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Laboratory Evaluation of Cold Patching Asphalt Mixture with Refined–Processed Recycled Asphalt Pavement

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Abstract: This study investigates the effects of two separation processes: traditional separation technology (TST) and refined separation technology (RST), on the characteristics of recycled asphalt pavement (RAP) and the performance of cold patching asphalt mixtures (CPAM). The research evaluates the RAP separation efficiency, focusing on asphalt content and agglomeration degree, and examines the mechanical, high- and low-temperature, moisture susceptibility, anti-stripping, and fatigue performance of CPAM with varying RAP content (0–75%). A key innovation of this study is the exploration of using RST-RAP for CPAM production in comparison to TST-RAP. The findings reveal that the RST process significantly enhances the separation of coarse aggregates from asphalt mortar, leading to improved gradation, reduced agglomeration, and better overall RAP quality compared to TST. Incorporating RAP into CPAM improved the Marshall stability, with RST-RAP showing higher performance gains than TST-RAP, particularly at higher RAP content. Additionally, the dynamic stability, low-temperature cracking resistance, moisture resistance, and fatigue life of CPAM were positively influenced by RST-RAP, with optimal performance achieved at 25–50% RAP content. In contrast, excessive RAP content, especially with TST-RAP, negatively impacted the mixture's properties, leading to higher brittleness and reduced stability. This study highlights the novelty of using RST-RAP to enhance CPAM performance, suggesting that the RST process is more effective in improving CPAM performance. However, RAP content should be carefully controlled (25–50% for RST-RAP and $\leq$25% for TST-RAP) to meet technical standards and ensure optimal durability. These findings provide valuable insights for optimizing RAP utilization in sustainable pavement maintenance practices.

Keywords: asphalt pavement; reclaimed asphalt pavement; cold patching asphalt mixture; traditional separation technology; refined separation technology; road performance

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1. Introduction

Asphalt pavements are susceptible to various types of distress, including potholes, stripping, raveling, and rutting, which occur under prolonged traffic loads and adverse environmental conditions [1–3]. These issues result in a decline in pavement performance and a reduction in service life. Based on production methods and construction temperatures, the asphalt mixtures can be divided into hot mix asphalt (HMA), warm mix asphalt

(WMA) and cold patching asphalt mixtures (CPAMs), which directly influence their maintenance procedures. HMA is produced at high temperatures (150–180 °C) and requires strict weather conditions, making it challenging and economically inefficient for small repairs in cold or wet conditions. WMA, produced at lower temperatures (100–140 °C) with additives, reduces energy consumption and extends the paving season, yet still demands controlled conditions, limiting its immediate use for localized repairs. These distinctions underscore the limitations of traditional HMA and WMA maintenance and motivated the development of cold patching asphalt mixtures (CPAMs) as a more adaptable and sustainable alternative. CPAM consists of aggregate, cold mix asphalt binder, fillers, additives, and solvents [4]. Compared to HMA and WMA, CPAM offers several significant advantages, including the elimination of heating requirements, excellent storage stability, superior workability, enhanced adaptability to diverse climatic conditions, and energy-efficient, environmentally friendly properties [5–7]. Furthermore, CPAM can be quickly put into service after application, minimizing traffic disruptions and reducing the environmental impact of construction. As a result, CPAM has become an ideal material for small-scale and emergency repairs.

There are various types of CPAM, each with significant differences in road performance and quality. Based on the mechanism of strength formation, CPAM can be classified into solvent-based, emulsion-based, and reactive-based [5,8]. The primary distinction between CPAM and HMA lies in the binder used: CPAM employs diluted asphalt, while HMA uses viscous asphalt. However, when CPAM is diluted with solvents, the cohesion of the asphalt binder significantly decreases, leading to insufficient adhesion between the asphalt and aggregate. As a result, under the influence of traffic loads and water erosion, CPAM is prone to issues such as loosening and water damage in the short term. To enhance the adhesion between CPAM asphalt and aggregate, a common approach is to incorporate higher-performance materials, such as additives and more effective diluents, to improve its road performance [9,10]. CPAM technology is well-established and performs excellently in developed countries like the United States and Japan, though it is relatively expensive. A study by Hammel indicated that the cost of CPAM materials is more than five times that of HMA materials [11]. Wang et al. have found that the market price of CPAM ranges from 850 CNY/ton to 2000 CNY/ton in China, which is significantly higher than the price of HMA [12]. Consequently, achieving a balance between material cost and performance remains a key factor limiting the widespread adoption of CPAM.

In recent years, the recycling of recycled asphalt pavement (RAP) has become a major focus in road engineering, driven by growing environmental awareness and the increasing scarcity of resources. Hundreds of millions of tons of RAP per year are generated due to road maintenance. Therefore, expanding recycling methods and improving the utilization of RAP in asphalt mixtures are research hotspots aimed at promoting energy conservation, reducing emissions, and fostering resource recycling in the field of road engineering. Currently, several application methods for RAP in pavement engineering include hot mix recycled asphalt, cold mix recycled asphalt, warm mix asphalt, and recycled base materials. In addition, some studies propose combining cold repair technology with RAP recycling to produce CPAM using RAP [6,7,13,14]. On the one hand, utilizing RAP as aggregate in CPAM can reduce the cost of virgin aggregates. Sun proposed a type of CPAM containing RAP, and demonstrated the feasibility of RAP-CPAM based on road performance tests [13]. Similarly, Yan developed a type of RAP-CPAM suitable for cold regions and analyzed the impact of varying the RAP content on its road performance [8]. The study concluded that an optimal RAP content of 30% provides a balanced road performance. On the other hand, the strong adhesion between the aged asphalt in the RAP and the aggregates helps compensate for the lack of adhesion in current cold patch materials, which leads to premature failure. A study on the diffusion mechanism of diluted asphalt and aged RAP binder found that

the diluent diffuses into the RAP binder, and additives ensure good bonding between the diluent and the exposed surfaces of the RAP [14]. At the same time, the diluents in CPAM can reduce the viscosity and soften the old asphalt in RAP. The long storage period of CPAM allows sufficient time for the diffusion of the unaged and aged asphalts, which improves the utilization of RAP and reduces production costs. A study conducted by Liu indicated that the degree of diffusion increased with extended storage time, which contributed to the restoration of aged asphalt properties [15]. Additionally, the production and application of CPAM are carried out at ambient temperature, effectively preventing secondary aging of the aged asphalt in the RAP [6]. Utilizing RAP to produce CPAM not only leverages the inherent properties of the RAP but also maintains excellent performance characteristics. Therefore, replacing virgin aggregates with RAP in the CPAM holds significant potential.

However, RAP frequently contains extensive agglomeration and pseudo-aggregates, resulting in significant gradation changes, fluctuations in road performance, and poor-quality stability in recycled asphalt mixtures [16,17]. To address these challenges, researchers have proposed RAP-separation technology, which aims to isolate asphalt mastic from coarse aggregates within the pseudo-aggregates. This approach reduces the variability in the RAP and enhances its recycling potential. According to technical principles, it can be subdivided into physical separation, chemical separation, and microbial separation [18–20]. The chemical separation involves dissolving aged asphalt with organic solvents, offering high efficiency [16]. However, its application is limited due to the high cost and toxicity of solvents, which pose potential risks to both the environment and human health. In addition, microbial separation utilizes specific microbial communities to reduce the adhesion between asphalt and aggregates, followed by centrifugal action to achieve separation [21]. This method is environmentally friendly and energy-efficient but remains technically underdeveloped. Currently, physical separation is the most widely employed method. The traditional separation technology (TST) primarily relies on mechanical impact to crush RAP [22]. However, this approach often results in a decline in the mechanical properties of the aggregate and an increased proportion of pseudo-aggregates, ultimately reducing the strength of RAP in asphalt mixtures [23]. To address these issues, a refined separation technology (RST) has been developed in recent years. This method utilizes a specialized centrifugal device to shear and grind the coarse RAP materials, effectively detaching the asphalt mortar adhered to their surfaces [24]. This approach enables precise control over the quality of RAP without causing significant damage to the mechanical properties of the aggregates, thus demonstrating promising potential for future application. Currently, research on the RAP-CPAM primarily focuses on RAP treated by TST, while studies on the application of RST and refined-processed RAP in CPAM have not yet been reported.

Based on this, the objective of this study innovatively investigates the potential of RST in CPAM preparation, introducing a novel approach to enhance RAP utilization. This study explores fully leveraging the unique characteristics of refined-processed RAP to develop low-cost, high-performance CPAM. Extensive experiments were conducted to analyze the effects of RAP processing methods and RAP content on the service performances of CPAM. The findings of this research are expected to provide valuable insights for the widespread application of CPAM and contribute to the sustainable development of road maintenance technologies.

2. Methodology

2.1. Raw Materials

2.1.1. Cold Patching Asphalt (CPA)

(1) Asphalt

The asphalt used in this study was styrene–butadiene–styrene (SBS)-modified asphalt provided by Guizhou Qianhe Logistics Co., Ltd., Guiyang City, China with an SBS content of 4.5%. The technical properties of the SBS-modified asphalt were measured, as shown in Table 1.

Table 1. The technical properties of SBS-modified asphalt.

Indices	5 °C Ductility (cm)	Softening Point (°C)	Penetration (0.1 mm)	Solubility (%)
Value	31	70	56.6	99.97
Standard [25]	≥20	≥60	40~60	≥99

(2) Diluent

The primary role of the diluent is to lower the viscosity of asphalt, thereby improving the workability of the CPAM. Considering the technical characteristics of CPAM, the diluent must demonstrate excellent compatibility with asphalt and additives, maintain a moderate volatilization rate, and possess a high flash point to ensure optimal performance. In this study, 0# diesel was selected as the diluent in the CPA, and its technical specifications were measured, as shown in Table 2.

Table 2. The technical properties of diesel.

Indices	Density (g/cm^3)	Kinematic Viscosity (mm^2/S)	Flash Point (°C)	Solidifying Point (°C)
Value	0.87	7.0	70	−1

(3) Additive

The use of a diluent can result in a reduction in asphalt performance. To mitigate this issue, additives are incorporated into CPA to enhance its adhesion to aggregates, as well as to improve the low-temperature performance and water stability of CPAM. In this study, an amidoamine-based additive was provided by Sichuan Yamei Road Co., Ltd., Chengdu City, China and its technical specifications were provided by the producer, as presented in Table 3.

Table 3. The technical properties of additive.

Indices	Appearance	25 °C Viscosity (cps)	25 °C Relative Density	Flash Point (°C)
Value	Dark brown	300	0.94	>93

(4) CPA Preparation

The CPA was prepared using a JB300-SH high-speed shearing mixer manufactured by Shanghai Huxi Industrial Co., Ltd., Shanghai City, China. The mixture was formulated by uniformly blending asphalt, diluent, and additive in specific proportions: 72% SBS-modified asphalt, 26% 0# diesel as the diluent, and 2% additive. The preparation process involved the following steps. The SBS-modified asphalt was initially heated to 130 °C until it reached a flowable state. Subsequently, the 0# diesel diluent was introduced, and the mixture was stirred at 130 °C for 0.5 h. Finally, the additive was incorporated, and the mixture was continuously stirred for an additional 0.5 h at 130 °C.

2.1.2. Virgin Aggregate

The virgin aggregates used in this study include coarse and fine basalt aggregates, categorized by particle sizes of 0–5 mm, 5–10 mm, and 10–15 mm. All materials met the technical specifications in the Chinese Technical Specification for Construction of Highway Asphalt Pavement (JTG F40-2004) [25].

2.1.3. RAP

The RAP material was sourced from the SMA-13 pavement of a highway in Guizhou Province. After undergoing RST processing, the material was categorized into aggregate fractions with particle sizes of 10–15 mm, 5–10 mm, 3–5 mm, and 0–3 mm, as illustrated in Figure 1. The extraction tests were performed on the RAP aggregates of various particle sizes [26], and the technical properties of both the aged asphalt and the extracted aggregates were evaluated. The results are presented in Tables 4 and 5.

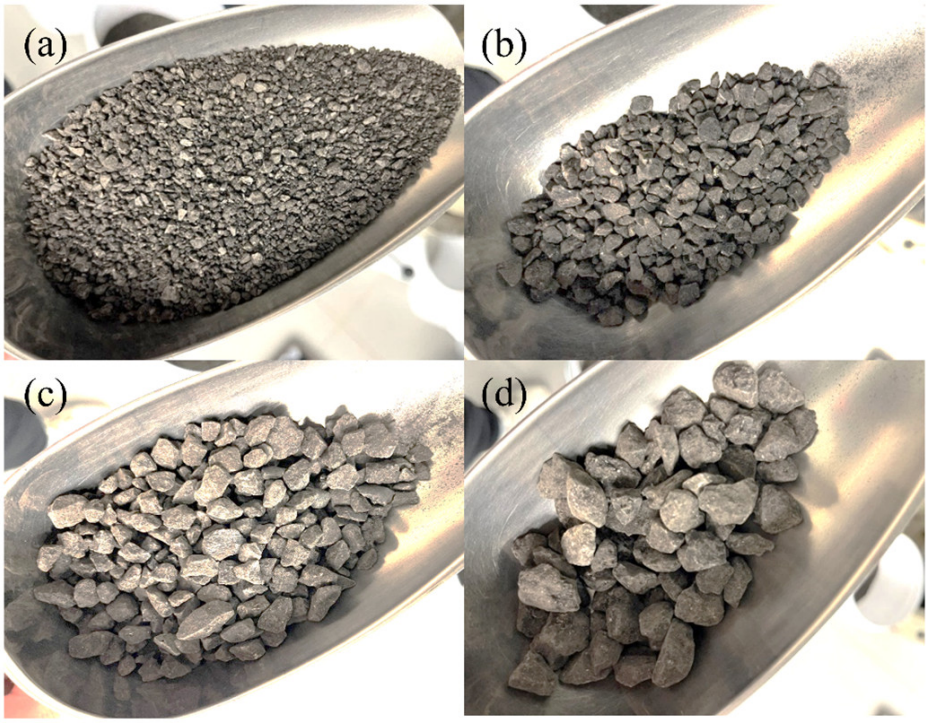


Figure 1. The RAP material after RST processing: (**a**) 0–3 mm; (**b**) 3–5 mm; (**c**) 5–10 mm; (**d**) 10–15 mm.

Table 4. The technical properties of aged asphalt.

Indices	15 °C Ductility (cm)	Softening Point (°C)	25 °C Penetration (0.1 mm)
Value	20.3	61.2	15.8

Table 5. The technical properties of RST-RAP.

Particle Size (mm)	0–3	3–5	5–10	10–15
Water absorption (%)	/	2.92	1.15	0.87
Apparent relative density	2.690	2.716	2.733	2.749

2.2. Principle of RAP Separation Technology

2.2.1. Traditional Separation Technology (TST)

The TST process begins by using a jaw crusher or impact crusher to perform the initial crushing of large RAP materials, reducing their particle size to facilitate subsequent

processing [27]. This is followed by classifying the crushed RAP materials by particle size using a vibrating screen. The process flow is depicted in Figure 2.

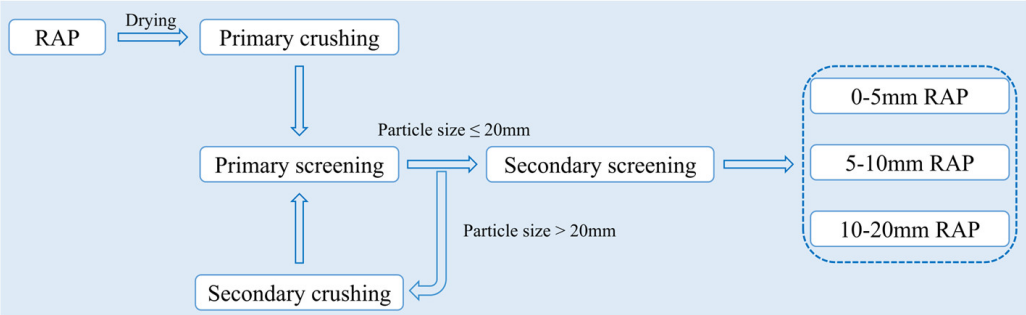


Figure 2. The flowchart of TST.

2.2.2. Refined Separation Technology (RST)

Figure 3a displays a refined separation device, which consists of a feeding system, a centrifugal separation system, a screening system, a dust removal system, and a discharge system, etc. The core principle of RST is to peel off the asphalt mortar adhered to the surface of RAP aggregates through centrifugal separation [28,29]. The separated RAP materials are then classified into 3 to 5 size fractions based on particle size. The detailed process flow is shown in Figure 3b.

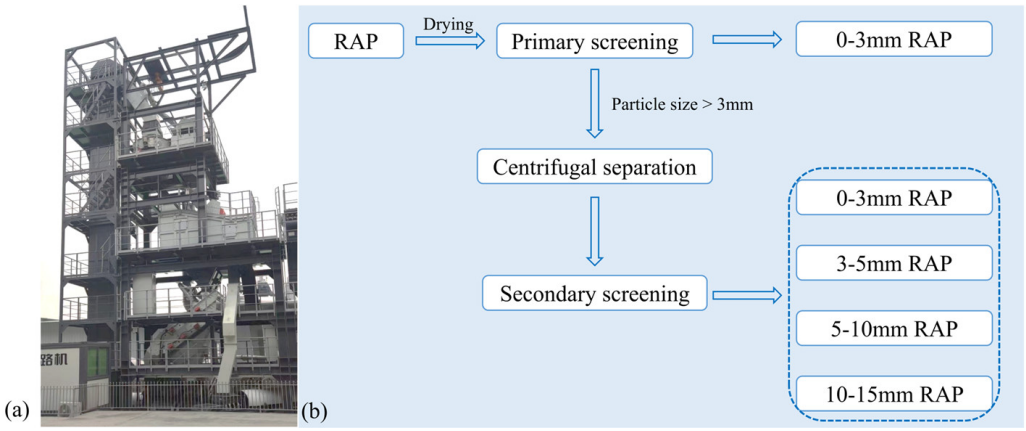


Figure 3. The flowchart of RST: (**a**) refined separation device; (**b**) RAP processing.

2.3. CPAM Preparation and Mix Design

2.3.1. CPAM Preparation

The CPAM production method is based on the preparation process for solvent-based cold patching materials. To ensure uniform mixing, RAP was preheated under optimized conditions established through preliminary experiments. The specific preparation procedure was as follows: (1) the designated amounts of RAP and virgin aggregates were placed in an oven and preheated at 120 °C for 30 min; (2) the freshly prepared CPA, as described in Section 2.1.1, was poured into the mixing pot and blended with the preheated RAP at ambient temperature for 180 s; (3) the preheated new aggregates were then added to the mixing pot, and the mixture was further stirred for 180 s to complete the production of the recycled asphalt cold patching mixture.

2.3.2. CPAM Mix Design

In accordance with the Chinese standard JTG F40-2004 [25], the LB-13 gradation was selected to assess the impact of RAP pretreatment processes and content on the road

performance of CPAM. In this study, RAP was processed using TST and RST, with RAP content levels set at 0%, 25%, 50%, and 75%. The aggregate gradation was designed using a combination of virgin aggregates and RAP materials, as illustrated in Figure 4.

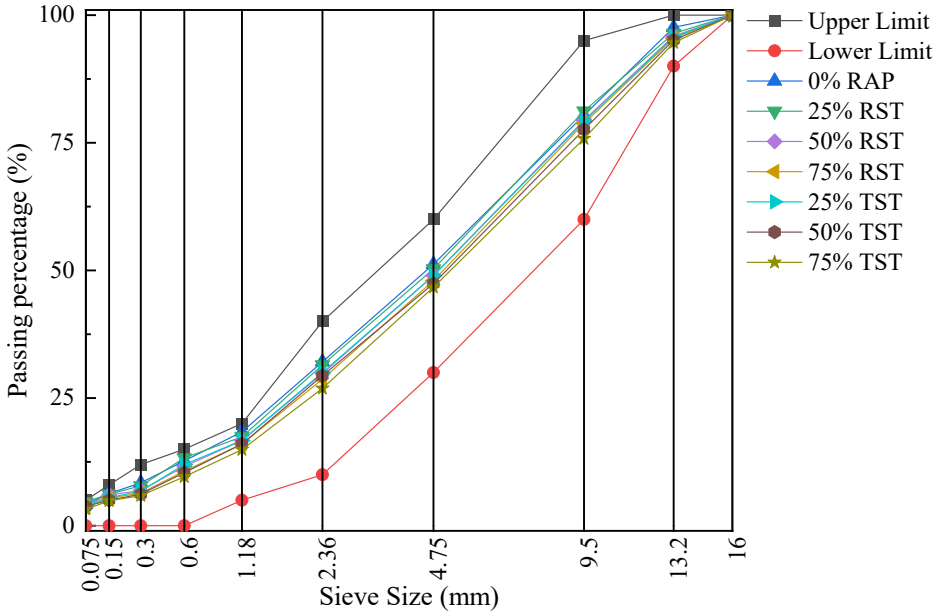


Figure 4. The CPAM gradation.

The Chinese standard JTG F40-2004 recommends a modified Marshall test method for CPAM mix design [25]. CPAM Marshall specimens with varying RAP content were prepared, and their volumetric and mechanical properties were tested. Through analysis of these results, the optimal asphalt content was determined. The mix design results for CPAM are presented in Table 6. For the control group without RAP, the estimated optimal CPA content in CPAM was 5.25%. In contrast, for CPAM mixtures containing RST-RAP or TST-RAP, the estimated optimal CPA content was reduced to 4.57% and 4.46%, respectively. This reduction is attributed to the asphalt film coating the surface of RAP, where aged asphalt may be softened by diesel oil, partially restoring its bonding capability.

Table 6. The mix design results.

Group ID	OAC (%)	VA (%)	VMA (%)	VFA (%)	Theoretical Maximum Specific Gravity
0% RAP	5.25	4.4	18.0	72.2	2.402
25% RST	5.05	4.5	17.9	71.5	2.406
50% RST	4.80	4.4	18.5	71.7	2.401
75% RST	4.57	4.8	18.8	70.7	2.404
25% TST	4.96	4.6	18.3	71.9	2.406
50% TST	4.73	4.8	18.4	72.0	2.409
75% TST	4.46	4.9	19.0	71.2	2.406

2.4. Test Method

2.4.1. RAP Extraction and Screening Test

In accordance with Sections T0722-1993 [26] and T0725-2000 [26] for Chinese Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011) [26], extraction and screening tests were carried out on RAP materials, respectively, to determine both the asphalt–aggregate ratio and the agglomeration degree of RAP materials with different particle sizes.

Based on the study by Wang et al. [30], the agglomeration degree index (ADI) of RAP was chosen to assess the effect of different RAP treatment technologies on the agglomeration degree of RAP materials. The calculation formula is presented in Equation (1).

$$ADI = \frac{\sum_{i=1}^{n} \left| P_i^b - P_i^a \right|}{n} \quad (1)$$

where P_i^a and P_i^b represent the passing percentage of each sieve size of RAP material before and after extraction and sieving, respectively.

2.4.2. CPAM Road Performance Test

(1) Marshall Stability (MS) Test

The MS of CPAM increases as the diluent volatilizes, prompting a two-stage evaluation of its strength: initial MS and cured MS. The initial MS test was performed on φ 101.6 × H 63.5 mm specimens, which were compacted 50 times on both sides using a Marshall compactor.

Subsequently, the Marshall specimens were placed in an oven at 110 °C for 24 h to cure. Following the curing process, the specimens were removed from the oven and subjected to an additional 25 double-sided compaction cycles. They were then left to rest at room temperature for 24 h before demolding. The cured MS was measured in accordance with Section T0709 of the Chinese standard JTG E20-2011 [26].

(2) Wheel Tracking Test

The preliminary test revealed that CPAM contained a high content of diluent in its initial stage, resulting in poor stability of the mixture. As a result, the wheel tracking test showed rapid increases in rutting deformation and significant aggregate detachment from the mixture. To address this issue, an improved wheel tracking test was employed to characterize the high-temperature stability of CPAM. First, CPAM rutting specimens were molded according to the T0719 method outlined in the Chinese standard JTG E20-2011 [26]. The specimens were then placed in a 110 °C oven for 24 h to promote the volatilization of the diluent. After curing, the specimens were subjected to additional compaction cycles on the wheel tracking machine, followed by a 24 h resting period at room temperature. In this study, the test was conducted at temperatures of 40 °C and 60 °C, with a loading pressure of 0.7 MPa and a test duration of 60 min.

(3) Low-Temperature Splitting Test

Asphalt mixtures are susceptible to brittle fracture in low-temperature environments. In accordance with the T0716 method of the Chinese standard JTG E20-2011 [26], the low-temperature performance of the CPAM was evaluated using a low-temperature splitting test. The test was performed at a temperature of −10 °C with a loading rate of 1 mm/min.

(4) Moisture Susceptibility Test

Compared to HMA, the asphalt binder in CPAM exhibits weaker adhesion to aggregates and is more susceptible to water damage due to the presence of diluents. The immersion Marshall stability test and freeze–thaw splitting test were performed on cured Marshall specimens to evaluate the moisture performance of CPAM. The experimental procedures and evaluation metrics were conducted in strict accordance with the T0709 and T0729 methods outlined in the Chinese standard JTG E20-2011 [26].

(5) Cantabro Test

The Cantabro test was conducted to assess the aggregate loss of CPAM under simulated vehicular loading. The test methods and procedures followed the T0733 method

outlined in the Chinese standard JTG E20-2011 [26]. In this study, Marshall specimens were subjected to 300 rotations and impacts in the testing machine, and the anti-stripping performance of CPAM was evaluated based on the mass percentage of material loss from the specimens.

(6) Four-Point Bending Fatigue Test

Asphalt mixtures are susceptible to fatigue cracking under prolonged traffic loading, ultimately leading to performance degradation. In accordance with Section T0739 of the Chinese standard JTG E20-2011 [26], the four-point bending fatigue test is employed to assess the fatigue resistance of asphalt mixtures under cyclic loading. Fatigue life is defined as the number of loading cycles required for the specimen's modulus to attenuate by 50% under specified loading conditions. In this study, the test was conducted at a temperature of 20 °C, with a loading frequency of 10 Hz and a loading strain of 600 με.

3. Results and Discussion

3.1. Effect of Separation Technology on RAP Characteristics

3.1.1. Asphalt Content of RAP Materials

The asphalt content of RAP effectively reflects the processing efficiency of the separation technology on RAP materials. Figure 5 presents the asphalt content results for RAP materials processed by various separation technologies.

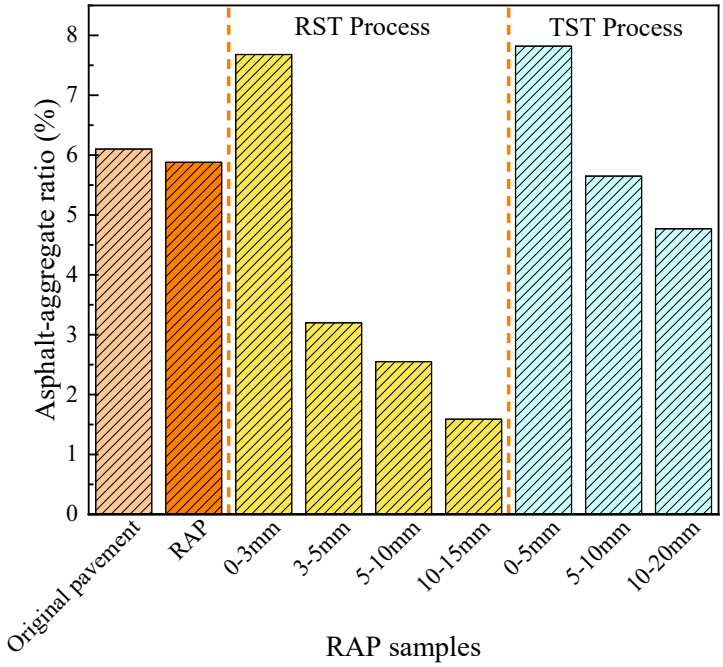


Figure 5. Asphalt content of RAP materials processed by TST and RST.

As illustrated in Figure 5, the asphalt–aggregate ratio of the milled RAP material was measured at 5.88%, reflecting a 0.22% decrease relative to the original pavement. This reduction was attributed to the wear and aging of the asphalt mixture, driven by the combined effects of environmental factors and vehicular traffic. For RAP materials treated using the separation process, the asphalt–aggregate ratio of the RAP aggregates generally decreased as the particle size increased. Notably, compared to the original RAP materials, the change in the asphalt–aggregate ratio of TST-RAP materials was relatively minor, while the difference was more pronounced in RST-RAP materials. This discrepancy arose because the TST process primarily involved simple physical crushing and screening, whereas the RST process used centrifugal force to separate the coarse aggregates from

the asphalt mortar [27]. It was clear that the asphalt–aggregate ratio of the 10–15 mm, 5–10 mm, and 3–5 mm RST-RAP aggregates decreased significantly compared to that of the 0–3 mm RST-RAP aggregate. These results demonstrated that the refined separation technology effectively enhanced the stripping efficiency between coarse aggregates and asphalt mortar [31,32].

3.1.2. Agglomeration Degree of RAP Materials

The agglomeration characteristics of RAP, often referred to as pseudo-particles, significantly contribute to the considerable variability in RAP gradation. This study evaluates the agglomeration degree by comparing the sieve passing percentage difference before and after the extraction of the RAP material. The ADI of the RAP aggregates treated using the different processes is shown in Figure 6.

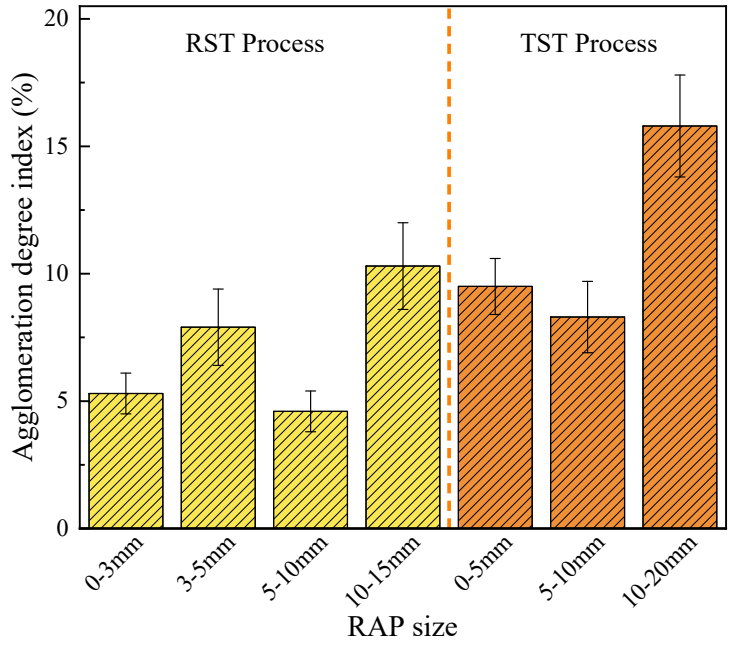


Figure 6. Agglomeration degree of RAP materials processed by TST and RST.

As shown in Figure 6, the average ADI of 0–3 mm and 3–5 mm RST-RAP aggregates was 6.6%, representing a 2.9% reduction compared to the 9.5% ADI of 0–5 mm TST-RAP aggregates. The ADI of 5–10 mm RST-RAP aggregates decreased by 3.7% relative to that of 5–10 mm TST-RAP aggregates. Furthermore, when compared with 10–20 mm RST-RAP aggregates, the ADI of 10–15 mm TST-RAP aggregates decreased by 5.5%. These results indicate that the agglomeration of RAP material treated by TST was significantly reduced, with the separated RAP aggregates being more similar to virgin aggregates [28]. This improvement was primarily attributed to the ability of the PAR process to effectively break up pseudo-coarse particles in coarse RAP through the action of the rotor centrifugal crusher [33]. As a result of friction and impact, the asphalt mortar was peeled off from the surface of the coarse particles. Consequently, compared with RST, the treatment of RAP with TST effectively reduced the gradation variability of RAP, enhancing both the quality and stability of the RAP materials.

3.2. Evaluation of CPAM Road Performance

3.2.1. Mechanical Performance

The Chinese standard JTG F40-2004 recommends using Marshall stability (MS) to evaluate the mechanical properties of CPAM [25]. Figure 7 presents the MS results for different types of CPAM. As illustrated in Figure 7a, the initial MS of CPAM increased

with the incorporation of RAP. Specifically, compared to CPAM without RAP, the initial MS rose by an average of 8.4% for each 25% increment in TST-RAP and by 11.8% for each 25% increment in RST-RAP. This improvement was primarily attributed to the cohesive properties and inherent strength of the aged asphalt and aggregate in RAP, which enhanced the initial stability of the mixture by reinforcing the internal bonding structure [34].

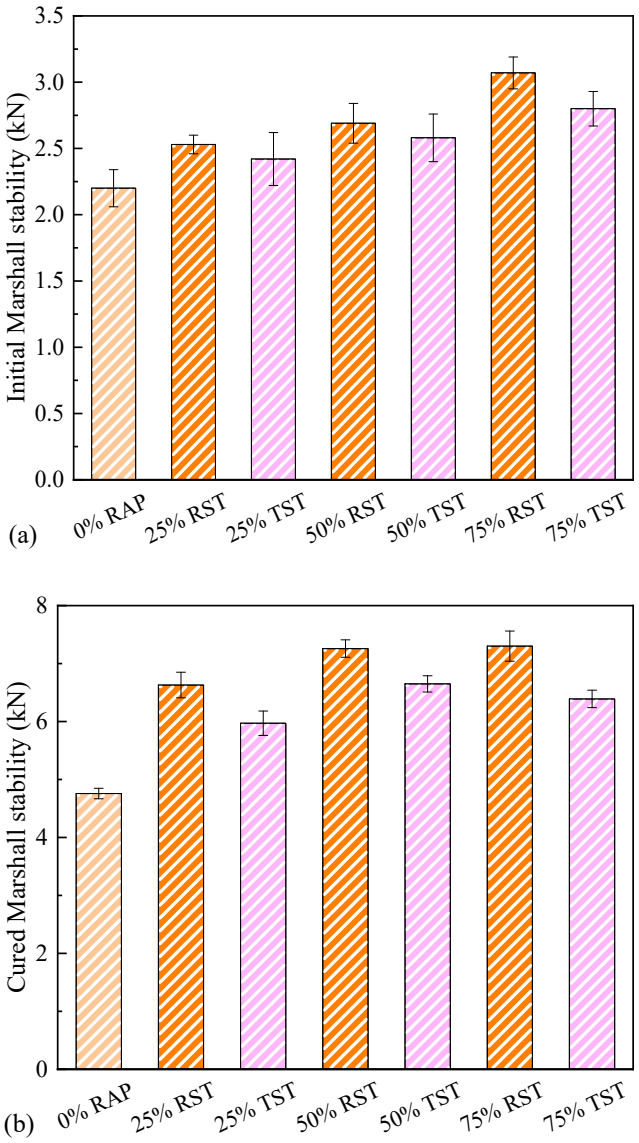


Figure 7. The MS results of different CPAM: (**a**) initial MS; (**b**) cured MS.

As depicted in Figure 7b, the cured MS of CPAM demonstrated a parabolic trend with increasing TST-RAP content, reaching its peak at 50% RAP content. Excessive TST-RAP negatively impacted compaction efficiency and disrupted the uniformity of the internal structure, ultimately leading to a decline in cured MS [35]. In contrast, the cured MS of CPAM incorporating RST-RAP initially increased with RAP content and then stabilized. The RST treatment effectively removed pseudo-coarse particles, refined the aggregate gradation, and promoted a more uniform RAP particle distribution [33]. Additionally, it mitigated the adverse effects of aged asphalt, facilitating better adhesion between RAP and new asphalt. These improvements enhanced the compactability and internal cohesion of the mixture. However, when the RST-RAP content exceeded 50%, the advantages of RST processing reached saturation point, resulting in a plateau in cured MS. The cured MS values of all CPAM mixtures exceeded 3 kN, fully complying with the technical requirements

specified in the Chinese Technical Specification for Cold Patch Asphalt Mixture for Asphalt Pavement (JT/T 972-2015) [36]. This indicated that the mixtures maintained sufficient structural integrity and load-bearing capacity after curing, ensuring their suitability for practical application.

3.2.2. High-Temperature Performance

Figure 8 presents the effects of the RAP treatment process and RAP content on the high-temperature stability of CPAM. The results demonstrate a positive correlation between dynamic stability and RAP content, with limited improvement observed beyond 50% RAP content. This threshold effect can be attributed to two competing mechanisms: while increased RAP content enhances the mixture modulus through additional aged asphalt, it simultaneously compromises the asphalt–aggregate adhesion [37]. Moreover, excessive RAP content (>50%) may induce material heterogeneity within the mixture, ultimately undermining its structural integrity. Comparative analysis revealed that CPAM incorporating RST-RAP exhibited superior performance to its TST-RAP counterpart, showing dynamic stability enhancements of 13.9%, 11.8%, and 9.7% at RAP contents of 25%, 50%, and 75%, respectively. This performance differential stemmed from the RST treatment's dual advantage in optimizing aggregate gradation and strengthening the interfacial bonding between new and aged asphalt [8]. In contrast, TST-treated RAP, characterized by basic physical crushing, contained significant quantities of pseudo-particles and elevated proportions of aged asphalt [22]. These inherent limitations of the TST process resulted in reduced overall stability and diminished high-temperature performance enhancement in CPAM applications. The findings suggest that while RAP content positively influences dynamic stability, the treatment methodology plays a crucial role in determining the final performance characteristics of CPAM, with RST-treated RAP demonstrating clear advantages over traditional TST processing.

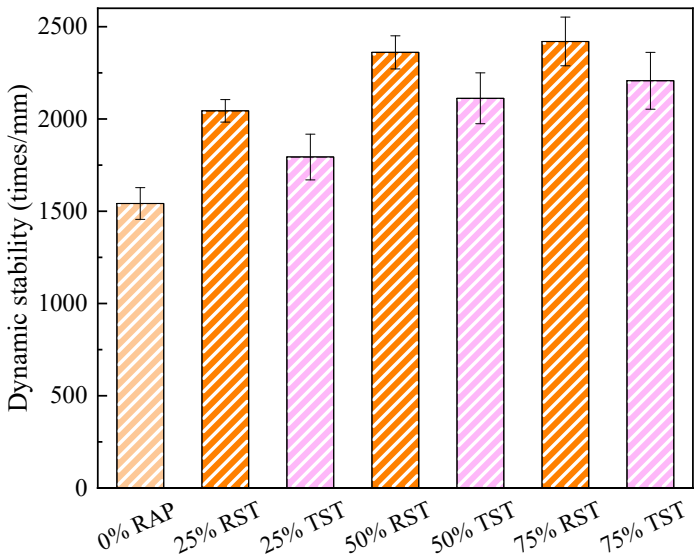


Figure 8. The results of wheel tracking test.

3.2.3. Low-Temperature Performance

Figure 9 illustrates the −10 °C low-temperature splitting strength results of CPAM. For CPAM containing TST-RAP, the splitting strength progressively decreased with increasing RAP content. Specifically, compared to the 0% RAP control group, the incorporation of 25%, 50%, and 75% TST-RAP led to reductions in cracking resistance of 1.5%, 12.8%, and 28.2%, respectively. This performance degradation was primarily attributed to two factors, as evidenced by the analysis of Figures 5 and 6: (1) significant particle agglomeration in

TST-treated RAP materials, and (2) the high content of aged asphalt [28]. In contrast, CPAM containing RST-RAP exhibited a different trend, with splitting strength initially increasing and then decreasing as RAP content rose. The optimal performance was observed at 25% RST-RAP content, showing a 5.8% improvement in cracking resistance compared to the 0% RAP control group. However, when the RST-RAP content exceeded 25%, the low-temperature performance began to deteriorate, characterized by increased material brittleness and reduced crack resistance. Specifically, splitting strength decreased by 4.8% and 16.5% at 50% and 75% RST-RAP contents, respectively. Compared with CPAM containing TST-RAP, the −10 °C splitting strength of CPAM incorporating RST-RAP showed significant improvement. This enhancement was attributed to the RST process, which effectively removed a portion of the aged asphalt, reduced the agglomeration of RAP materials, and promoted stronger bonding between the old and new asphalt [34]. These modifications collectively enhanced the binder's flexibility and deformation capacity under low-temperature conditions.

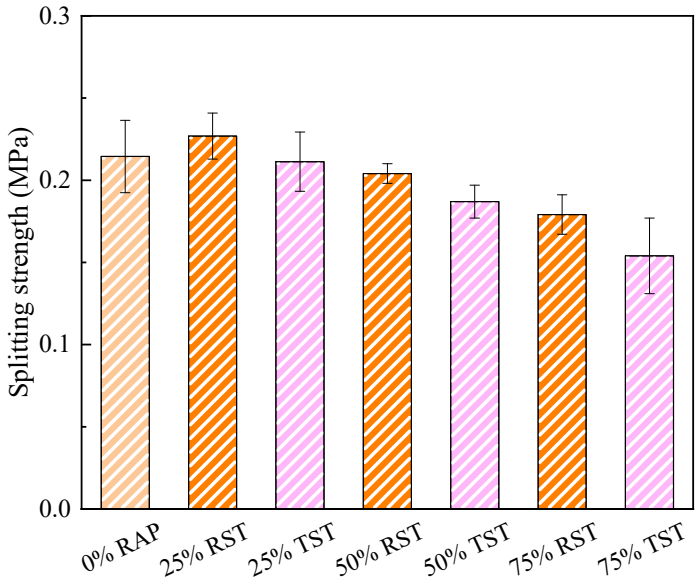


Figure 9. The results of low-temperature splitting test.

3.2.4. Moisture Performance

Figure 10 presents the results of the Marshall stability ratio (MSR) and tensile strength ratio (TSR) for different types of CPAM. As illustrated in Figure 10a, the TSR values exhibited a parabolic trend with increasing RST-RAP content. Specifically, at TST-RAP incorporation rates of 25%, 50%, and 75%, the TSR values changed by 1.3%, 2.0%, and −5.3%, respectively. These results indicate that the use of RST-RAP at appropriate incorporation levels could mitigate the negative impact on the freezing–thawing resistance of CPAM. However, the TSR values decreased with increasing TST-treated RAP content. Compared to the 0% RAP control group, the TSR values of CPAM containing 25%, 50%, and 75% TST-RAP showed reductions of 0.7%, 6.0%, and 14.5%, respectively. This could be attributed to the higher aggregation of TST-treated RAP, which led to the formation of voids and defects in CPAM [27,28]. Under freeze–thaw conditions, these structural weaknesses expanded, exacerbating mixture damage and resulting in significant structural strength degradation.

Figure 10b shows that the MSR value of CPAM decreased with increasing RAP content. Compared to the 0% RAP control group, each 25% increment in TST-RAP resulted in an average MSR reduction of 4.2%, while each 25% increment in RST-RAP led to an average MSR reduction of 2.8%. This behavior can be attributed to the higher internal void content

in RAP-incorporated CPAM, which facilitated moisture infiltration [30]. The ingress of water reduced the adhesive bond between the asphalt and aggregate, particularly in cases of severe asphalt aging. Prolonged exposure to high-temperature water baths further accelerated mixture deterioration, leading to structural strength reduction [21].

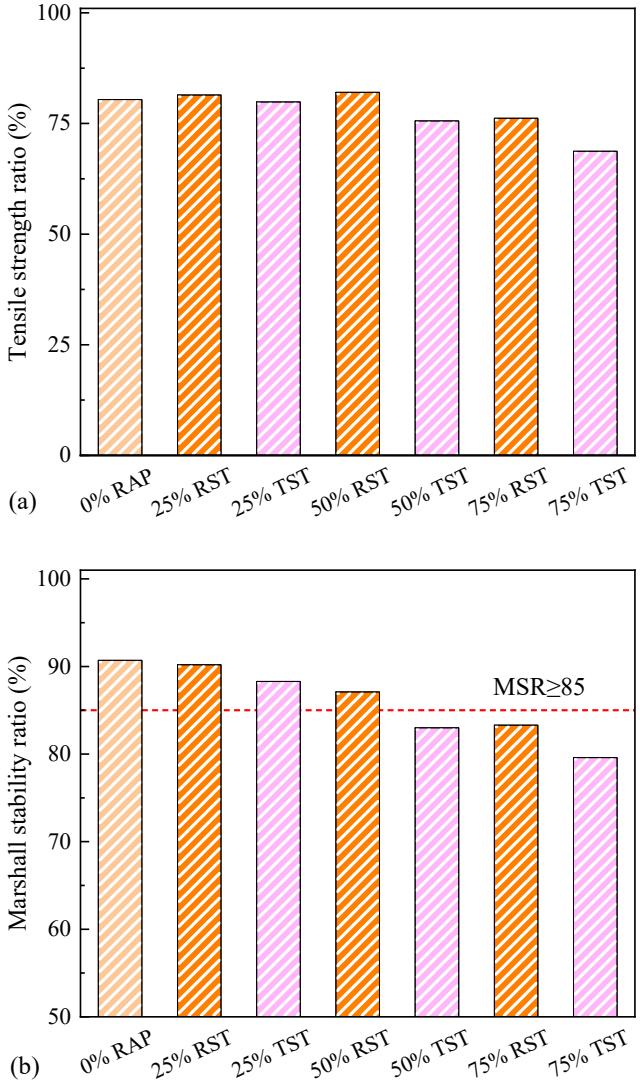


Figure 10. The results of moisture susceptibility test: (**a**) TSR test values; (**b**) MSR test values.

In summary, compared to the TST process, the RST process effectively mitigated the negative impact of RAP materials on the water damage resistance of CPAM. RST-treated RAP particles exhibited surface characteristics more akin to virgin aggregates, resulting in a denser internal structure and improved inter-aggregate bonding in the prepared CPAM, thereby enhancing water stability [31]. It should be noted that the Chinese standard JT/T 972-2015 recommends an MSR value of ≥85% for CPAM [36]. Therefore, the RAP content in CPAM should be strictly controlled to ensure compliance with performance standards.

3.2.5. Anti-Stripping Performance

Figure 11 illustrates the influence of RAP treatment processes and content on the raveling resistance of CPAM. The results demonstrated a general increasing trend in mass loss rate with higher RAP content. Notably, high RAP incorporation (≥50%) significantly elevated the mass loss rate (MLR), leading to deterioration in the anti-stripping performance of CPAM. A comparative analysis revealed significant performance differences between

CPAMs incorporating RST-RAP and TST-RAP. As the RAP content increased from 0% to 70%, the absolute increase in MLR was 3.3% for CPAM with RST-RAP, compared to 6.6% for CPAM with TST-RAP. This performance disparity could be attributed to the inherent characteristics of TST-treated RAP, where the high content of aged asphalt and suboptimal aggregate gradation led to a higher MLR. The advantage of RST-treated RAP in CPAM applications was primarily due to its ability to improve the skeletal structure of the mixture, thereby reducing material loss under external impacts [24].

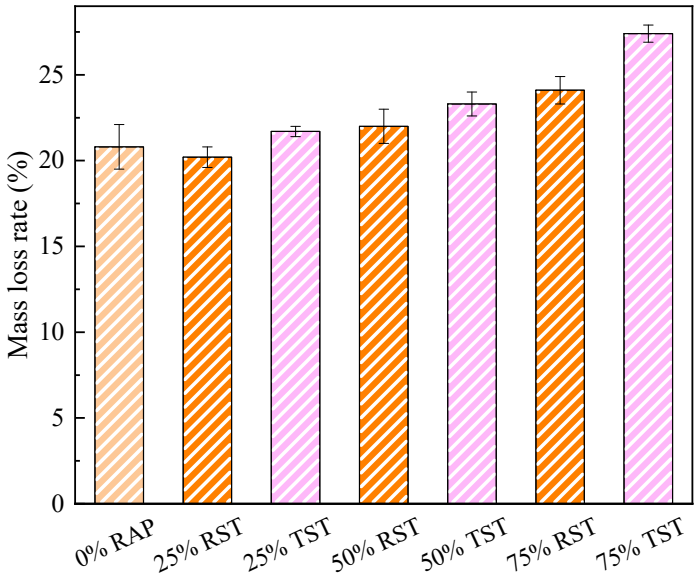


Figure 11. The results of Cantabro test.

3.2.6. Fatigue Performance

Figure 12 presents the fatigue test results for different types of CPAM. As shown in Figure 12a, the initial stiffness modulus (ISM) exhibited a positive correlation with RAP content. Specifically, each 25% increment of RST-RAP resulted in a 14.8% increase in ISM, whereas the same increment of TST-RAP led to a more pronounced 22.2% increase. The observed increase in ISM suggested enhanced deformation resistance of the mixture under loading conditions. However, excessive stiffness could lead to stress concentration, promoting crack propagation and ultimately reducing the mixture's fatigue resistance under repeated loading [38].

Figure 12b shows that the fatigue life of CPAM followed a parabolic trend as RAP content increased. For RST-RAP, the optimal fatigue life occurred at a RAP content of 50%, with an improvement of approximately 20.1%. For TST-RAP, the optimal fatigue life occurred at a RAP content of 25%, with an improvement of about 13.4%. The incorporation of RAP at appropriate levels enhances the stiffness and modulus of asphalt mixtures, effectively absorbing and dispersing stress, thereby reducing microcrack formation and mitigating fatigue damage [39]. However, excessive RAP content (RST-RAP > 50% or TST-RAP > 25%) increases the proportion of aged asphalt in the mixture, resulting in greater brittleness, reduced ductility, and accelerated fatigue failure [29].

Furthermore, a comparative analysis revealed that CPAM containing RST-RAP exhibited at least a 5.3% improvement in fatigue life compared to CPAM with TST-RAP at equivalent RAP contents, with the improvement becoming more significant as RAP content increased. These results demonstrate the superior performance of the RST process in treating RAP materials. Based on the experimental findings, it is recommended to maintain RAP content within the range of 25% to 50% to achieve an optimal balance between durability and resource recycling.

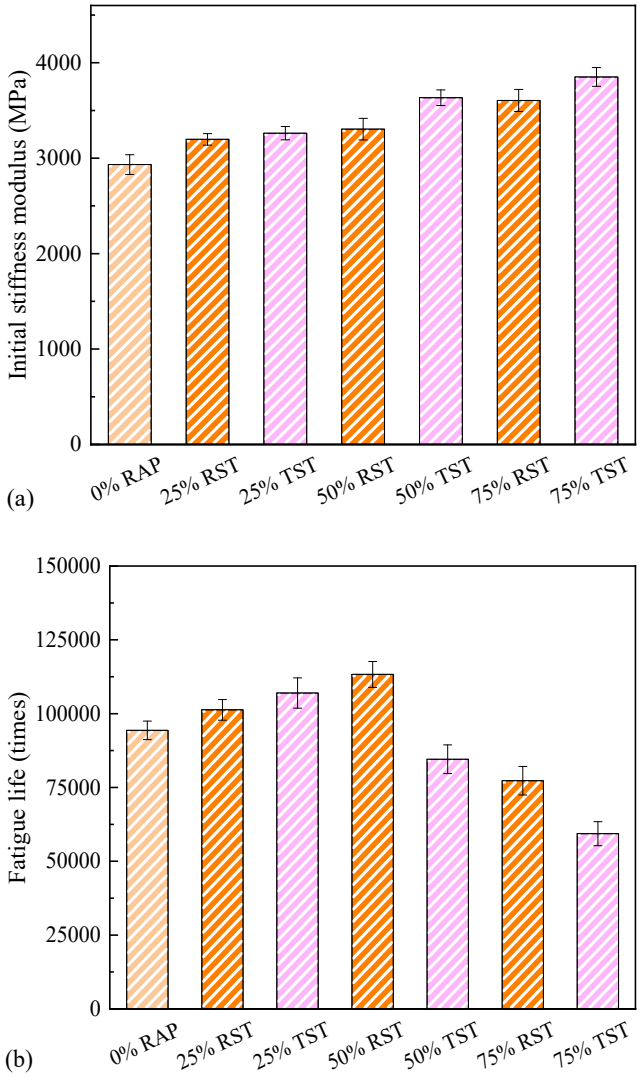


Figure 12. The results of four-point bending fatigue test: (**a**) initial stiffness modulus; (**b**) fatigue life.

4. Conclusions

This study comprehensively evaluates the effects of two separation processes, TST and RST, along with varying RAP content, on the performance of CPAM. The key findings can be summarized as follows:

(1) The RST process improved the separation of coarse aggregates and asphalt mortar, leading to more uniform aggregate distribution and reduced agglomeration. In contrast, the TST process caused higher agglomeration and more asphalt content, negatively affecting RAP properties.

(2) Incorporating RAP improved the initial MS, with TST-RAP and RST-RAP increasing it by 8.4% and 11.8%, respectively. The cured MS for TST-RAP peaked at 50% content, while RST-RAP increased initially and then stabilized due to better gradation and uniform particle distribution.

(3) The dynamic stability of CPAM improved with increasing RAP content, with RST-treated RAP showing better high-temperature stability than TST-treated RAP. For low-temperature cracking resistance, CPAM with RST-RAP initially improved (peaking at 25% RAP) but then decreased, while CPAM with TST-RAP worsened as RAP content increased.

(4) RST-RAP improved freezing–thawing resistance at optimal levels (25–50%), while TST-RAP reduced TSR due to voids and structural weaknesses. Both MSR and TSR

decreased with higher RAP content, but RST-RAP showed slower declines (2.8% per 25% increment) compared to TST-RAP (4.2% per 25% increment), indicating better moisture stability with the RST process.

(5) RST-RAP reduced the MLR value by 50% compared to TST-RAP, demonstrating enhanced raveling resistance due to improved skeletal structure and reduced aged asphalt content.

(6) RST-RAP extended fatigue life, with optimal performance at 50% RAP content (20.1% improvement). TST-RAP peaked at 25% RAP content (13.4% improvement), but excessive RAP content increased brittleness and accelerated fatigue failure.

In conclusion, the RST process outperforms TST in improving the performance of CPAM, especially in mechanical strength, high- and low-temperature stability, moisture resistance, and fatigue life. However, careful control of RAP content (25–50% for RST-RAP and $\leq$25% for TST-RAP) is necessary to achieve optimal performance. These findings offer valuable insights for optimizing RAP use in CPAM, balancing performance with sustainable resource recycling.

This study is limited by its laboratory-scale conditions, the use of a single RAP source, and the absence of economic and environmental assessments for RST processing. Future research should prioritize field validation, investigate RAP from diverse sources, evaluate cost-effectiveness, assess long-term performance, and explore the use of additives to enhance CPAM properties, thereby ensuring its broader applicability in sustainable pavement maintenance.

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Conflicts of Interest: Authors Jing Yan, Hongbo Liao and Xin Yang were employed by the company Guizhou Expressway Industry Co., Ltd. and the company Guizhou Highway Traffic Maintenance Technology Innovation Center. Author Dawei Shi was employed by the Guizhou Expressway Group Co., Ltd. Author Hongwei Lin was employed by the Guangzhou Baiyun International Airport Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

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