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Experimental Study of Permeable Asphalt Mixture Containing Reclaimed Asphalt Pavement

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Abstract: The current focus of research attention on reclaimed asphalt pavement (RAP) utilization is expanding the applications of RAP. This study aims to analyze the road performance of recycled permeable asphalt mixtures (RPAMs), which represents a novel direction for utilizing RAP. Firstly, the Marshall design method was used to carry out the material composition design of the RPAM with varying RAP contents (10%, 20%, and 30%). Subsequently, the performance of the RPAM with different RAP contents (10%, 20%, and 30%) and preheating temperatures (120 °C, 130 °C, 140 °C, 150 °C, and 160 °C) was tested with a permeable asphalt mixture containing 12% high-viscosity asphalt as the control group. The mixture's performance included high-temperature stability, low-temperature crack resistance, water stability, anti-raveling performance, and dynamic mechanical properties. The results indicate that the higher the RAP content, the better the high-temperature performance of the RPAM, while the low-temperature performance, water stability, and anti-raveling performance deteriorate. At 30% RAP content, its pavement performance is comparable to that of the control group mixture. However, increasing RAP preheating temperature can improve low-temperature and water stability but may reduce high-temperature performance. The optimal RAP preheating temperature for pavement performance is between 140 and 150 °C. The dynamic modulus test showed that the higher the RAP content, the greater the dynamic modulus of the RPAM, leading to better high-temperature stability but reduced low-temperature crack resistance. The influence of RAP preheating temperature is the opposite. These test results demonstrate the feasibility of utilizing RAP for paving permeable asphalt pavement under controlled RAP content and preheating temperature conditions.

Keywords: recycled permeable asphalt mixture; reclaimed asphalt pavement; RAP contents; preheating temperatures; road performance

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1. Introduction

With the increasing service life of roads, a significant accumulation of reclaimed asphalt pavement (RAP) has resulted from renovating and maintaining asphalt surfaces to prevent diseases [1,2]. The comprehensive utilization of RAP has garnered widespread attention from scholars domestically and internationally [3]. Relevant studies have confirmed the continued value of RAP material even after years of use [4–6]. Some scholars have introduced virgin asphalt (modified asphalt) into recycled RAP, and the results have shown that the aged modified asphalt can be regenerated and modified by virgin asphalt [7,8]. In certain studies, virgin aggregates have been directly added to RAP to regenerate the recycled modified asphalt mixture [9,10]. In most cases, the findings have revealed that the recycled modified asphalt has undergone oxidation and hardening [11,12]. Furthermore, no polymers have been detected in the aged asphalt binder, indicating that the SBS modifier in the modified asphalt has degraded during aging. Most regeneration-related research has observed an improvement in the rutting resistance of the recycled modified asphalt mixture with an increasing RAP content while the fatigue resistance gradually decreases [13,14]. Similarly, some scholars have investigated the performance changes in aged SBS-modified asphalt mixture by adding regeneration agents to it, and they have found that incorporating RAP into the asphalt mixture can enhance the high-temperature performance [15–18]. Scholars have restored the functional performance of aged asphalt by adding virgin asphalt, and the results have indicated that the proportion of virgin asphalt added influences the performance of recycled asphalt [19,20]. To enhance the functional performance of recycled mixtures, numerous researchers have utilized the blending method to prepare recycled SBS-modified asphalt [21–26]. They have employed thin-layer chromatography with flame ionization detection (TLC/FID) and Fourier transform infrared spectroscopy (FTIR) to verify the relationship between the recycled asphalt's physical properties and the rejuvenator's proportion. The findings have demonstrated that recycled asphalt can exhibit good physical and functional performance when the rejuvenator reaches an appropriate proportion [27–29].

Permeable friction course mixtures (PFC) encompass porous asphalt pavements, representing a novel pavement type. According to the specification [30], porous asphalt pavement is the type of asphalt pavement where the surface layer is paved by an asphalt mixture with a void ratio of ≥18%, and the road surface water can penetrate the interior of the pavement and drain out laterally. With an approximate porosity of 20%, they possess outstanding weather resistance, flowability, and resistance to plastic deformation [31–33]. Various countries have undertaken a series of research endeavors to enhance the performance of porous asphalt pavements. It was a conventional practice to improve their functional performance by employing high-performance asphalt binders, such as highly viscous modified asphalt, rubber-modified asphalt, and bio-oil-modified asphalt [33–37]. Additionally, some studies have optimized the design process of porous asphalt mixtures to enhance their functional performance further [38]. Exploring the preparation of a recycled permeable asphalt mixture (RPAM) by adding reclaimed asphalt pavement (RAP) materials with high-viscosity asphalt and aggregates presents a new direction, as RAP materials exhibit high modulus properties after long-term use. However, there remains controversy regarding the potential impact of RAP addition on the functional performance of porous asphalt pavements. Specific research findings indicate that recycled mixtures' performance is comparable to conventional asphalt mixtures when the RAP content is sufficiently low [39].

Similarly, increasing the preheating temperature of RAP facilitates the better blending of the aged and virgin materials in the recycled mixture, improves uniformity, and subsequently enhances the performance of the recycled mixture [40,41]. Considering the current research status, limited studies have focused on utilizing RAP in RPAMs [42]. Particularly, the influence of RAP's performance on the properties of porous asphalt mixtures remains unclear. Therefore, an important research question was investigating the effects of RAP content and preheating temperature on RPAMs' high-temperature, low-temperature, and water stability properties.

Considering the current research status of RPAMs, the following shortcomings exist:

1. Currently, the term "recycled porous asphalt pavements" refers to the recycling of milled porous asphalt pavement materials, and does not include the application of traditional RAP materials for porous asphalt pavements;
2. Research on the recycling of porous asphalt pavements often focuses on using conventional modified asphalt as the virgin binder. In contrast, studies on high-viscosity modified asphalt as the virgin binder were scarce;
3. The RAP content was relatively conservative during recycling, and the preheating temperature was below 130 °C. There was a lack of research on the effects of different RAP contents and preheating temperatures on the functional performance of RPAMs.

2. Objective and Research Approach

The following research objectives were identified to verify the feasibility of using RAP material for RPAMs:

- Firstly, conduct material composition design for the RPAM;
- Next, verify the functional performance of the RPAM with different RAP contents and preheating temperatures;
- Finally, analyze the dynamic mechanical response of the RPAM with different RAP content and preheating temperatures.

With this objective of conducting laboratory tests on RPAMs, Figure 1 summarizes the research approach used. Initially, the mix design of the RPAM was conducted. Subsequently, the wheel track rutting test, low-temperature bending test, freeze–thaw splitting test, and Cantabro raveling test were carried out on the RPAM with different RAP content (10%, 20%, and 30%) and various RAP preheating temperatures (120 °C, 130 °C, 140 °C, 150 °C, and 160 °C). Fresh porous asphalt mixtures with 12% high-viscosity asphalt (HVA) as a cementing agent were used as a control group to verify the road feasibility of RPAMs for porous asphalt pavements. Lastly, dynamic modulus tests were conducted on the RPAM with different RAP contents (10%, 20%, and 30%) and various RAP preheating temperatures (120 °C, 130 °C, 140 °C, 150 °C, and 160 °C).

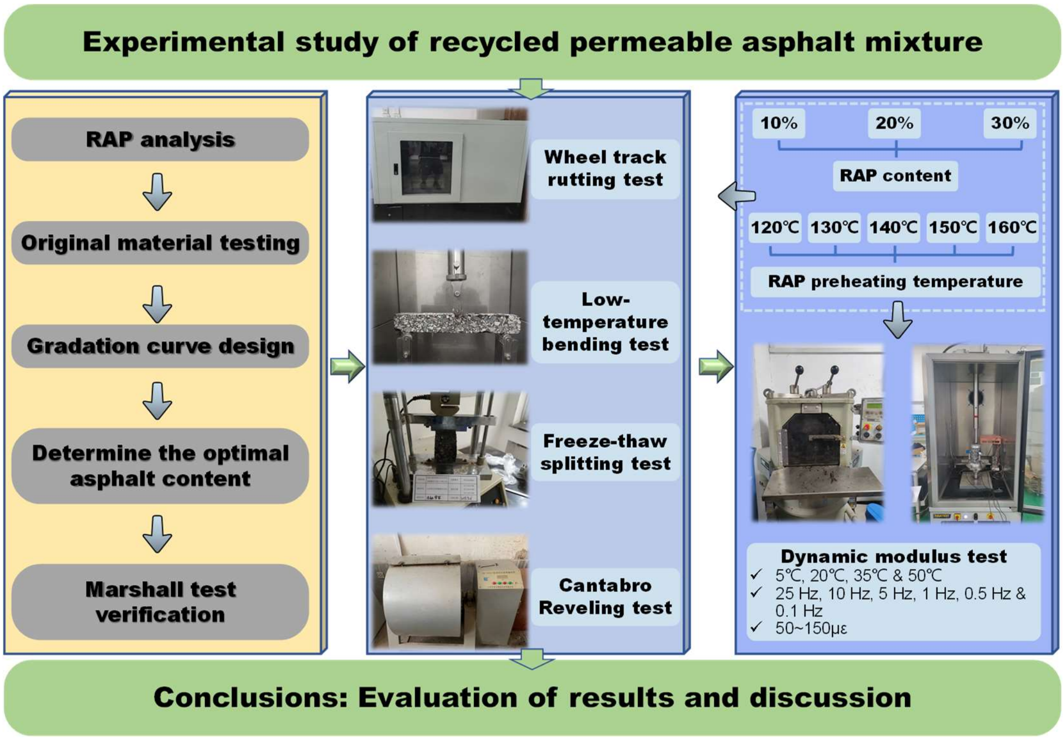


Figure 1. Research approach.

3. Materials and Methods

3.1. Raw Materials

3.1.1. RAP Material

The RAP utilized in this study was sourced from the surface layer of a specific highway and was classified into three gradations: 0–8 mm, 8–12 mm, and 12–16 mm. The performance characteristics of the recycled asphalt are presented in Table 1, while the gradations of RAPs are provided in Table 2.

Table 1. General physical properties of asphalt.

Item	RA	Test Methods
Penetration at 25 °C (0.1 mm)	25.8	ASTM D5 [43]
Softening point (°C)	72.5	ASTM D36 [44]
Ductility at 10 °C (cm)	3.2	ASTM D113 [45]
Dynamic viscosity at 60 °C (Pa·s)	3706	ASTM D2171 [46]

Table 2. The gradations of three RAP materials.

Particle Size (mm)	Sieve Size (mm)										
	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
0–8	100	100	100	100	85.3	56.3	44.2	34.2	23.1	18.4	11.8
8–12	100	100	100	86.1	19.6	14.3	12.2	10.2	7.6	6.1	4.2
12–16	100	100	81.5	34.0	16.1	12.1	10.3	8.5	6.2	5.0	3.5

3.1.2. Asphalt Binder

The neat asphalt was blended with 18% of a high-viscosity modifier to produce HVA as the virgin asphalt. The technical specifications of HVA are presented in Table 3.

Table 3. Technical performance indicators of 18% HVA.

Performance Indicators	Test Results
Dynamic viscosity at 60 °C (Pa·s)	306,645
Viscosity–toughness (N·m)	24.84
Toughness (N·m)	16.64
Brookfield viscosity at 135 °C (Pa·s)	4.50
Brookfield viscosity at 170 °C (Pa·s)	1.41
Penetration at 25 °C (0.1 mm)	40.6
Softening point (°C)	85.7
Ductility at 5 °C (cm)	78.9

3.1.3. Aggregates

The coarse aggregate chosen for the reclaimed porous asphalt mixture was diabase, while the fine aggregate consisted of manufactured sand. All the aggregates used in this study meet the specified requirements. The gradations of the coarse aggregate and fine aggregate are shown in Table 4.

Table 4. The gradations of coarse and fine aggregates.

Particle Size (mm)	Sieve Size (mm)										
	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
10–15	100	100	79.3	14.8	0.9	0.8	0.8	0.8	0.8	0.8	0.7
5–10	100	100	100	97.5	7.8	1.3	1.1	1.0	0.9	0.9	0.8
0–3	100	100	100	100	100	84.7	65.2	36.3	13.9	9.2	5.6

3.2. Experimental Methods

3.2.1. Mix Design

(1) Material selection and testing

The material selection and testing of the RPAM were conducted following the procedure outlined in Section 3.1.

(2) Gradation curve design

Considering the characteristics of porous asphalt pavement, a commonly used target void content of 20% was chosen. According to the China Specification [30], each grade of mineral for RPAM should be between grading upper and grading lower limits. The gradations of the blended mixture are shown in Table 5. The gradation design curves for the reclaimed porous asphalt mixture with different RAP contents (10%, 20%, and 30%) are illustrated in Figure 2.

Table 5. The gradations of RPAM with different RAP contents (10%, 20%, and 30%).

Particle Size (mm)	**Sieve Size (mm)**										
	19	**16**	**13.2**	**9.5**	**4.75**	**2.36**	**1.18**	**0.6**	**0.3**	**0.15**	**0.075**
10% RAP	100	100	89.7	57.0	19.0	15.0	12.9	10.1	7.8	6.5	4.6
20% RAP	100	100	89.7	57.0	19.1	14.9	12.9	10.07	7.71	6.4	4.5
30% RAP	100	100	89.7	57.1	19.2	14.9	12.8	10.1	7.7	6.3	4.5

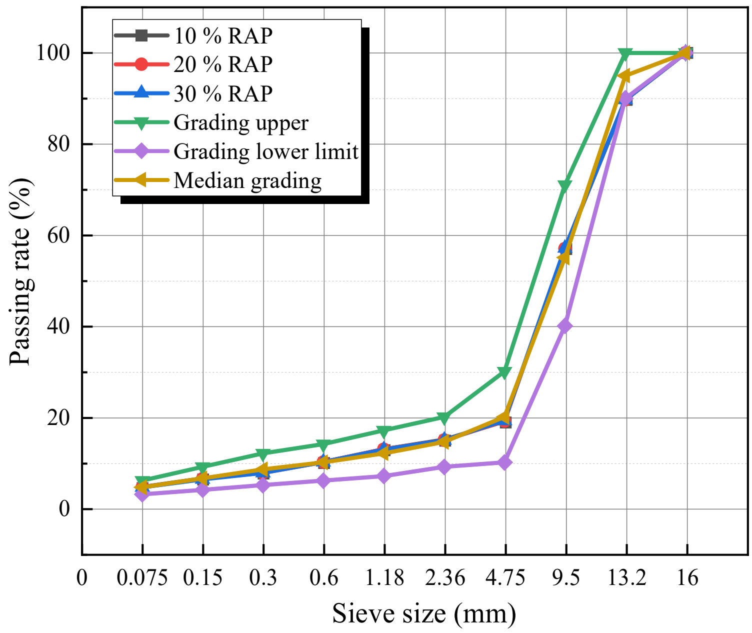


Figure 2. Gradation curves of the reclaimed mixture with different RAP contents (10%, 20%, and 30%).

(3) Determining the best asphalt–stone ratio

First, the initial asphalt dosage is determined based on the thickness of the asphalt film adsorbed on the surface of the aggregates, as shown in Equations (1) and (2):

$$d = \frac{Pa}{A} \times 1000 \quad (1)$$

$$A = 0.41a + 0.41b + 0.82c + 1.64d + 2.87e + 6.14f + 12.29g + 32.77h \quad (2)$$

where Pa is the asphalt–stone ratio, d is the thickness of the asphalt film, A is the aggregate surface area, and a, b, c, d, e, f, g, and h are 19, 4.75, 2.36, 1.18, 0.6, 0.3, 0.15, and 0.075 mm sieve passage percentage.

Then, Marshall specimens were prepared using RPAMs with asphalt–stone ratios of 5.0%, 5.0 ± 0.5%, and 5.0 ± 1.0%. The newly added asphalt-to-stone ratio can be calculated using Equation (3):

$$P_{a(new)} = \frac{\left(100 - \sum_{i=1}^{3} P_i P_{bi} \times 10^{-2}\right) \times P_{a(total)} - \sum_{i=1}^{3} P_i P_{bi}}{100 - \sum_{i=1}^{3} P_i P_{bi}} \times 100\% \quad (3)$$

where $P_{a(new)}$ is the newly added asphalt–stone ratio, which denotes the mass ratio of virgin asphalt to total aggregate, $P_{a(total)}$ is the total asphalt–stone ratio, indicating the mass ratio of total asphalt to total aggregate, P_i is the dosage of RAP in the i-th grade, and P_{bi} is the content of aged asphalt in the i-th grade RAP, representing the mass ratio of aged asphalt to RAP.

Finally, through the drain-down test and raveling loss test, the optimal asphalt–stone ratios for RPAM with different RAP contents (10%, 20%, and 30%) were determined as 5.0%, 5.0%, and 4.9%, respectively.

(4) Marshall test verification

The Marshall test was conducted to verify the RPAM with different RAP contents (10%, 20%, and 30%). The volumetric parameters of the RPAM, as well as the mechanical properties, meet the specification requirements; the test results are shown in Table 6.

Table 6. Marshall test results of RPAM with different RAP contents (10%, 20%, and 30%).

RAP Contents (%)	Optimal Asphalt–Stone Ratios (%)	Marshall Stability (kN)	Flow Value (0.1 mm)	Marshall Relative Density	Maximum Theoretical Relative Density (g/cm^3)	Void Ratio (%)	Connected Porosity (%)
Specification values	/	≥5	20~40	/	/	18~25	/
10	5.0	5.82	27.4	2.223	2.743	20.2	15.4
20	5.0	6.0	25.2	2.199	2.711	20.5	15.8
30	4.9	6.25	24.8	2.184	2.684	20.4	15.6

3.2.2. Wheel Track Rutting Test

High-temperature rutting tests were conducted to evaluate the performance of RPAM with different RAP contents (10%, 20%, and 30%) and various preheating temperatures for RAP (120 °C, 130 °C, 140 °C, 150 °C, and 160 °C). A porous asphalt mixture with 12% HVA as the binder (without RAP) was used as a control group. The rutting test was conducted at 60 °C with a tire pressure of 0.7 MPa. The calculation formula for dynamic stability is shown in Equation (4):

$$DS = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \times C_1 \times C_2 \quad (4)$$

where DS is the dynamic stability of the asphalt mixture, d_1 is the deformation corresponding to t_1, t_1 = 45 min, d_2 is the deformation corresponding to t_2, t_2 = 60 min, C_1 = 1.0, C_2 = 1.1, and N is 42 times/mm.

3.2.3. Low-Temperature Bending Test

The low-temperature cracking resistance of different RAP (10%, 20%, and 30%) contents and different preheating temperatures of RAP (120 °C, 130 °C, 140 °C, 150 °C, and 160 °C) in the RPAM was evaluated using the low-temperature bending test. A porous asphalt mixture with 12% HVA as the binder (without RAP) was used as the control group. The test was conducted at a temperature of −10 °C, and the dimensions of the beam specimen were 250 mm in length, 30 mm in width, and 35 mm in height, with a span of 200 mm. The universal testing machine was used for the test.

The indicators of flexural strength R_B, maximum bottom bending strain ε_B at failure, and bending stiffness modulus S_B at failure were calculated using Formulas (5)–(7), respectively. The flexural strength indicator is directly proportional to the asphalt mixture's resistance to shrinkage stress and its resistance to failure.

$$R_B = \frac{3 \times L \times P_B}{2 \times b \times h^2} \tag{5}$$

where R_B is the flexural strength at specimen failure, P_B is the maximum load at specimen failure, L is the span of the specimen, b is the width of the specimen at midspan section, and h is the height of the specimen at midspan section.

$$\varepsilon_B = \frac{6 \times h \times d}{L^2} \tag{6}$$

where ε_B is the maximum bending strain at specimen failure and d is the midspan deflection at specimen failure.

$$S_B = \frac{R_B}{\varepsilon_B} \tag{7}$$

where S_B is the bending stiffness modulus at specimen failure.

3.2.4. Freeze–Thaw Splitting Test

The water stability of different RAP contents (10%, 20%, and 30%) and different RAP preheating temperatures (120 °C, 130 °C, 140 °C, 150 °C, and 160 °C) in the RPAM was evaluated using the freeze–thaw splitting test. A porous asphalt mixture with 12% HVA as the cementing agent (without RAP) was used as the control group. The specimens were of standard Marshall size. The specific test procedures for the freeze–thaw splitting test can be found in the specification (JTG E20-2011 T0729). The test was conducted at a temperature of 25 °C and a loading rate of 50 mm/min. Four similar specimens were used in this test.

3.2.5. Cantabro Raveling Test

The bond performance of RPAM with different RAP contents (10%, 20%, and 30%) and different RAP preheating temperatures (120 °C, 130 °C, 140 °C, 150 °C, and 160 °C) was evaluated using the raveling loss test. A porous asphalt mixture with 12% HVA as the cementing agent (without RAP) was used as the control group. The test was conducted by rotating and impacting the formed standard Marshall specimens in a Los Angeles abrasion tester for 300 cycles, with a test temperature of 20 °C.

3.2.6. Dynamic Modulus Test

The dynamic mechanical properties of RPAM were evaluated using the dynamic modulus test. Four test temperatures (5 °C, 20 °C, 35 °C, and 50 °C) were selected to simulate actual pavement conditions. Six loading frequencies (25 Hz, 10 Hz, 5 Hz, 1 Hz, 0.5 Hz, and 0.1 Hz) were chosen to represent different driving speeds while maintaining a strain level of 50–150 $\mu\varepsilon$. The specimens were subjected to sinusoidal vibration loading. The specimens were formed using a rotational compaction method, with dimensions of Φ150 × 170 mm, and then core samples were taken to obtain dimensions of Φ100 × 150 mm.

The dynamic modulus of the RPAM at different temperatures was shifted based on the time–temperature equivalence principle [16], resulting in a smooth curve. The Sigmoidal model was then used to fit the primary curve of the dynamic modulus of different asphalt mixtures, and the dynamic mechanical properties of different asphalt mixtures were evaluated over a wider frequency range using 35 °C as the reference temperature, as shown in Equation (8):

$$\log|E^*| = \delta + \frac{\alpha}{1 + e^{(\beta + \gamma \log \omega)}} \tag{8}$$

where $\log \omega$ is the logarithm of reduced frequency, δ is the asymptotic line for the lower limit of modulus on the main curve, α is the maximum value of modulus on the main curve, β and γ are shape parameters of the curve segment between the asymptotic lines of the complex modulus on the main curve and the upper limit inflection point, and E^* is dynamic modulus of asphalt mixture.

4. Results and Discussion

4.1. Effect of RAP Content and Preheating Temperature on the Performance of RPAM

4.1.1. High-Temperature Stability

The admixture of RAP increases the high-temperature stability of the mix. It can be seen in Figure 3a that the dynamic stability of the RPAM increases by 15% when the RAP admixture reaches 30% compared to that of the porous asphalt mixture without RAP. The main reason for this phenomenon is that as the amount of RAP increases, the aged asphalt in RAP is not involved in the fusion. The aged asphalt has a higher modulus of stiffness and hardness than the virgin asphalt, so this can improve the high-temperature deformation resistance of the asphalt to a certain extent. Finally, the high-temperature stability of the RPAM is improved.

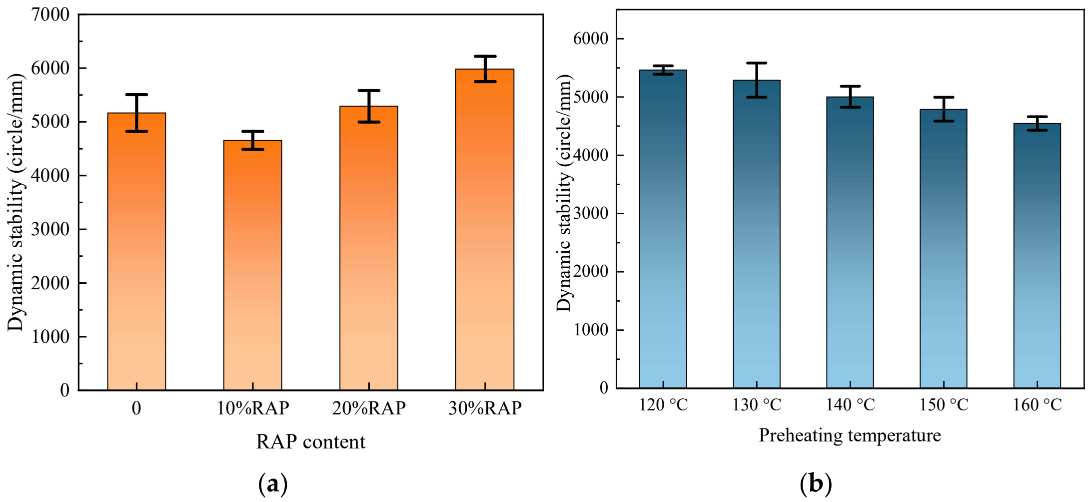


Figure 3. Effect of RAP content and preheating temperature on the high-temperature performance of RPAM: (**a**) RAP content and (**b**) preheating temperature.

Similarly, in Figure 3b, as the RAP preheating temperature increases, the dynamic stability of the RPAM decreases, indicating that raising the RAP's preheating temperature reduces the high-temperature performance of the RPAM. When the RAP preheating temperature exceeds 140 °C, the dynamic stability of the RPAM is less than 5000 times/mm, indicating that its high-temperature deformation resistance fails to meet the specifications. The reason behind this phenomenon is twofold: firstly, as the preheating temperature of RAP increases, more aged asphalt is dissolved and incorporated into the fusion of aged and virgin asphalt, leading to a decrease in the stiffness modulus of the recycled asphalt and a subsequent decrease in dynamic stability of the RPAM; secondly, the increased content of recycled asphalt enhances the lubrication effect between the aggregate particles in the mixture, resulting in a decrease in dynamic stability.

4.1.2. Low-Temperature Crack Resistance

When the RPAM is in a low-temperature environment, the temperature change will generate temperature stress inside the mixture [47]. When the temperature stress is too large, the RPAM will produce low-temperature cracking damage. From Figure 4, with the increase in RAP, the maximum bending strain of the RPAM gradually decreases, while the bending tensile strength and stiffness modulus show a rising trend. When the RAP content reaches 30%, the maximum bending strain is 2560 με, which is slightly larger than the strain value of 2500 με required by the specification. The low-temperature crack resistance of the RPAM is general, then continue to increase the amount of RAP. The low-temperature performance may not meet the specification requirements.

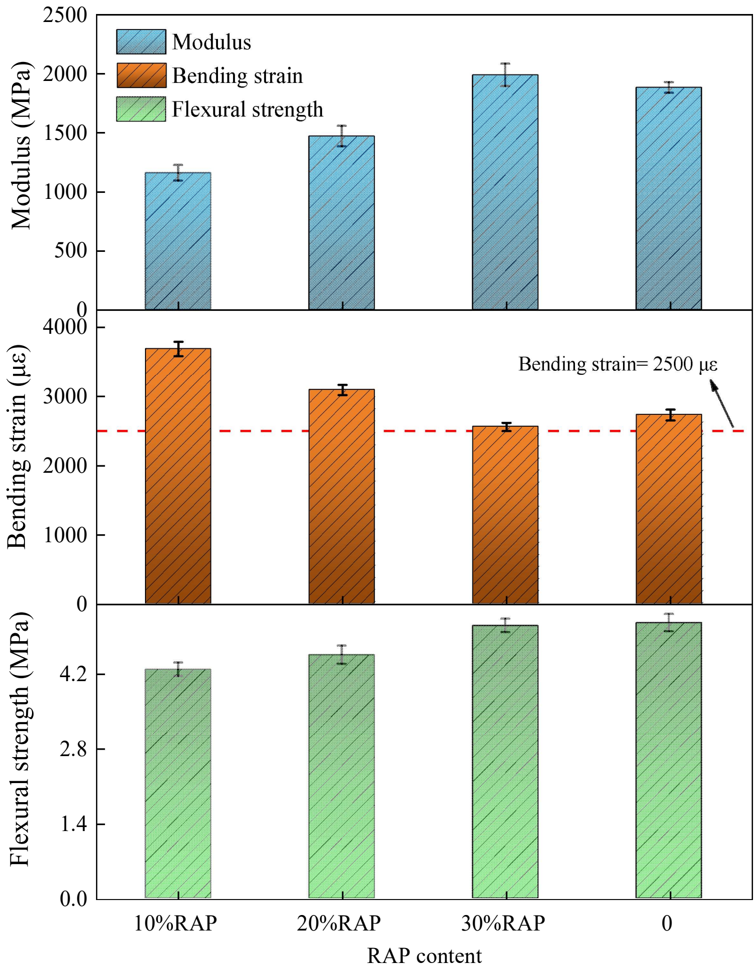


Figure 4. Effect of RAP content on low-temperature performance of RPAM.

The influence law illustrated in Figure 4 reveals that, under low-temperature conditions, an increase in RAP content enhances the load-bearing capacity of the RPAM. However, it concurrently weakens its resistance to low-temperature deformation. The primary underlying cause of this phenomenon lies in the escalating RAP content, which gradually increases the proportion of aged asphalt. Consequently, the plasticity of the recycled asphalt diminishes while its brittleness amplifies. Although adding virgin asphalt partly restores the performance of the aged asphalt, the substantial increase in RAP content leads to a higher concentration of unrejuvenated aged asphalt within the RPAM, thus reducing the proportion of fresh asphalt. Consequently, augmenting the RAP content diminishes the low-temperature crack resistance of the RPAM.

The greater the maximum bending strain of the asphalt mixture, the less prone it is to cracking under low-temperature conditions. In Figure 5, the maximum bending strain of the RPAM at different RAP preheating temperatures shows an increasing trend followed by stabilization as the RAP preheating temperature rises. When the RAP preheating temperature reaches 150 °C, the bending strain of the RPAM peaks, but it slightly decreases when the temperature rises to 160 °C.

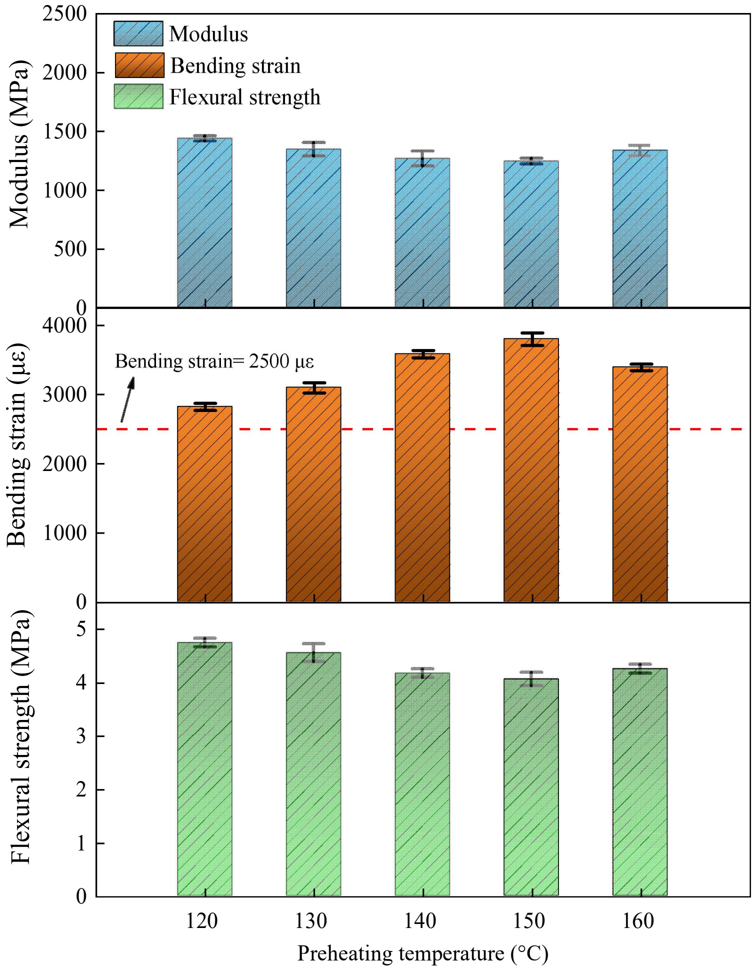


Figure 5. Effect of preheating temperature on low-temperature performance of RPAM.

A smaller bending stiffness modulus indicates the mixture's more robust stress relaxation capacity, allowing for the timely elimination or reduction of temperature-induced stresses under low-temperature conditions. Conversely, a higher bending stiffness modulus suggests poor flexibility of the mixture, making it susceptible to brittle fractures. In Figure 5, as the RAP preheating temperature increases, the flexural stiffness modulus of the RPAM initially rises and then stabilizes at a 20% RAP content. When the RAP preheating temperature reaches 150 °C, the flexural stiffness modulus of the RPAM reaches its minimum value of 1066 MPa. As the temperature rises to 160 °C, the stiffness modulus gradually increases to 1250 MPa.

The ability of the asphalt mixture to withstand tensile forces can be characterized by its flexural strength, where a higher flexural strength under low-temperature conditions indicates better low-temperature tensile performance. The flexural strength of the RPAM at different RAP preheating temperatures initially decreases and then levels off as the RAP preheating temperature increases. When the RAP preheating temperature is 150 °C, the flexural strength reaches its lowest value of 4.05 MPa. When the temperature rises to 160 °C, the flexural strength increases to 4.24 MPa.

Analysis of the reasons can be seen; it can be determined that as the RAP temperature rises, some of the aged asphalt is rejuvenated, and an increasing amount of aged asphalt separates from the RAP and blends with the fresh asphalt to form a rejuvenated high-viscosity asphalt. The rejuvenated high-viscosity asphalt meets the performance standards of high-viscosity asphalt, enhancing the overall toughness of the RPAM and thereby improving its bending strain. However, the increasing amount of rejuvenated asphalt indirectly increases the plasticity of the recycled mixture, resulting in a decrease in the stiffness modulus and flexural strength. When the temperature reaches 160 °C, the high temperature may cause secondary aging of the aged asphalt in the RAP, weakening the bonding strength of the mixture and leading to a decrease in bending strain while slightly improving the flexural strength.

4.1.3. Water Damage Resistance

Due to its highly porous structure, porous asphalt pavement is prone to water infiltration [48], reducing adhesion between asphalt and aggregate. Remarkably, the water stability of RPAMs is a crucial area of research, especially when incorporating RAP materials with poor adhesion properties between the aggregate and asphalt. The water stability of the RPAM was assessed using the freeze–thaw splitting method, and the experimental results are depicted in Figure 6. The freeze–thaw splitting residual strength ratio (TSR) of the three different RAP contents (10%, 20%, and 30%) in the RPAM meets the requirements specified in the specification regulations. Moreover, an increasing RAP content correlates with a downward trend in TSR for RPAMs. This phenomenon can be attributed, on the one hand, to the gradual increase in RAP content, leading to a higher proportion of aged asphalt. Not all aged asphalt is effectively rejuvenated by virgin asphalt, resulting in a lower degree of fusion between the aged and virgin asphalt. Consequently, some aged asphalt persists in a relatively hard and brittle state, thereby progressively compromising the bonding capacity and resistance to deformation of the recycled asphalt.

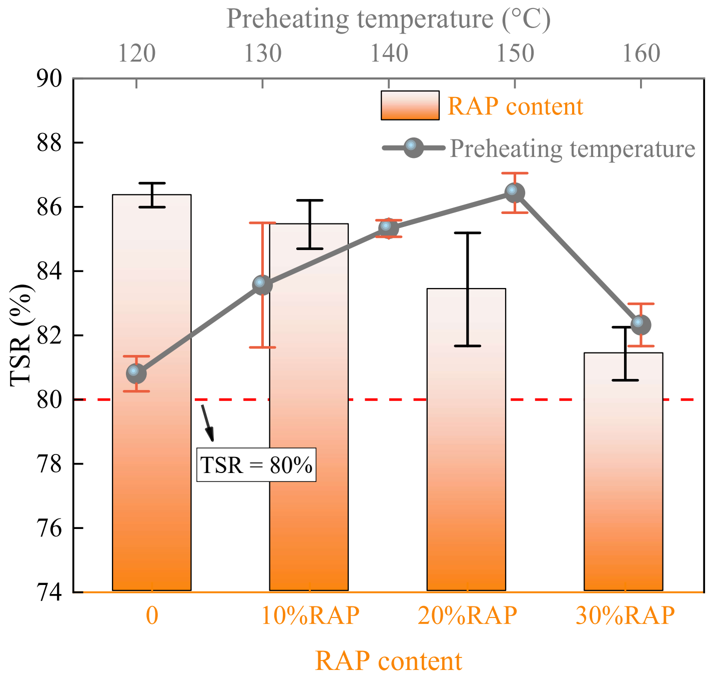


Figure 6. Effect of RAP content and preheating temperature on the water stability performance of RPAM.

On the other hand, the relatively large voids in the RPAM make it more susceptible to water infiltration. With increased RAP content, the weak interface between the asphalt and RAP within the mixture increases, making the interface more vulnerable to damage. Ultimately, this leads to a decrease in the water stability of the mixture.

When the preheating temperature of RAP is set at 120 °C, the TSR of the RPAM is relatively low. This is attributed to the lower preheating temperature of RAP, which fails to activate some of the aged asphalt in RAP. Consequently, the recycled asphalt content in the mixture is reduced, leading to poorer water stability of the recycled mixture. As the preheating temperature of RAP increases, the TSR of the RPAM also rises. At a RAP temperature of 150 °C, the TSR of the mixture reaches its maximum, indicating a reasonable degree of fusion between the new and aged asphalt, with the aged asphalt in RAP being adequately rejuvenated. However, when the preheating temperature of RAP reaches 160 °C, the RPAM's TSR decreases to only 82.3%. This phenomenon is caused by excessively elevating the preheating temperature of RAP, which results in secondary aging of the asphalt in RAP and a subsequent decline in the performance of the recycled asphalt, thereby leading to a decrease in the water stability of the recycled mixture.

4.1.4. Raveling Resistance

The adhesive performance is crucial for evaluating the porous asphalt mixture [49]. Cantabria raveling tests were conducted on the RPAM with different RAP contents (10%, 20%, and 30%), and the test results are presented in Figure 7. As the RAP content increases, the raveling loss of the RPAM gradually rises. When the RAP content reaches 30%, the raveling loss of the RPAM approaches 15%, reaching the upper limit specified by the specification. This indicates that adding RAP significantly impacts the adhesive performance of the RPAM.

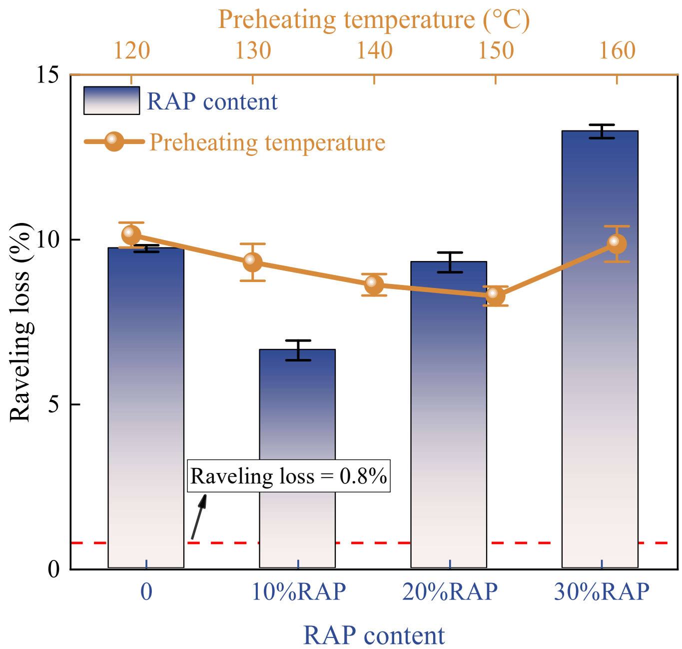


Figure 7. The effect of RAP content and preheating temperature on the raveling resistance of RPAM.

Similarly, the elevation of RAP preheating temperature also substantially influences the raveling loss of the RPAM. At a RAP preheating temperature of 150 °C, the mixture demonstrates a minimal raveling loss of 8.29%, and as the temperature further rises to 160 °C, the raveling of the mixture stabilizes. The underlying reason for this phenomenon is that the increased preheating temperature of RAP gradually dissolves the aged asphalt in RAP under high-temperature conditions, leading to a gradual increase in the effective asphalt content in the recycled mixture. As a result, the overall adhesive performance improves, resulting in a reduction in raveling loss.

4.2. Dynamic Responses of RPAM

4.2.1. Dynamic Modulus

In order to have a more realistic analysis of the mechanical response of the regenerated porous asphalt pavement under the actual traffic load, the dynamic modulus test was used in this study to analyze the dynamic mechanical properties of the regenerated porous asphalt mixes. From Figure 8, it can be seen that when the frequency is fixed, the dynamic modulus of both the recycled porous asphalt mixes with different RAP dosing and the 12% HVA fresh porous asphalt mixes decrease with the increase in temperature, and all four different asphalt mixes show the same pattern. Take 20% RAP as an example. When the frequency is specific, the dynamic modulus decreases significantly when the test temperature is at 20 °C to 35 °C. In contrast, at 35 °C to 50 °C, the dynamic modulus gradually decreases and slowly tends to level off. The main reason for such a result is that in a low-temperature environment, asphalt is in an elastic state, and as the temperature continues to rise, asphalt changes to a viscoelastic state, making the asphalt part of the modulus decrease. On the other hand, the RPAM is composed of a large amount of coarse aggregate and a small amount of fine aggregate; its void ratio is significant when the temperature gradually increases, and the structure of the specimen will slide under the action of load, resulting in a recycled porous asphalt mixture. The dynamic modulus of the asphalt mixture is reduced.

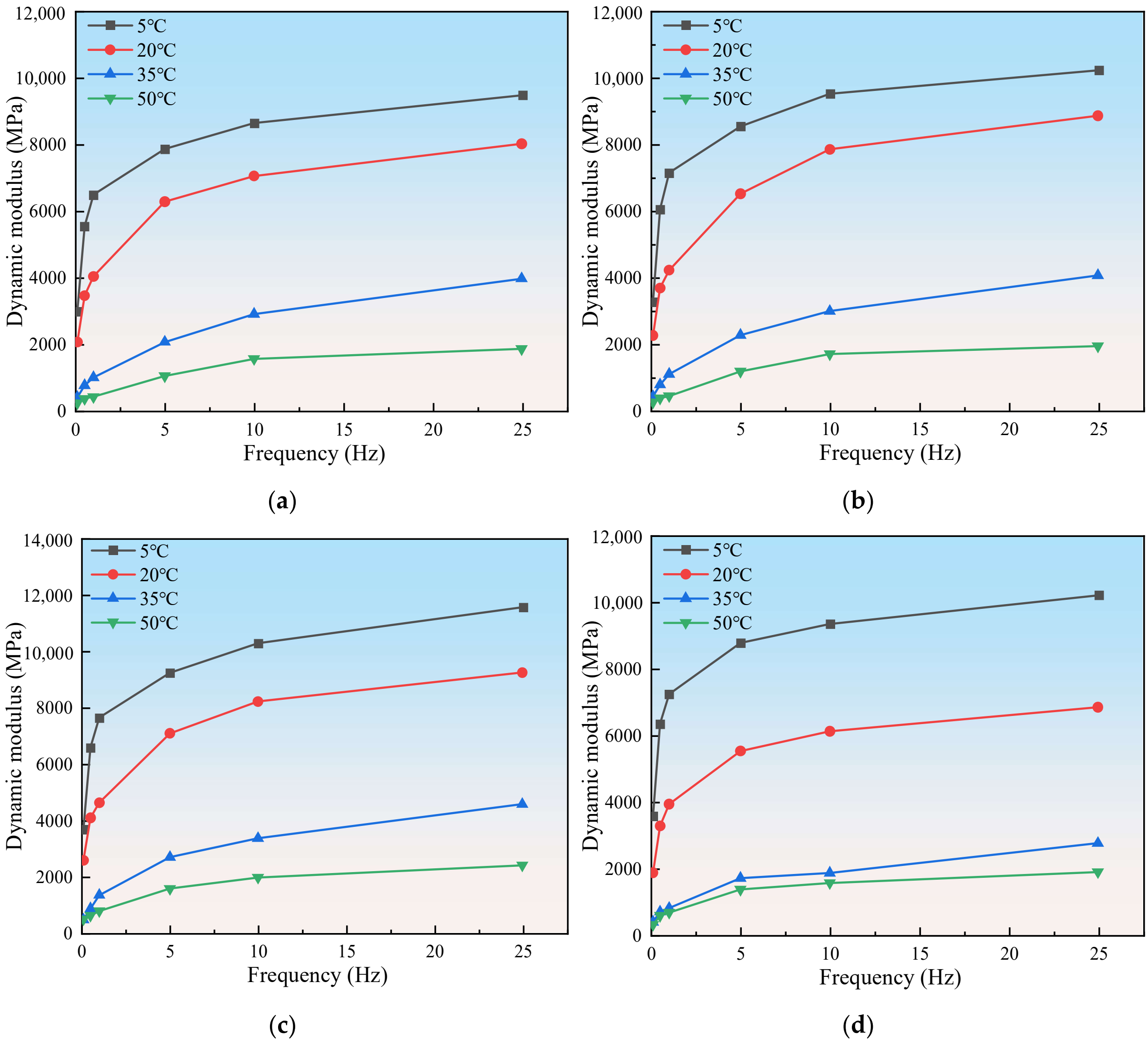


Figure 8. Dynamic mechanical response of RPAM with different RAP content: (**a**) 10% RAP recycled mixture; (**b**) 20% RAP recycled mixture; (**c**) 30% RAP recycled mixture; and (**d**) 12% HVA fresh mixture.

When the test temperature is fixed, the dynamic modulus of different asphalt mixtures gradually increases with the increase in loading frequency, and this pattern is consistent across the four asphalt mixtures. In the frequency range of 0.1 Hz to 5 Hz, the dynamic modulus of the asphalt mixture exhibits exponential growth as the frequency increases. However, in the range of 5 Hz to 25 Hz, the dynamic modulus of the asphalt mixture reaches a plateau as the frequency increases. The reason behind this phenomenon is that as the loading frequency increases, the interval time between loads acting on the specimen decreases, resulting in less recovery of the asphalt mixture's elastic deformation and a decrease in the amount of deformation that is restored, ultimately leading to an increase in its dynamic modulus.

The dynamic modulus decreases with increasing temperature when the frequency is constant for different RAP preheating temperatures but the same RPAM gradation. This pattern is consistent across the RPAM's five different RAP preheating temperatures. In Figure 9, taking the example of RAP preheating temperature of 130 °C at a constant frequency, there is a noticeable decrease in dynamic modulus in the temperature range of 20 °C to 35 °C. Subsequently, in the range of 35 °C to 50 °C, the dynamic modulus gradually decreases and tends to level off. The result can be attributed to the fact that at low temperatures, the asphalt exhibits elastic behavior, while as the temperature continues to rise, the asphalt transitions into a viscoelastic state, decreasing the modulus of the asphalt. Additionally, the RPAM comprises many coarse aggregates and a small number of fine aggregates, resulting in a high void ratio. As the temperature gradually increases, the structure of the specimens undergoes sliding under the applied load, reducing the dynamic modulus of the RPAM.

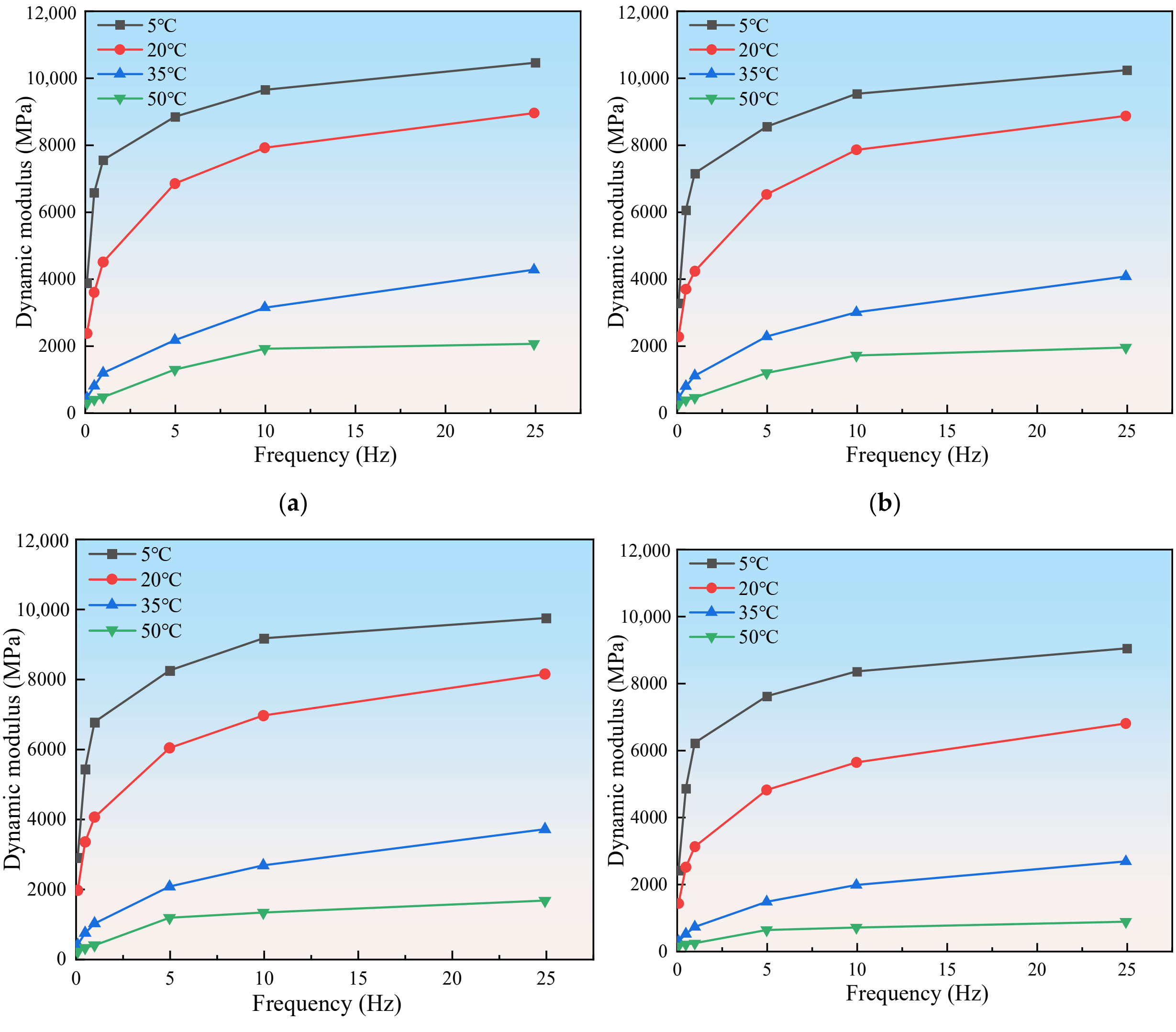
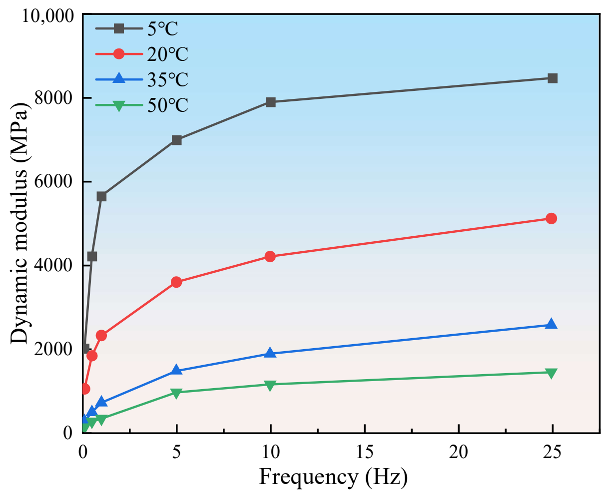


Figure 9. *Cont.*



(**e**)

Figure 9. Dynamic mechanical response of RPAM with different RAP preheating temperatures: (**a**) 120 °C; (**b**) 130 °C; (**c**) 140 °C; (**d**) 150 °C; and (**e**) 160 °C.

When the test temperature is fixed, the dynamic modulus of the RPAM gradually increases with the increase in loading frequency, and this pattern is consistent across the five different RAP preheating temperatures. In the frequency range of 0.1 Hz to 5 Hz, the dynamic modulus of the recycled mixture exhibits exponential growth as the frequency increases. However, in the range of 5 Hz to 25 Hz, the dynamic modulus of the recycled mixture reaches a plateau as the frequency increases. The reason behind this phenomenon is that as the loading frequency increases, the interval time between loads acting on the specimen decreases, making it difficult for the elastic deformation of the RPAM to recover fully, resulting in a decrease in the amount of deformation that is restored and ultimately leading to an increase in its dynamic modulus.

4.2.2. Master Curve of Dynamic Modulus

(1) Dynamic modulus master curves of mixtures with different RAP content

The Sigmoidal model parameters were calculated, and the dynamic modulus master curves of the RPAM with different RAP admixtures were plotted. The results are shown in Figure 10. regardless of the high-frequency or low-frequency range, the master curve of the dynamic modulus for the recycled mixture with higher RAP content is higher than that of the recycled mixture with lower RAP content, and the master curves of the dynamic modulus for the RPAM at different RAP contents are all located above those of the 12% HVA freshly mixed porous asphalt mixture. The result indicates that the RPAM exhibits excellent high-temperature stability while slightly lower in low-temperature crack resistance compared to the 12% HVA porous asphalt mixture, which is consistent with the results of the high-temperature rutting test and the low-temperature bending test. This phenomenon is because as the RAP content increases, the content of aged asphalt in the recycled mixture also increases. Since aged asphalt has a higher stiffness modulus, the increasing content of aged asphalt prevents it from blending effectively with virgin asphalt. Consequently, the dynamic modulus of the RPAM increases, and its high-temperature performance gradually improves, which aligns with the findings of previous studies.

(2) Master curve of dynamic modulus of mixtures with different RAP preheating temperatures

By applying the time–temperature equivalence principle, the dynamic modulus of the RPAM was fitted with the sigmoidal model to obtain the master curve. The reference temperature of 35 °C was used to evaluate the dynamic mechanical properties of the recycled mixtures with different RAP preheating temperatures over a more comprehensive frequency range. Figure 11 shows that when the RAP content is 20%, the master curve of the dynamic modulus for the RPAM gradually decreases with increased RAP preheating temperature. In other words, at the same frequency, the dynamic modulus of the recycled mixture with higher RAP preheating temperature is lower than that of the recycled mixture with a lower RAP preheating temperature. The result indicates that an elevated RAP preheating temperature promotes the fusion between the aged and virgin asphalt in the recycled mixture, resulting in a high content of free asphalt in the recycled mixture and ultimately leading to a decreasing trend in the dynamic modulus with an increased in RAP preheating temperature.

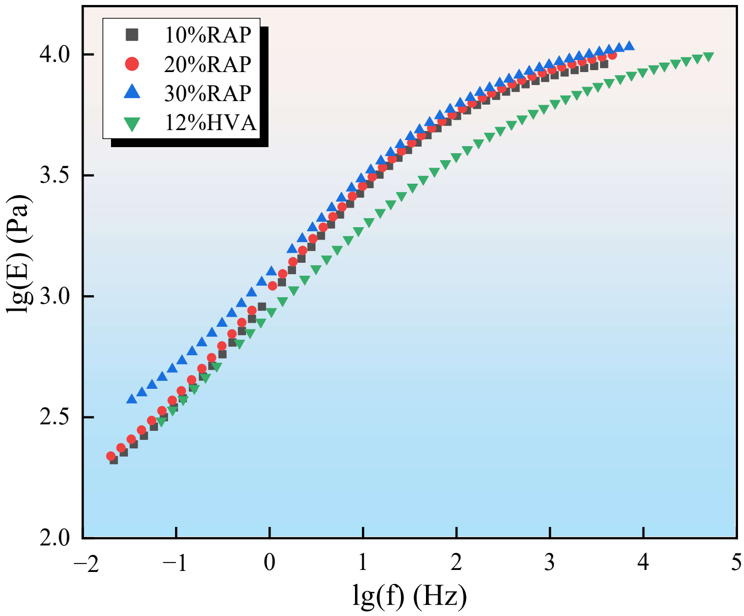


Figure 10. Dynamic modulus master curve of RPAM with different RAP dosages.

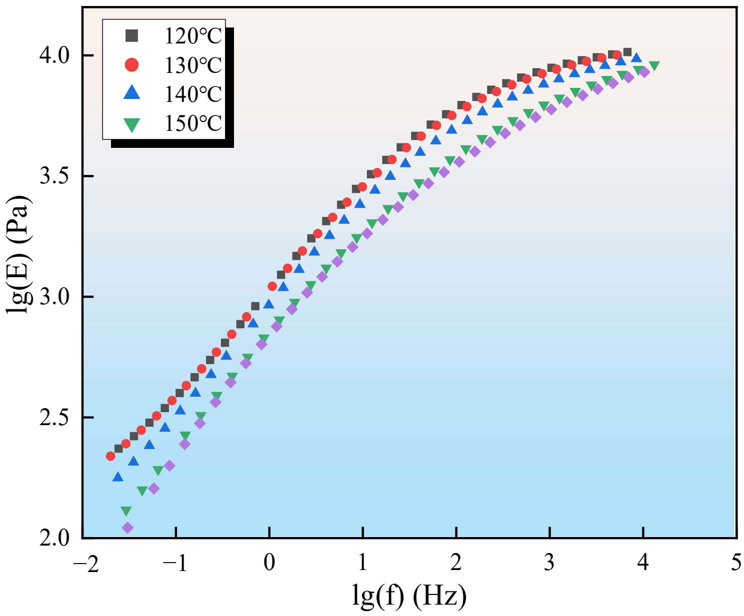


Figure 11. Dynamic modulus master curve of RPAM with different RAP preheating temperatures.

5. Conclusions

This study focuses on the material composition design of RPAMs. It proposes a method for recycling porous asphalt pavement based on the performance of RAP materials. The investigation examines the high-temperature stability, low-temperature crack resistance, water stability, anti-raveling performance, and dynamic mechanical properties of the RPAM under different RAP content (10%, 20%, and 30%) and various RAP preheating temperatures (120 °C, 130 °C, 140 °C, 150 °C, and 160 °C). The main conclusions are as follows:

1. The RAP content and preheating temperature significantly influence the pavement performance of the RPAM. When the RAP content reaches 30%, and the preheating temperature ranges from 140 °C to 150 °C, the performance of the mixtures meets the specification requirements for porous asphalt mixtures. It is comparable to that of non-RAP mixtures;
2. RPAMs demonstrate excellent resistance to rutting. With a RAP content of 20%, their high-temperature stability is comparable to porous asphalt mixtures with 12% HVA. However, increasing the preheating temperature of RAP may reduce its high-temperature performance; when the preheating temperature exceeds 150 °C, the mixtures may fail to meet the specifications for high-temperature deformation resistance;
3. The addition of RAP enhances the load-bearing capacity of the RPAM but weakens its resistance to deformation. The maximum bending strain of the mixtures at different RAP preheating temperatures initially increases and then levels off as the preheating temperature of RAP rises;
4. The water stability of RPAMs is inferior to mixtures with 12% HVA. As the RAP preheating temperature increases, RPAMs' TSR increases. However, when the temperature exceeds 150 °C, the TSR decreases, indicating that excessively high preheating temperatures reduce the water stability of the mixtures;
5. Increasing the RAP content increases the raveling loss of RPAMs. When the RAP content reaches 30%, the raveling loss approaches 15%. The resistance to the raveling of the mixtures does not vary significantly with changes in RAP preheating temperature, and the optimal resistance is observed at a preheating temperature of 150 °C;
6. Under dynamic loading, increased RAP content results in higher dynamic modulus and better high-temperature stability for the RPAM but lower resistance to low-temperature cracking. Increasing the RAP preheating temperature decreases dynamic modulus, enhancing resistance to low-temperature cracking and slightly reducing high-temperature deformation resistance;
7. The present study focuses solely on investigating the experimental performance of RPAMs. In the future, field research on RPAMs will be an important research direction. Based on the findings of this study, it is recommended to incorporate RAP (10–30%) into permeable asphalt pavements on highways or local roads.

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