according to Equation (2):

$$G_f = \frac{W_f}{A_{lig}} \quad (2)$$

where W_f represents the fracture work, corresponding to the area below the vertical load–displacement curve, and A_{lig} represents the area of the fracture surface.

The flow chart of the performance-related tests for RAM is illustrated in Figure 4. The blue line portion represents the experimental information for the RAM prepared using RAM-FR and CCRMA.

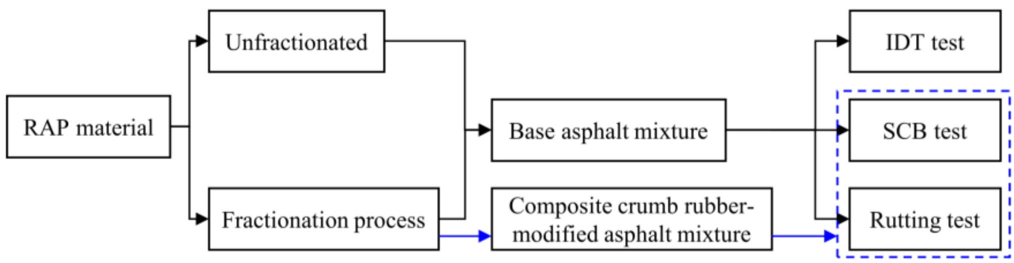

Figure 4. Laboratory experimental design flow chart.

3. Results

3.1. Analysis of the Variability in Road Properties for Recycled Asphalt Mixtures with High RAP Content

Figure 5 shows the results of the rutting test, IDT test, and SCB test. The data dispersion of the RAM-UR was significantly greater than that of the RAM-FR. The experimental results of the RAM were subjected to a normal distribution test to intuitively display the results, as listed in Tables 3–5. The results show that the performance indicators of the RAM obeyed a normal distribution at the 0.05 level, i.e., all data obeyed a normal distribution at the 95% confidence level. The normal distribution curves were fitted with different performance indicators and their frequency of occurrence as horizontal and vertical coordinates, as shown in Figure 6 [36,37]. The combination of Tables 3–5 and Figure 6 shows that for the RAM containing 50% RAP, the curve of the RAM-FR was significantly narrower than that of the RAM-UR, implying that the dispersion of road performance test results for the RAM-FR became lower. This indicates that the road performance variability of the RAM can be effectively controlled by the fractionation process of RAP material [38]. Compared with the curves of the RAM-UR, the curves of the RAM-FR showed a significant forward shift, indicating that the road performance of the RAM can be improved by controlling the variability. This is because the fractionation process can reduce the agglomeration phenomenon produced by the bonding action of the aged asphalt in the RAP, reduce the degree of RAM grade separation, and realize the fine fractionation of the RAP [39]. That is, the variability of RAM road performance is reduced by reducing the variability of RAP materials, which is consistent with the studies of Wang et al. [18]. and Feng et al. [17].

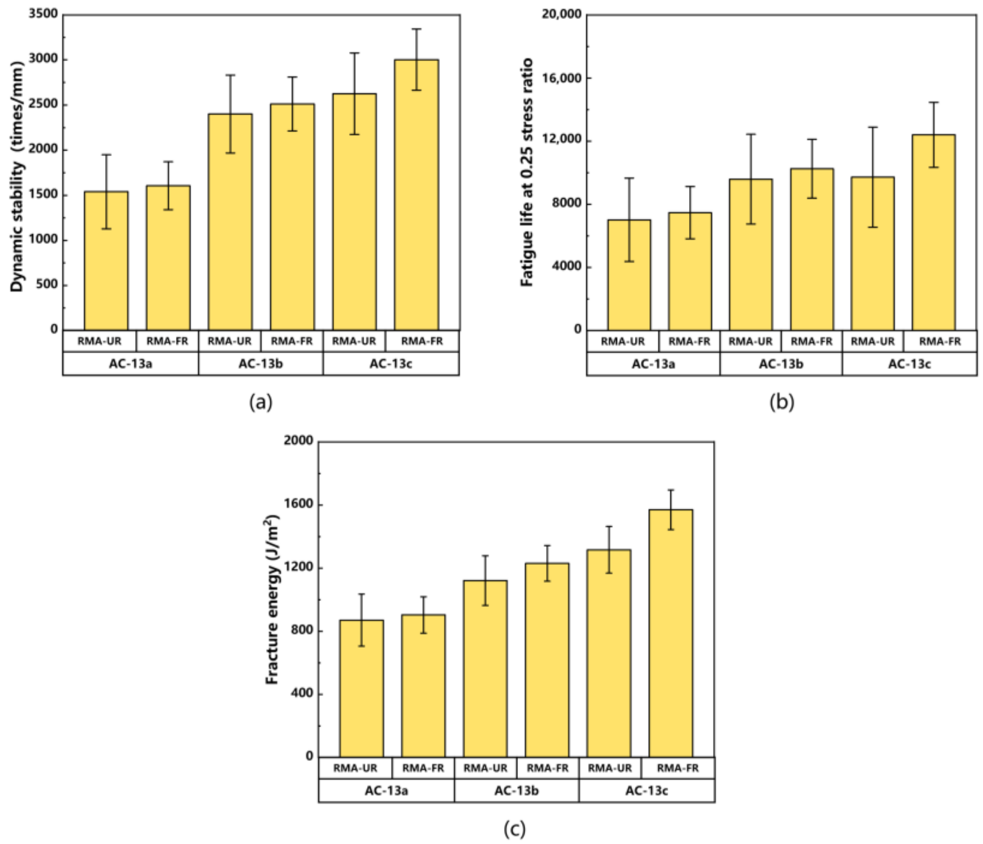

Figure 5. Test results on road performance of RAM-UR and RAM-FR: (**a**) dynamic stability; (**b**) fatigue life at 0.25 stress ratio; and (**c**) fracture energy.

Table 3. Parameters of the normal distribution curve on dynamic stability of RAM with various gradations.

Gradation	Material	Statistics	*p*-Value	μ	σ
AC-13a	RAM-UR	0.903	0.267	1539	410.61
AC-13a	RAM-FR	0.874	0.136	1606	265.69
AC-13b	RAM-UR	0.886	0.181	2400	431.19
AC-13b	RAM-FR	0.952	0.709	2512	298.37
AC-13c	RAM-UR	0.897	0.232	2626	452.15
AC-13c	RAM-FR	0.966	0.859	3003	339.27

Table 4. Parameters of the normal distribution curve on fatigue life of RAM with various gradations.

Gradation	Material	Statistics	*p*-Value	μ	σ
AC-13a	RAM-UR	0.947	0.679	7017	2646.00
AC-13a	RAM-FR	0.912	0.368	7471	1657.91
AC-13b	RAM-UR	0.919	0.425	9591	2839.83
AC-13b	RAM-FR	0.868	0.145	10,250	1858.70
AC-13c	RAM-UR	0.939	0.602	9715	3166.34
AC-13c	RAM-FR	0.930	0.512	12,402	2057.89

Table 5. Parameters of the normal distribution curve on fracture energy of RAM with various gradations.

Gradation	Material	Statistics	*p*-Value	μ	σ
AC-13a	RAM-UR	0.868	0.117	871	164.77
AC-13a	RAM-FR	0.948	0.667	903	115.46
AC-13b	RAM-UR	0.979	0.961	1121	156.97
AC-13b	RAM-FR	0.935	0.527	1230	112.88
AC-13c	RAM-UR	0.950	0.688	1316	147.76
AC-13c	RAM-FR	0.921	0.400	1570	125.40

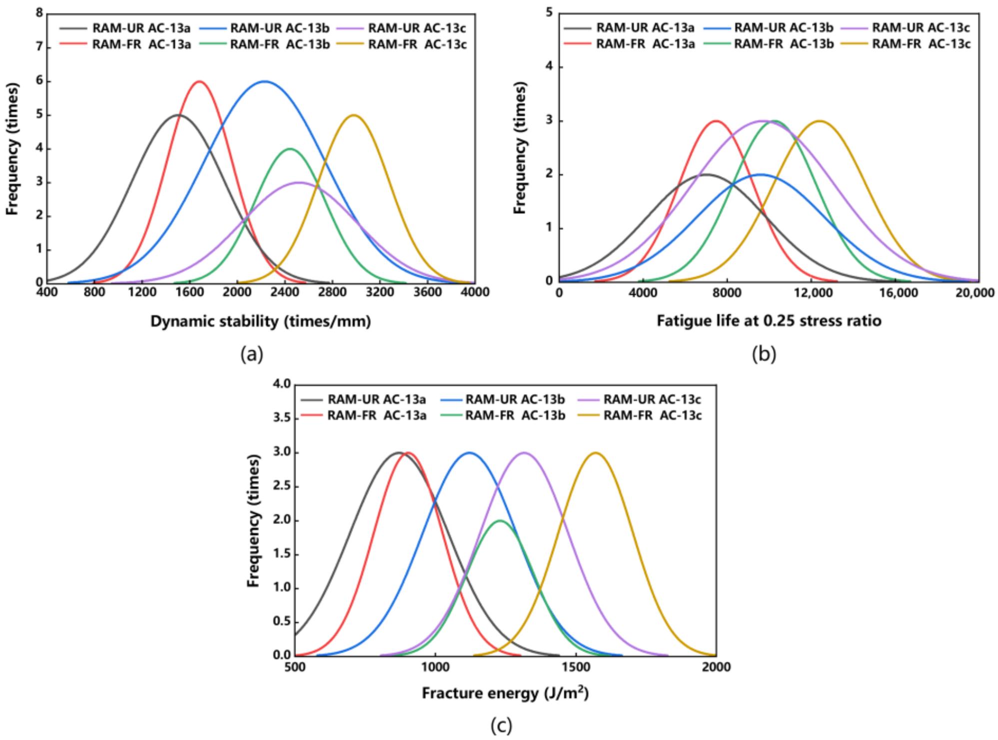

Figure 6. Normal distribution curves for road properties of RAM with various gradations: (**a**) dynamic stability; (**b**) fatigue life at 0.25 stress ratio; and (**c**) fracture energy.

To further evaluate the effect of the fractionation process on the variation of road performance for the RAM, the coefficient of variation was calculated [40], as displayed in Figure 7. A smaller coefficient of variation indicates less variability; conversely, more variability indicates less homogeneity. The coefficient of variation for fatigue life fluctuated between 16 and 37 with high variability, while the coefficient of variation for fracture energy fluctuated between 8 and 19 with low variability. The greater variability in fatigue life among asphalt mixture specimens is a consequence of the reduced constraints on the specimens and the longer loading times during the IDT test in comparison to the SCB test. As a result, various factors affect the fatigue life of asphalt mixture specimens [41,42].

Although the coefficients of variation were not identical, the coefficients of variation for the six different RAMs with different road performances reflected a common trend. The coefficients of variation of the road performance indicators of the RAM-FR were all less than those of the RAM-UR, indicating that the fractionation process of RAP material can reduce the variability of the road performance for the RAM with high RAP content.

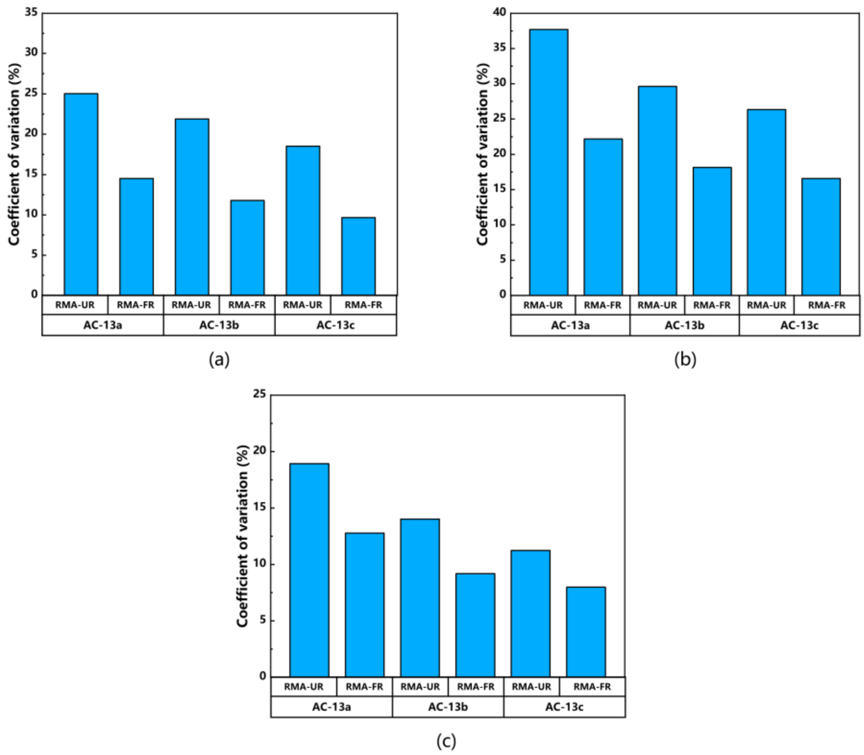

Figure 7. Coefficient of variation of road performance for RAM-UR and RAM-FR: (**a**) dynamic stability; (**b**) fatigue life at 0.25 stress ratio; and (**c**) fracture energy.

3.2. Reliability Calculation Based on Variability Control for Recycled Asphalt Mixtures with High RAP Content

Figure 7 shows that the coefficient of variation is not only related to whether or not the RAP material is fractionated but also to the gradation of the RAM. The fineness modulus is often used to evaluate the gradation of asphalt mixtures [43,44]. The larger the fineness modulus, the coarser the corresponding gradation. The calculation results are shown in Table 6.

Table 6. The fineness modulus of RAM with different gradations.

Gradation	Fineness Modulus
AC-13a	5.61
AC-13b	5.83
AC-13c	6.05

Combined with Table 6 and Figure 7, for both the RAM-UR and RAM-FR, the coefficient of variation on the RAM road performance decreased as the fineness modulus increased. This suggests that higher fineness modulus values in asphalt mixtures can improve the variability of RAM road performance. This is because a larger fineness modulus represents less fine aggregate content, making it easier to mix asphalt and coarse aggregate, thus reducing the difference between the road performance of the RAM [44]. This is consistent with Pan et al. [16]. That is, the high proportion of fine aggregate is not conducive to forming a stable skeleton structure, resulting in greater variability of RAM road performance. Therefore, to control the variability of road performance for the RAM with high RAP content, a reliability calculation scheme was established in this study by taking the fineness modulus as the design indicator and the coefficient of variation on the RAM road performance containing 50% RAP as the performance indicator. Considering that there is no clear regulation on the variability of road performance, the threshold value of the coefficient of variation for the fracture energy was set to 10%, and the threshold values of the coefficient of variation for the dynamic stability and the fatigue life were both set to 20%.

Figure 8 shows the fitted curves of the coefficient of variation on road performance for the RAM with the variation of the fineness modulus (the dotted lines are the threshold values for the coefficient of variation). After establishing the relationship curve, considering that the probability distribution function of the fineness modulus is unknown, the reliability was obtained in this study by calculating the probability that the fineness modulus M_x falls in the reliability interval [45]. Here, the "reliability interval" is the range of fineness modulus for which the performance of the RAM satisfies all three indicators simultaneously. The "reliability" is the probability that the performance of the asphalt mixture meets the target. In addition, due to the small sample size in this study, only the RAM with a range of fineness modulus values from 5.61 to 6.05 were considered. Based on the fitted curves in Figure 8, the fineness modulus of the RAM was calculated once the threshold of variability for road performance was reached. After obtaining the reliability intervals of the fineness modulus meeting the requirements of different road performance variability, the reliability intervals of the RAM meeting the requirements of road performance variability were obtained by taking the intersection of multiple reliability intervals. Finally, the reliability was obtained by calculating the probability of the fineness modulus falling in the reliability interval, as shown in Table 7. It can be seen that the reliability interval for the RAM meeting the requirements for performance variability increased after the fractionation process, with a significant increase in reliability to 50%. This further illustrates that the fractionation treatment can significantly enhance the road performance of a RAM with high RAP content.

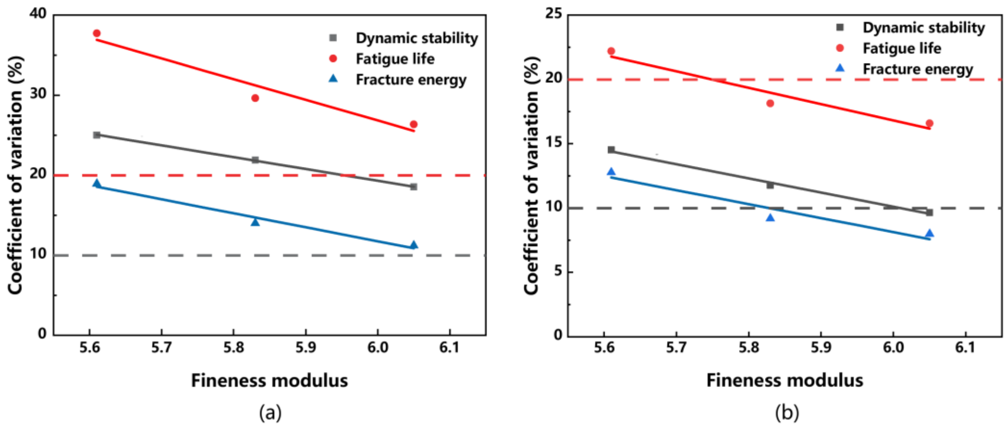

Figure 8. Relationship between the coefficient of variation on road performance and fineness modulus for RAM containing 50% RAP: (**a**) RAM-UR and (**b**) RAM-FR.

Table 7. The calculated reliability intervals and reliability of RAM-UR and RAM-FR.

Material	Reliability Intervals	Reliability (%)
RAM-UR	-	0
RAM-FR	5.81–6.05	50

The milling process causes a decrease in the aggregate size of the RAP material [46]. Therefore, for a RAM with different RAP contents, the increase in RAP content led to a decrease in the fineness modulus of the asphalt mixture, increasing the variability of road performance for the RAM [47]. To analyze the relationship between RAP content and the coefficient of variation on road properties of the RAM, the fineness modulus of the RAM corresponding to different RAP contents was calculated based on the fitted curves in Figure 8. Table 8 shows the reliability intervals determined with the same proportion of new aggregate. The RAP content and its corresponding reliability were further fitted in a quadratic form, as shown in Figure 9. Combining Table 8 and Figure 9, the maximum and minimum values of the fineness modulus intervals for the RAM decreased with increasing RAP content, and the reliability intervals to meet the requirements of road performance variability of the RAM gradually became smaller, and the reliability decreased. This suggests that a higher RAP content increases the variability of RAM road performance. This is in agreement with the study of Yang et al. [48]. An increase in RAP content causes a decrease and instability in the moisture susceptibility, cracking resistance, and fatigue properties of the RAM. The reliability of the RAM-FR containing 70% RAP was 37.7%, which is greater than the reliability of the RAM-UR containing 50% RAP and meets the variability requirement. This further illustrates that the fractionation process of RAP material can effectively reduce the variability of road performance for a RAM.

Table 8. The calculated reliability intervals and reliability of RAM with various RAP contents.

RAP Content (%)	Total Interval	Reliability Intervals	Reliability (%)
30	5.64–6.09	5.81–6.09	62.2
40	5.62–6.07	5.81–6.07	57.8
50	5.61–6.05	5.81–6.05	54.5
60	5.55–6.03	5.81–6.03	45.8
70	5.48–6.01	5.81–6.01	37.7

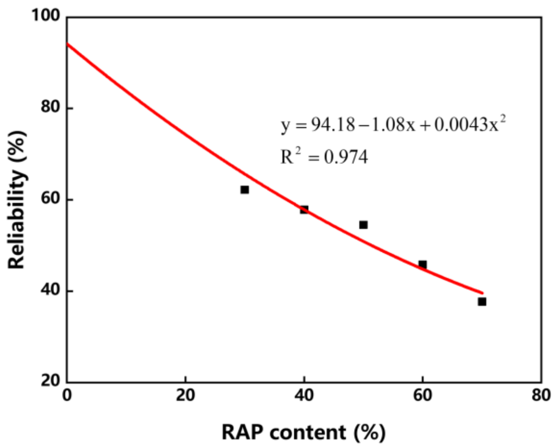

Figure 9. Fitting curve of reliability with RAP content.

3.3. *Proportional Design of Recycled Asphalt Mixtures with High RAP Content*

3.3.1. Determination of Gradation and Volumetric Parameters for RAM with High RAP Content

The Superpave design method was used in the mix design of the RAM containing 50% RAP. The asphalt content for the RAM was established through the utilization of the SGC method, aiming to achieve 4% air voids at N_{design} = 100. According to the study of Zhou et al. [49], the addition of 0.3% asphalt to the determined optimal amount of asphalt promoted the blending between the new and old asphalt. Therefore, the CCRMA asphalt content in this study was an addition of 0.3% CCRMA asphalt to the determined optimal amount of asphalt. As a blank control sample, asphalt mixture specimens were prepared using base asphalt and new aggregate with the same gradation and 5% asphalt content. For the convenience of presentation, the RAM prepared using CCRMA was referred to as the CRAM, and the asphalt mixture prepared using base asphalt was referred to as the NAM.

The gradation and volumetric parameters for the RAM containing 50% RAP are shown in Tables 9 and 10.

Table 9. The gradation of CRAM containing 50% RAP.

Indicators	CRAM Containing 50% RAP									
Sieve size (mm)	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing (%)	100	95.7	77.6	47.8	38.9	30.3	19	13	10.5	7.3
RAP content (%) (>4.75 mm)	35.0%									
RAP content (%) (<4.75 mm)	15.0%									

Table 10. The volumetric parameters of CRAM containing 50% RAP.

Indicators	NAM
Asphalt content (%)	5.0
Addition of new asphalt (%)	2.39
Gross volume relative density (g/cm^3)	2.494
Maximum theoretical relative density (g/cm^3)	2.598
Air void (%)	4.0

3.3.2. Evaluation of High-Temperature Stability Performance for Recycled Asphalt Mixtures with High RAP Content

The rutting test results of asphalt mixtures are shown in Table 11. A normal distribution curve was fitted with relative frequency as the vertical coordinate and dynamic stability as the horizontal coordinate, as shown in Figure 10. Table 12 displays the parameters of the normality test. The dynamic stability of the CRAM was four times higher than that of the NAM, suggesting that CCRMA can significantly enhance the high-temperature performance of the RAM. This is consistent with our previous studies. That is, CCRMA can effectively enhance the elastic recovery and stiffness of aged asphalt compared to base asphalt, thereby improving the high-temperature performance [27,50]. To further verify the effect of the fractionation process on the high-temperature performance of the CRAM, the coefficients of variation on dynamic stability for the CRAM and NAM were calculated, as shown in Table 13. The coefficient of variation on dynamic stability of the CRAM was 40% higher compared to the NAM but still met the threshold requirement. In addition, combined with Figure 7, the coefficient of variation on dynamic stability for the CRAM decreased by 26–45% compared to that for RAM-UR. Therefore, the CRAM has excellent resistance to deformation at high temperatures while controlling variability.

Table 11. The rutting test results of CRAM and NAM.

Specimen Number	Dynamic Stability (times/mm)	
	NAM	CRAM
1	1845.77	10,597.34
2	1960.68	7146.88
3	2124.66	8576.70
4	2021.06	7011.87
5	1737.42	9455.69
6	2207.10	10,171.49
7	1948.30	8642.65
8	1615.13	8785.95

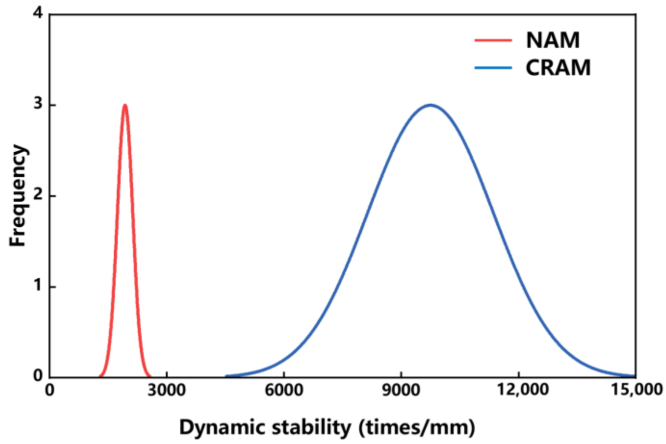

Figure 10. Normal distribution fitting results for dynamic stability.

Table 12. The parameters of the normality test.

Gradation	Material	Statistics	*p*-Value	μ	σ
NAM	0.980	0.963	1932	182.87	NAM
CRAM	0.936	0.576	8978	1201.37	CRAM

Table 13. The coefficients of variation on dynamic stability for CRAM and NAM.

Gradation	Dynamic Stability (times/mm)	Total Deformation (mm)	Coefficient of Variation
NAM	1933	1.158	9.46
CRAM	8798	0.286	13.65

3.3.3. Evaluation of Low-Temperature Crack Resistance for RAM with High RAP Content

The SCB test results of asphalt mixtures are shown in Table 14. A normal distribution curve was fitted with frequency as the vertical coordinate and fracture energy as the horizontal coordinate, as shown in Figure 11. The parameters of the normality test are shown in Table 15. The fracture energy of the CRAM was greater than that of the NAM, indicating that its low-temperature cracking resistance is better than that of the NAM. This is because the addition of 0.3% asphalt increases the asphalt content in the asphalt mixture and also promotes the integration of the new asphalt with the old asphalt, which ultimately increases the bonding between the asphalt mixtures [49,51,52]. On the other hand, the high elasticity of CCRMA leads to its ability to withstand greater damage loads [53]. At the same time, CCRMA can delay the extension of cracks, resulting in a significant increase in both peak force load and fracture energy of CRMA, which ultimately improves the low-temperature crack resistance of the RAM [54,55]. According to Figure 11 and Table 15, the dispersion degree in the fracture energy of the CRAM was larger than that of the NAM. Therefore, the coefficient of variation was further computed to assess the variability of the CRAM and NAM in terms of low-temperature fracture resistance, as shown in Table 16. Although the coefficient of variation in fracture energy for the CRAM was greater than that for the NAM, it still met the requirements of the SCB test for the coefficient of variation for the fracture energy.

Notably, the change in damage displacement was less for the CRAM compared to that of the NAM. Considering that the base asphalt used in the preparation of the NAM has weak low-temperature cracking resistance, the CRAM, which has the same damage displacement as the NAM, may be susceptible to low-temperature cracking. This susceptibility could be attributed to the higher modulus of the CCRMA, rendering it more prone to cracking under load [35,56]. Therefore, it is necessary to soften the asphalt by adding recycling agents during the mixing process of the asphalt mixture to enhance the low-temperature cracking resistance of the CRAM, thus improving the durability of the CRAM in road engineering.

Table 14. The SCB test results of CRAM and NAM.

Test Number	Fracture Energy (J/m^2)	
	NAM	CRAM
1	1345.67	1816.20
2	1238.02	2154.22
3	1233.29	2088.92
4	1387.16	1924.66
5	1435.83	2056.35
6	1235.98	1742.26
7	1132.89	1553.70
8	1201.34	1844.34

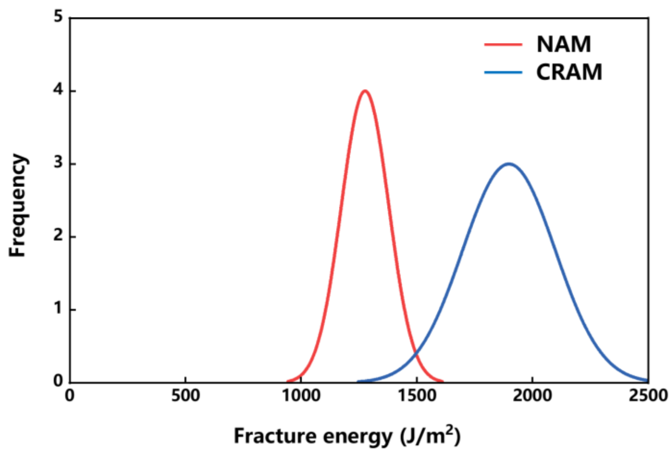

Figure 11. Normal distribution fitting results for fracture energy.

Table 15. The parameters of the normality test.

Gradation	Statistics	*p*-Value	μ	σ
NAM	0.931	0.523	1276.33	95.97
CRAM	0.963	0.841	1892.50	187.17

Table 16. The coefficients of variation on low-temperature performance for CRAM and NAM.

Gradation	Peak Force Load (kN)		Disruption Displacement (mm)		Fracture Energy (J/m^2)	
	Average	Coefficient of Variation	Average	Coefficient of Variation	Average	Coefficient of Variation
NAM	10.85	7.64	1.37	4.23	1276.53	7.52
CRAM	13.37	9.43	1.39	6.91	1892.50	9.86

4. Conclusions

This study evaluates the effect of the fractionation process on controlling the variability of the road properties for a RAM and the effect of the combined use of CCRMA as a blending asphalt and fractionation process on the road properties for the RAM and their variability. This study proposes a method to control and enhance the road performance of RAM with high RAP content. The major findings and significant conclusions are as follows.

(1) All the performance indicators of the RAM exhibited significant adherence to the normal distribution at the 0.05 level, i.e., all the data obeyed the normal distribution with

95% confidence. The coefficients of variation in the road performance indicators for the RAM-UR were larger than those of the RAM-FR, indicating that the fractionation process reduces the variability of the road performance for the RAM containing high RAP content.

(2) The variability in the road performance for the RAM gradually increased with the increase in RAP content, but the reliability of the RAM-FR containing 70% RAP was 37.7%, which is greater than the reliability of the RAM-UR containing 50% RAP and meets the variability requirement.

(3) The high-temperature and low-temperature cracking resistance of the CRAM containing 50% RAP were both better than those of the NAM. Although the dispersion of its performance indicators was higher than that of the NAM, the CRAM met the requirements of the corresponding variability in both the fracture energy index and the dynamic stability index.

5. Limitations and Recommendations

In this study, only continuous dense gradation of RAP material from a single source was investigated, and only the road performance of a RAM containing 50% RAP was studied. It is recommended to further investigate the effect of RAP material source, pretreatment method, grading, and RAP content on the road performance of the RAM.

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Nomenclature

CCRMA	composite crumb rubber-modified asphalt
CRAM	recycled asphalt mixture prepared using composite crumb rubber-modified asphalt
DS	dynamic stability
G_f	fracture energy
IDT	indirect tensile test
NAM	asphalt mixture prepared using base asphalt
RAM	recycled asphalt mixture
RAM-FR	recycled asphalt mixture with fractionated reclaimed asphalt pavement materials
RAM-UR	recycled asphalt mixture with unfractionated reclaimed asphalt pavement materials
RAP	reclaimed asphalt pavement
RD	rutting depth
SCB	semi-circular bending
SGC	Superpave gyratory compactor

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