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Hot In-Place Recycled Asphalt Mixtures: RAP Analysis, Compaction Characteristics and Field Evaluation

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Abstract: The substantial accumulation of reclaimed asphalt pavement (RAP) poses a pressing issue in road construction. The hot in-place recycling (HIR) technique has garnered widespread attention due to its high recycling rates of RAP and minimal environmental hazards. This study focuses on the RAP analysis, compaction characteristics, and field evaluation of hot in-place recycled asphalt pavements (HIRAP). Firstly, a novel test method of RAP analysis was proposed to evaluate the suitability of RAP. Subsequently, compaction tests reveal the compaction characteristics of hot in-place recycled asphalt mixture (HIRAM). Finally, the field performance of HIRAP was assessed. The research findings indicate that the RAP analysis method can accurately characterize the status of RAP. Increasing the RAP temperature improves the compaction characteristics of HIRAM. The field tests show that using HIR technology improves the performance of the pavement, in particular with a compaction of 99.7%. This study will establish a theoretical foundation for further promoting the HIR technique.

Keywords: hot in-place recycling; reclaimed asphalt pavement; compaction characteristics; volume of voids; field evaluation

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1. Introduction

The construction of asphalt pavements entails a substantial consumption of natural resources. A sizable amount of recovered asphalt pavement (RAP) is produced when road service life ends. RAP recycling is a primary objective for researchers in the road industry. As an environmentally friendly approach capable of fully harnessing RAP, the hot recycling technique has garnered widespread attention [1–3]. This technology can be categorized into hot central plant recycling and hot in-place recycling (HIR) [4–6]. Among these, the HIR technique distinguishes itself with advantages such as material transport cost savings, high utilization of RAP materials, optimization of the original pavement gradation, simplified construction, and minimal disruption to traffic [7–9]. HIR is well-suited for intersections, sloping pavement, and other heavily trafficked pavement. Compared to the hot central plant recycling technique, the HIR technique started later, with lower technological maturity and adoption levels [10]. A white paper published by the International Energy Agency in 1997 noted that while several countries have adopted the HIR technique, only a few have a high level of promotion, and it is less commonly used for highways [11–13]. However, due to its advantages, such as the high recycling rates of RAP materials and minimal impact on traffic, HIR has gradually gained attention in European and American countries. In recent years, countries like Germany, the United States, Finland, Japan, and Canada have developed well-performing HIR equipment, further advancing the application of this technique [14–16]. As sustainable development becomes ingrained, hot in-place recycled asphalt pavement (HIRAP) is poised for widespread development and significantly promotes sequestering carbon in road construction [17–19].

With the continuous increase in research and case studies on HIRAP, many issues related to this technique have been identified and addressed [20–22]. There is controversy surrounding three aspects of applying the HIR technique: RAP analysis, compaction characteristics and field evaluation [23–25]. Firstly, RAP performance is essential for the HIR technique. Some research indicates that the road performance of HIRAM cannot be improved by adding rejuvenators when the performance of RAP decreases [26,27]. Therefore, most studies emphasize that RAP analysis is necessary for HIR [28–30]. The current RAP analysis test is quite cumbersome, and many design and construction companies lack the necessary test equipment, leading to inaccurate results. Therefore, finding a more convenient and easily promotable RAP analysis method is a prerequisite for developing HIR technique. Secondly, limitations like RAP temperature and mechanical equipment restrict the mixture temperature from rising too high during the HIRAM compaction process, thereby preserving the compaction's effectiveness [22,31,32]. It is found that the compaction effectiveness of HIR is a crucial factor influencing the occurrence of early pavement diseases [33]. Unlike conventional hot mix asphalt mixtures, HIRAM may not achieve the required compaction degree after a brief mixing process in the recycling process. This is particularly true due to the lower heating temperature of RAP, resulting in a lower mixing temperature that affects the compaction effectiveness of the asphalt pavements [34–36]. Therefore, it is necessary to study the compaction characteristics of asphalt mixtures under different compaction times, temperatures and other conditions. Finally, most current research on HIRAM is conducted in laboratories, with minimal validation based on field performance [37–39]. Since HIR technology involves the entire process of field mixing, laying, and compacting, studying the field performance of hot recycled asphalt mixtures would better align with the characteristics of HIR [40–42]. In particular, the performance of asphalt pavements is compared before and after using HIR technology.

This study addresses the issues above by proposing a novel method for evaluating RAP for the HIR technique. It analyzes the impact of various factors on the compaction characteristics of HIRAM. Based on field test results, it validates the pavement performance of HIRAM. A comprehensive assessment of the applicability of HIRAM is conducted using RAP analysis, compaction characteristics, and field evaluation.

2. Objective and Research Approach

This study primarily focused on the RAP analysis, compaction characteristics, and field evaluation of HIRAM. The research objectives outlined were as follows:

- To propose a novel RAP analysis method, which assesses the applicability of RAP based on variations in voids during the compaction.
- To investigate the compaction characteristics of HIRAM under various compaction parameters.
- The conduct field testing of asphalt pavements before and after recycling to validate the performance advantages of HIR.

We achieved the above research objectives through laboratory experiments and field tests. Figure 1 summarizes the research methods employed in this study. Initially, this study investigated the impact of different compaction parameters on the volume of voids (VV) of RAP. Compaction tests were conducted on RAP with varying degrees of aging and bitumen content, proposing RAP evaluation indexes. Subsequently, the mixing procedure's impact on HIRAM's compaction properties was examined in a mix design for HIRAM. Finally, based on the proposed RAP evaluation method, this study assessed the applicability of HIR for the project and the field performance of HIRAP. The abbreviations and parameters mentioned are provided in Appendix A.

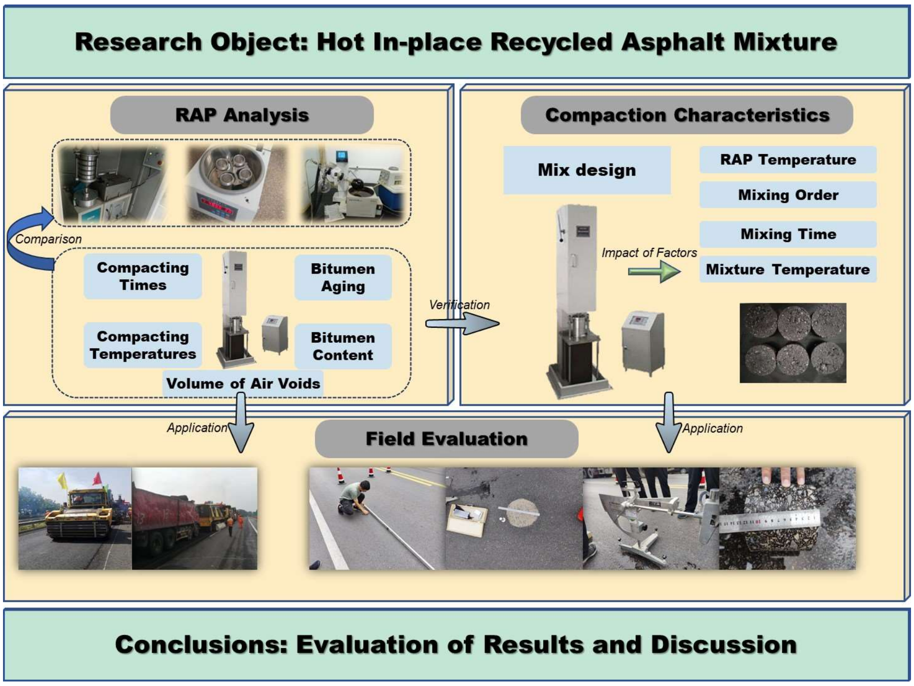


Figure 1. Research approach.

3. Materials and Methods

3.1. Raw Materials

3.1.1. RAP

The reclaimed bitumen extracted by RAP was tested. The main performance indexes are shown in Table 1. The reclaimed bitumen hardened and could not meet the index requirement. It was necessary to add fresh bitumen and a rejuvenator for the reclaimed bitumen.

Table 1. Technical index of reclaimed bitumen.

Technical Index	Unit	Measured Value	Index Requirement
Penetration (25 °C, 5 s, 100 g)	0.1 mm	25.5	60~80
Ductility (10 °C)	cm	4.2	>25
Softening point (ring-and-ball method)	°C	64.1	>46
Bitumen content in RAP	%	5.6	-

3.1.2. SBS Modified Bitumen

The fresh bitumen used in this study was styrene-butadiene-styrene (SBS)-modified bitumen, and its technical index is detailed in Table 2.

Table 2. Technical index of SBS-modified bitumen.

Technical Index	Unit	Measured Value	Index Requirement
Penetration (25 °C, 5 s, 100 g)	0.1 mm	58.8	40~60
Ductility at 5 °C (cm)	cm	30	≥20
Softening point (°C)	°C	70	≥60

3.1.3. Rejuvenator

The commercial R1 rejuvenator was utilized, and its technical index, as presented in Table 3, met the requirements of JTG E20-2011 [43].

Table 3. Technical index of the R1 rejuvenator.

Technical Index	Unit	Measured Value	Index Requirement
Dynamic viscosity at 60 °C	mm^2/s	251	176~900
Flashing point	°C	242	>220
Saturates	%	28	≤30
Aromatics	%	58	Measured
Mass variation before and after aging	%	2.6	≤3

3.1.4. Mineral Aggregates

Limestone aggregates were utilized in grades 10–15 mm, 5–10 mm, and 0–3 mm. The specific indexes are shown in Table 4.

Table 4. Technical index of mineral aggregates.

Technical Index	Unit	Measured Value			Index Requirement
		10–15 mm	5–10 mm	0–3 mm	
Bulk density	g/cm^3	2.75	2.84	2.69	Measured
Apparent density	g/cm^3	2.83	2.88	2.79	Measured
Needle flake content	%	10.13	12.76	-	≤15
Crush value	%	20.88	-	-	≤26
Water absorption	%	1.13	0.92	1.19	Measured
Wear value	%	21.98	-	-	≤28
Sand equivalent	%	-	-	72.69	≥60
Angularity	s	-	-	33.62	≥30

3.1.5. Gradation Design

HIRAM adopted SMA-13, and the designed gradation is shown in Table 5.

Table 5. Gradation design of SMA-13.

Sieve Opening (mm)	Gradation Composition (%)	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
10–15 mm	9	100.0	94.5	16.1	1.8	1.8	1.8	1.8	1.8	1.8	1.7
5–10 mm	9	100.0	100.0	96.9	12.8	0	0	0	0	0	0
RAP	80	99.7	95.5	65.8	34	27.8	23	18.6	14.4	12.8	10.2
Mineral powder	2	100.0	100.0	100.0	100.0	100.0	100.0	99.8	97.8	92.7	79.1
Lower limit	-	100.0	90.0	50.0	20.0	15.0	14.0	12.0	10.0	9.0	8.0
Upper limit	-	100.0	100.0	75.0	34.0	26.0	24.0	20.0	16.0	15.0	12.0
Gradation median	-	100.0	95.0	62.5	27.0	20.5	19.0	16.0	13.0	12.0	10.0
Composite gradation	100	99.8	95.9	64.8	30.5	24.4	20.6	17.0	13.6	12.3	9.9

3.2. Experimental Methods

3.2.1. RAP Analysis Method

(1) Conventional method

The experimental process of the conventional method is illustrated in Figure 2. The steps were as follows:

Step 1. Place RAP into an automatic extractor to separate reclaimed bitumen from aggregates, obtaining reclaimed aggregates and a trichloroethylene solution containing bitumen. Measure the technical index of the reclaimed aggregates.

Step 2. Place the trichloroethylene solution containing bitumen into a centrifuge to separate residual mineral powder, obtaining a pure trichloroethylene solution containing bitumen.

Step 3. Use a rotary evaporator to recover the reclaimed bitumen from the trichloroethylene solution and measure the technical index of the reclaimed bitumen. Based on the technical index of the reclaimed bitumen and aggregates, assess the degree of aging of RAP and whether it was suitable for HIR.

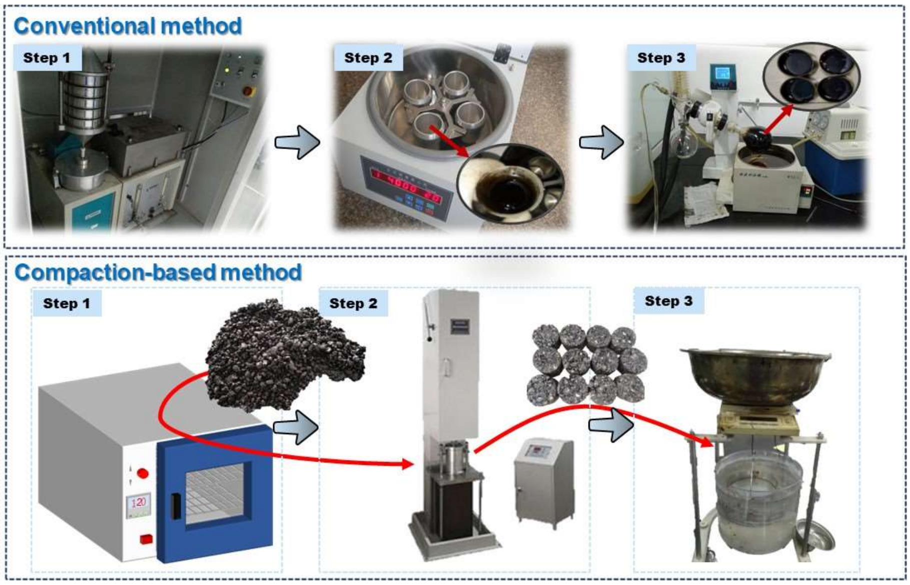


Figure 2. RAP analysis method.

(2) Compaction-based Method

A Marshall compactor was utilized to compact RAP and determine the *VV* of the specimens. The specific experimental process is shown in Figure 2. The experimental steps were as follows:

Step 1. Place RAP in an oven and heat at 110~120 °C for 2 h.

Step 2. Remove the RAP after heating and prepare Marshall specimens according to JTG E20-2011.

Step 3. Determine the *VV* and other relevant indexes of the specimens according to JTG E20-2011.

3.2.2. Compaction Characteristics Test

(1) Marshall compaction test

Marshall specimens were prepared for both RAP and HIRAM. As indicated in Tables 6 and 7, variables such as the compaction time, temperature, bitumen aging, binder content, mixing time, mixture temperature, and mixing order are considered [44–46]. The mixing order is illustrated in Figure 3, and bitumen aging was conducted through the rolling thin film oven test (RTFOT) and a pressure aging vessel (PAV), following the procedures outlined in JTG E20-2011.

Table 6. Compaction parameters for RAP.

Compaction Times (s)	Compaction Temperature (°C)	Bitumen Aging	binder Content (%)
25	100	Not aged	3
50	120	RTFOT	4
75	140	RTFOT + PAV10h	5
100	160	RTFOT + PAV20h	6
125	180	RTFOT + PAV30h	-

Table 7. Compaction parameters for HIRAM.

Mixing Time (s)	RAP Temperature (°C)	Fresh Asphalt Mixtures Temperature (°C)	Mixing Order
30	120	120	A
90	140	160	B
150	160	200	C
210	-	-	-
270	-	-	-

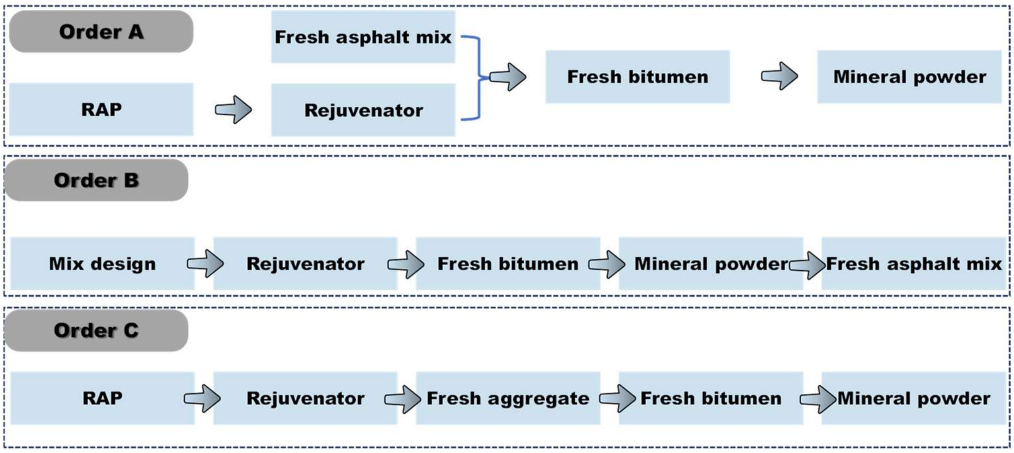


Figure 3. Mixing order of HIRAM.

(2) Volume index determination method

Mixture density tests were conducted on the compacted Marshall specimens of RAP and HIRAM according to the Chinese standards. We calculated the *VV*, the voids in mineral aggregate (*VMA*) and the voids filled with asphalt (*VFA*) based on the test results as shown in Equations (1)–(4).

$$VV = \left(1 - \frac{\gamma_f}{\gamma_t}\right) \times 100 \tag{1}$$

where *VV* is the volume of voids of the specimen, %, γ_t is the theoretical maximum relative density of the asphalt mixture, and γ_f is the relative density of the specimen by bulk volume, typically measured using the dry method. When the specimen's water absorption $S_a > 2\%$, the wax-sealing method is recommended; when the regulations permit the water submersion method to be used, the apparent relative density can be used as a substitute.

$$VMA = \left(1 - \frac{\gamma_f}{\gamma_{\text{sb}}} \times \frac{P_s}{100}\right) \times 100 \tag{2}$$

$$VFA = \frac{VMA - VV}{VMA} \times 100 \tag{3}$$

$$P_s = 100 - P_b \tag{4}$$

where *VV* is volume of voids of the asphalt mixture specimen, %, *VMA* represents the voids in mineral aggregate in the asphalt mixture specimen, %, *VFA* represents the voids filled with asphalt in the asphalt mixture specimen, %, P_s is the percentage of each aggregate type to the total mass of the asphalt mixture, %, and γ_{sb} is synthetic bulk volume relative density of the aggregates.

3.2.3. Field Test

(1) Roughness

The 3 m straightedge test for HIRAP was conducted according to the JTG 3450-2019 [47]. We utilized the 3 m straightedge roughness and the international roughness index (*IRI*) to represent the roughness of the HIRAP.

(2) Anti-skid performance

① Texture depth

The surface texture depth test for HIRAP was conducted according to JTG 3450-2019. The calculation formula for texture depth (*TD*) is shown in Equation (5).

$$TD = \frac{1000 \times V}{\pi \times D^2/4} \tag{5}$$

where V is the volume of sand, cm^3, and D is the average diameter of spread sand, mm.

② Friction coefficient

A lateral force testing system was used to determine the HIRAP's friction coefficient according to JTG 3450-2019. A pendulum-type friction coefficient measuring instrument was used according to JTG 3450-2019. The calculation formula is shown in Equation (6).

$$BPN_{20} = BPN_T + \Delta BPN \tag{6}$$

where BPN_{20} is the pendulum value converted to the standard temperature of 20 °C, BPN_T is the pendulum value measured at the pavement temperature, and ΔBPN is the temperature correction value.

(3) Water permeability

The permeability coefficient test for HIRAP was conducted according to JTG 3450-2019. The calculation formula is shown in Equation (7).

$$C_W = \frac{V_2 - V_1}{t_2 - t_1} \times 60 \tag{7}$$

where C_W is the water permeability coefficient, mL/min, V_1 is the water quantity during the first timing, mL, V_2 is the water quantity during the second timing, mL, t_2 is the time of the first timing, s, and t_1 is the time of the second timing, s.

(4) Degree of compaction

The pavement compactness test for HIRAP was conducted using core drilling according to JTG 3450-2019.

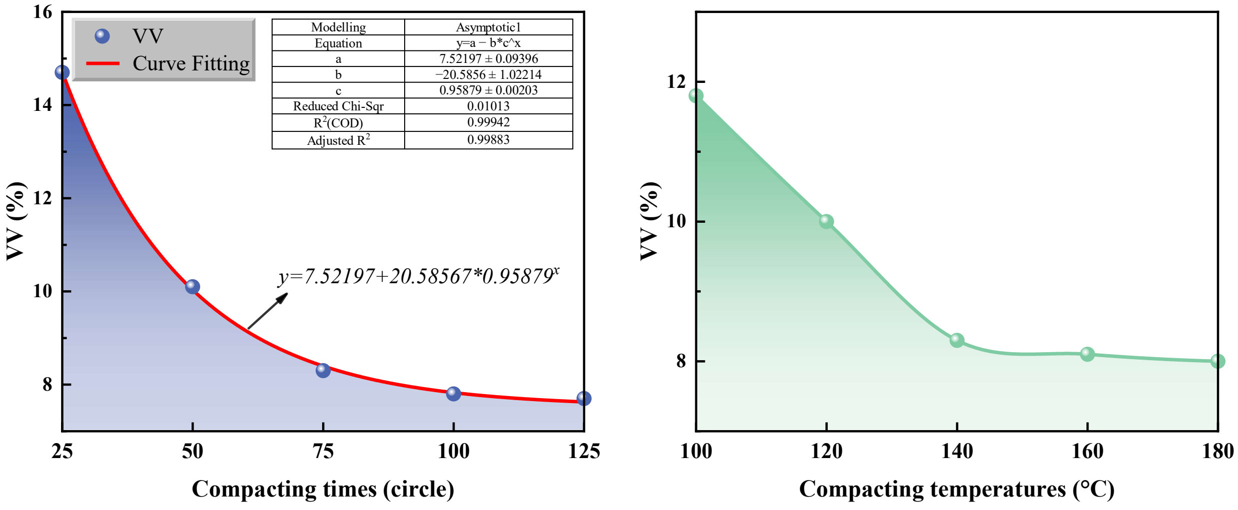
4. Results and Discussion

4.1. RAP Analysis

4.1.1. Impact of Compaction Parameters

(1) Compaction time

To better analyze the relationship between compaction times and RAP compaction, the *VV* of Marshall specimens was calculated for different compaction times. As shown in Figure 4a, the *VV* of RAP gradually decreases with the increase in compaction times. The exponential function fitting using the Asymptotic1 model reveals a good relationship between compaction times and *VV*. As the compaction times increase from 25 to 50, the *VV* of RAP decreases by 31.3% and then decreases by 17.8%, 6.0%, and 1.2% for each additional 25 compaction times. Because RAP particles are mutually squeezed, the compactness increases and the *VV* is reduced during compaction. The mixture is gradually densified with increased compaction, forming a stable interlocking structure between aggregates. Because aggregates are not crushed, the impact of compaction on the mixture's *VV* decreases significantly. The increase in compaction times has a limited impact on the *VV* of RAP, and the contribution to *VV* changes is relatively low for excessively high compaction times. During the experiments, it was observed that the surface of the formed RAP had already experienced aggregate crushing, indicating that excessively increasing the compaction times is not suitable as the primary method to increase the *VV*, and merely increasing compaction is not the primary approach to improve the compaction feasibility of RAP. Considering the changing pattern of *VV* and its compatibility with actual engineering, double-sided compaction 75 times was selected as the evaluation process parameter.



Modelling	Asymptotic1
Equation	y=a − b*c^x
a	7.52197 ± 0.09396
b	−20.5856 ± 1.02214
c	0.95879 ± 0.00203
Reduced Chi-Sqr	0.01013
R^2(COD)	0.99942
Adjusted R^2	0.99883

(**a**) (**b**)

Figure 4. The impact of compaction parameters on the *VV* of RAP: (**a**) compaction times and (**b**) compaction temperature.

(2) Compaction temperature

Temperature is a crucial factor influencing the quality of HIRAP [48–50]. Figure 4b shows the rate of change in *VV* of RAP. There is no apparent fitting relationship between compaction temperature and *VV*, but it is easy to see that the compaction temperature of 140 °C is the more critical parameter. *VV* is highest between 100 °C and 140 °C, with the minimum slope observed. As the compaction temperature exceeds 140 °C, the reduction in *VV* slows down, particularly in the temperature range of 160 °C to 180 °C, where the *VV* decreases only from 8.1% to 8.0%, a marginal 0.1% decrease. Overall, the *VV* of RAP exhibits a decreasing trend with increasing temperature. Analysis indicates that at a compaction temperature of 100 °C, higher asphalt viscosity hinders the compaction and re-arrangement of the mixture particles, requiring the mixture to overcome greater internal friction. With increasing temperature, the reduced asphalt viscosity contributes positively to overcoming internal friction, aiding in the re-arrangement of the mixture particles. Despite the lubricating effect of bitumen on aggregates with rising temperature, the aging of binder in RAP diminishes its lubricating effectiveness. When the compaction temperature is excessively high, the void size remains above 8%, exhibiting a converging trend, indicating a limit to the impact of temperature on *VV*. Simply elevating the compaction temperature does not significantly improve the compaction effect on the mixture, especially when the compaction temperature exceeds 160 °C. Moreover, excessively high temperatures exacerbate the secondary aging of binder in RAP, increasing the bitumen's stiffness modulus and making it more resistant to compaction. In conclusion, it is recommended to set the compaction temperature for RAP from 140 °C to 150 °C.

4.1.2. Evaluation Index of the RAP Analysis Method

(1) Effect of bitumen aging on *VV*

The aging degree of bitumen in RAP significantly impacts the compaction quality of the recycled pavement [51,52]. The index for aged bitumen is presented in Table 8.

Table 8. Technical index of aged bitumen.

Technical Index	1	2	3	4	5
Type of aging	Original sample	RTFOT	RTFOT + PAV10h	RTFOT + PAV20h	RTFOT + PAV30h
Penetration (25 °C, 5 s, 100 g) (0.1 mm)	70.2	52.3	34.8	20.5	15.8
Softening point (ring-and-ball method) (°C)	51.4	56.4	65.9	72.3	75.1
Ductility (5 cm/min,15 °C) (cm)	>100	94.5	10.6	3.5	brittle failure

Different aging levels of bitumen are mixed with recycled aggregates, and then Marshall specimens are formed to measure indexes such as *VV*, *VMA* and *VFA*. The influence of bitumen aging on RAP performance is illustrated in Figure 5. The *VV* of RAP continually increases with the deepening of bitumen aging. The highest increase in porosity is observed when RAP is mixed with bitumen aged by RTFOT, reaching approximately 43%. Conversely, the lowest increase in porosity is observed when RAP is mixed with bitumen aged by RTFOT + PAV30h, at approximately 1%. This indicates that bitumen aging significantly impacts the *VV* of RAP. After bitumen undergoes RTFOT + 30h aging, the *VV* of RAP increases by about 85% compared to simulated RAP without aging. At the same time, as the degree of aging increases, *VMA* shows an upward trend and *VFA* shows a downward trend. When the aging degree reaches RTFOT + 20h, it remains stable. Bitumen aged by RTFOT + 30h is equivalent to the aged state of asphalt pavement after 7~12 years. Severe bitumen aging poses a significant hindrance to the compaction of RAP, thereby affecting the *VV* of RAP after formation [53].

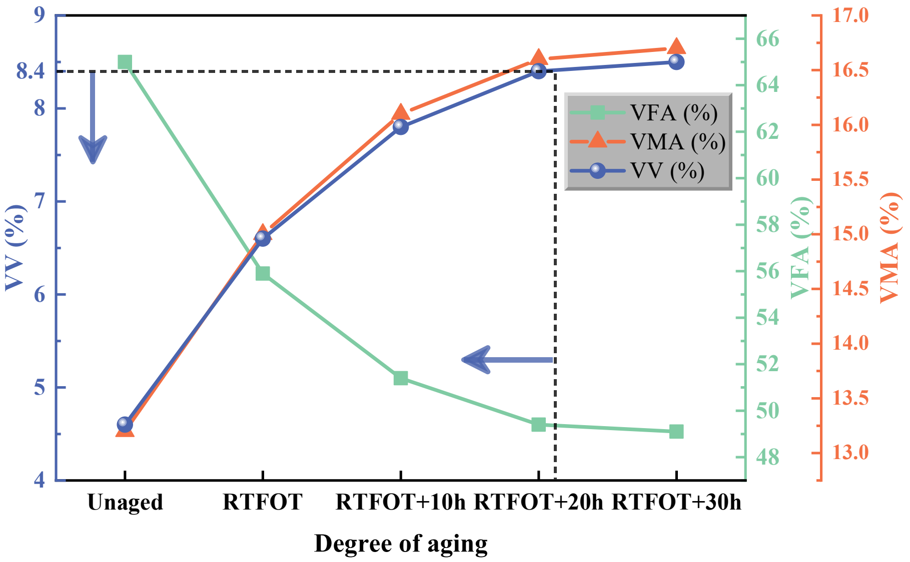


Figure 5. The influence of bitumen aging on the volumetric index.

(2) Effect of binder content on *VV*

The impact of different binder contents on the compaction characteristics of RAP is illustrated in Figure 6. As the bitumen content increases, the *VV* of RAP shows a decreasing trend. With each 1% increase in binder content, the *VV* decreases by approximately 26%. A turning point occurs when the bitumen content reaches 5%, where the reduction in *VV* slows down with further increases in binder content. Ultimately, the *VV* of RAP is approximately 4.5% when the binder content is 6%. The main reason for this phenomenon is that at lower binder contents, there is insufficient asphalt to fill the voids between aggregates, resulting in a higher *VV* that is more challenging to compact. Moreover, as the bitumen content increases, *VMA* also shows a downward trend, but *VFA* shows an upward trend. This indicates that the added asphalt fills more voids between the aggregates, which helps to improve the compactness and performance of the mixture. The experiments observed that when the binder content is less than 3%, particle detachment occurs during the demolding stage of the Marshall test, preventing the formation of compacted specimens, and the *VV* cannot be accurately measured. This indirectly indicates the difficulty in compaction. With increased bitumen content, the voids between aggregates are filled with bitumen, decreasing *VV* and making compaction easier. However, since the asphalt in the mixture is aged, the magnitude of the change in *VV* diminishes.

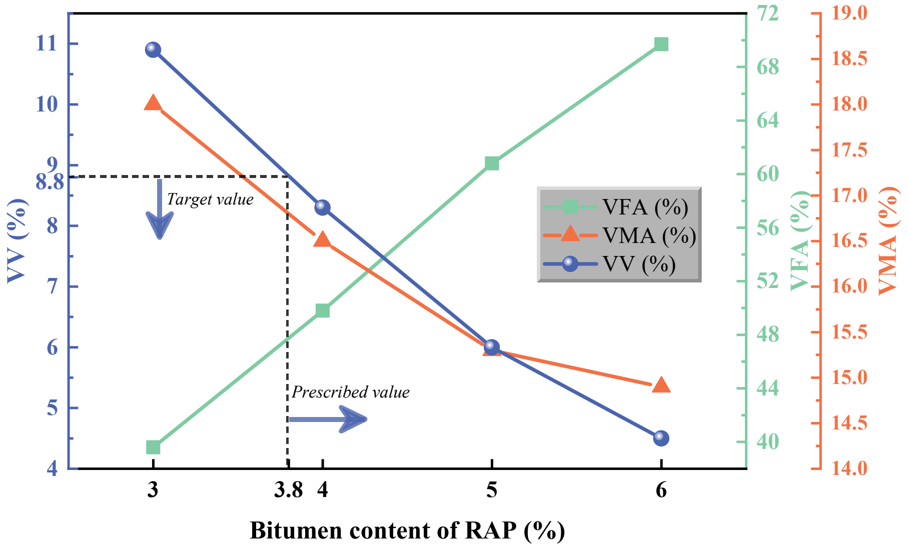


Figure 6. The influence of bitumen content on the volumetric index.

(3) Establishing the specified range for the control of *VV* index

The degree of bitumen aging and binder content are critical factors determining the viability of RAP for recycling [54–56]. Conventional methods rely on specified criteria, setting the penetration of aged bitumen of not less than 20 and a binder content of not less than 3.8% as benchmarks for assessment. According to Table 8, the *VV* of RAP is 8.4% for aged bitumen with a penetration of 20.5 and 8.5% for a needle penetration of 15.5. Using interpolation, the corresponding *VV* of RAP for a penetration of 20 is calculated as 8.4%, and similarly, the *VV* of RAP for a binder content of 3.8% is calculated as 8.8%. Applying the most unfavorable condition, the upper limit of the control range is set at a *VV* of 8.4%. Therefore, if the *VV* of RAP is less than 8.4%, and VMA and VFA are also within the corresponding range, it is suitable for HIR; otherwise, it is not. As a result, a new method is proposed, wherein determining the *VV* of RAP suffices to judge its suitability for the HIR technique.

In contrast to the conventional method, the compaction-based method exhibits a heightened succinctness in procedures, resulting in abbreviated testing cycles. Its operational ease is particularly advantageous during engineering construction. Moreover, it can be seen from the test results that the conclusions obtained by the novel method are consistent with those obtained by the conventional method. Hence, the proposed novel method warrants widespread endorsement.

(4) Economic benefit and the environmental impact

Grounded in the SWOT analytical framework, this study explores the economic and environmental implications of the proposed RAP analysis method, as shown in Figure 7. By eliminating the need for additional equipment and materials and ensuring low maintenance costs, the initial investment for deploying the RAP analysis method is significantly reduced, resulting in long-term financial advantages. However, manual intervention may increase labor costs and lead to potential inefficiencies and uniformity challenges. As the awareness of resource utilization grows, the adoption of the RAP analysis method is expected to rise, offering expanded economic opportunities. Nevertheless, the variability in test outcomes for mixtures may necessitate extra testing and quality control measures, which could negatively impact economic effectiveness. Environmentally, the RAP analysis method's reduced ecological impact supports the Sustainable Development Goals by lessening the environmental harm caused by new material extraction. Its streamlined approach compared to conventional methods reduces environmental risks during operations. Still, an unpredictable RAP supply might compel the use of new materials, thereby exacerbating environmental pressures from resource extraction. Overall, the RAP analysis method presents a comprehensive array of benefits and promotes sustainability.

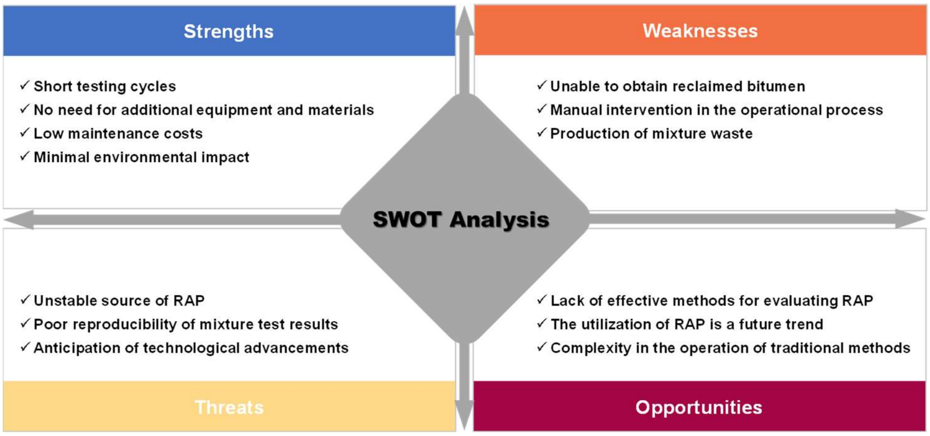


Figure 7. SWOT analysis of compaction-based method.

4.2. Compaction Characteristics of HIRAM

4.2.1. Mix Design

(1) Determination of the rejuvenator content

For HIRAM, the rejuvenator significantly impacts the restoration of aged bitumen [57–59]. Different amounts of the rejuvenator are sprayed onto the RAP, and after thorough mixing, the essential technical index of the recovered RAP is measured, as shown in Figure 8. The penetration value and ductility gradually increase with the increase in the content of the rejuvenator, while the softening point and Brookfield viscosity slightly decrease. This indicates that adding the rejuvenator is beneficial for restoring the performance of aged bitumen. With the increasing rejuvenator content, there is a noticeable change in the asphalt technical index in the initial stages. However, after reaching a certain content, the technical index stabilizes, indicating that more is not necessarily better. A reasonable content range for the rejuvenator exists. Considering all factors, the optimal content of the rejuvenator is determined to be 8%.

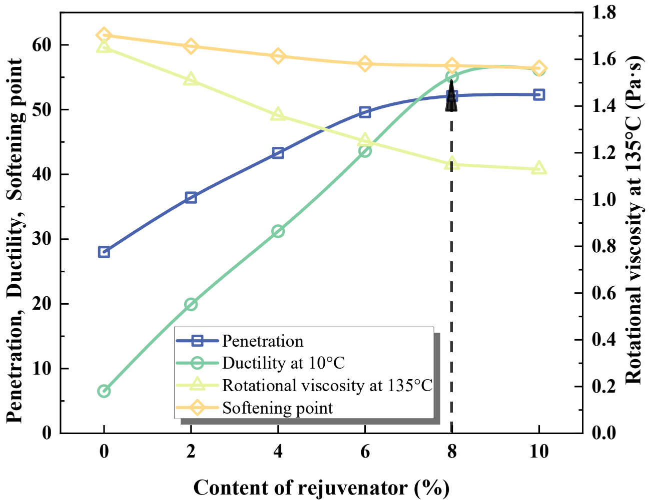


Figure 8. The impact of the rejuvenator content on aged bitumen.

(2) Determination of the optimum binder content

The binder content of RAP is 4.6%, and the rejuvenator content is 8% (as a percentage of the mass of aged bitumen). Three asphalt-aggregate ratios of 5.7%, 6.0%, and 6.3% are chosen, with a 20% addition of fresh asphalt mixture. Fresh bitumen is added based on the binder content of RAP and rejuvenator content (considering this quantity as part of the fresh bitumen content). The additional binder content is the difference between the total binder content and the binder content of the RAP. Marshall specimens are then formed [60–62]. The experimental results are presented in Table 9. The optimum binder content for HIRAM is determined to be 6.0%.

Table 9. Volumetric properties of HIRAM.

Bitumen Content (%)	5.7	6.0	6.3
Additional bitumen content (%)	1.1	1.4	1.7
VV (%)	4.6	4.0	3.8
VMA (%)	19.2	18.9	18.7
VFA (%)	76	78.8	79.7
Stability (kN)	11.29	11.69	11.86
Flow value (mm)	2.9	3.2	3.8
Drain-down test (%)	0.05	0.07	0.122
Raveling test (%)	10.6	7.2	5.7

4.2.2. Impact of Factors on Compaction Characteristics

(1) The impact of mixing time on compaction characteristics

From Figure 9, it can be observed that when the mixing time is less than 150 s, the *VV* of the mixture is 4.5%. When the mixing time exceeds 150 s, the *VV* decreases, and with further extension of the mixing time, the *VV* of the mixture stabilizes at 4.4%. This indicates that the mixing time exerts a negligible effect on the *VV*. Once the mixing time surpasses 30 s, the void content stabilizes at approximately 4.5%. During the blending process, the RAP and the fresh asphalt mixture achieve a thorough amalgamation under the influence of the rejuvenator, reaching an internal equilibrium. Consequently, the void content remains unchanged under consistent compaction efforts and temperature conditions.

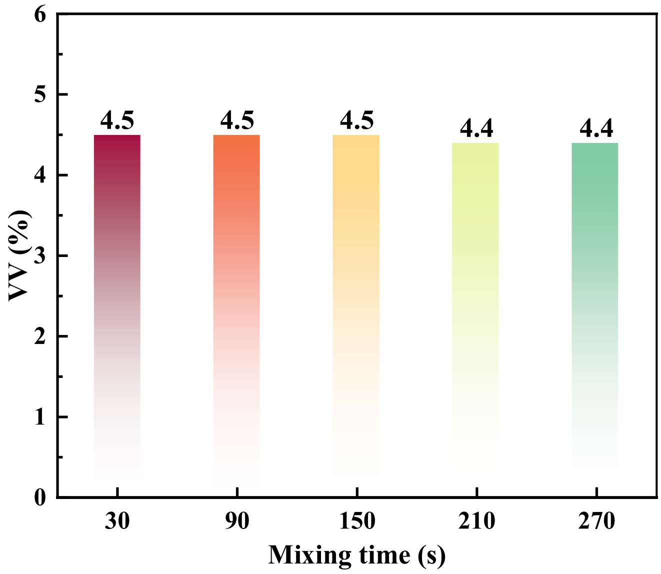


Figure 9. The impact of mixing time on compaction characteristics.

(2) The impact of mixture temperature on compaction characteristics

From Figure 10, it can be observed that when the temperature of RAP is constant, the *VV* of HIRAM decreases with the increasing heating temperature of the fresh asphalt mixtures. When the heating temperature of RAP is 160 °C, the *VV* shows the maximum reduction, reaching 14.3%. When the temperature of the fresh asphalt mixture is 200 °C, the *VV* reduction is the highest, reaching 41%. Comparing the column charts for RAP temperatures of 140 °C and 160 °C, it is evident that raising the mixture temperature of the fresh asphalt mixture does not effectively reduce the *VV* of HIRAM when the RAP temperature is relatively low. Therefore, increasing the mixture temperature or reducing the asphalt viscosity at the same temperature is advisable to facilitate better compaction during the compaction of SMA-grade mixtures.

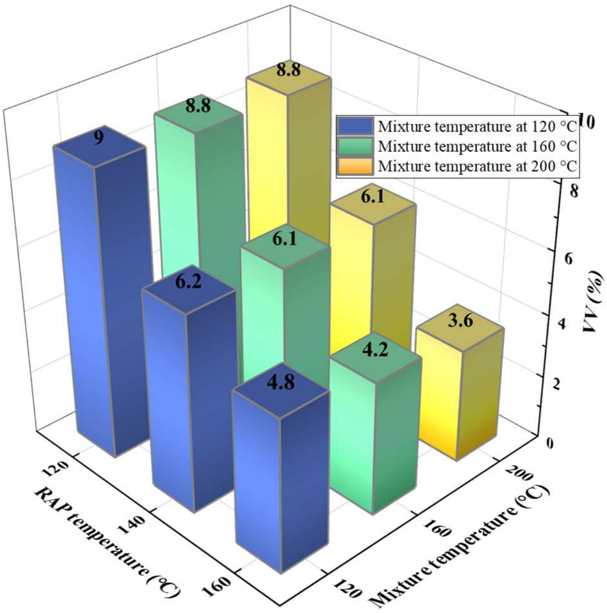


Figure 10. The impact of mixture temperature on compaction characteristics.

(3) The impact of mixing order on compaction characteristics

The mixing order determines the contact order between materials in the HIRAM, and whether the contact order affects the compaction characteristics of the asphalt mixture. The *VV* of HIRAM under different mixing orders is shown in Figure 11. The *VV* of HIRAM is not constant under different mixing orders. For orders B and C, the *VV* decreases by 5% and increases by 7% compared to order A. The reason for this is as follows.

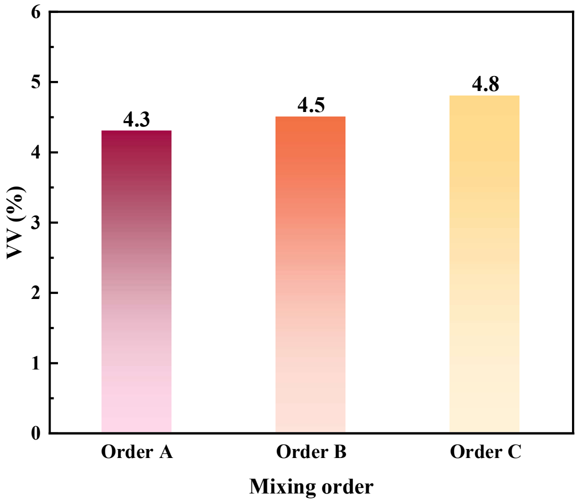


Figure 11. The impact of mixing order on compaction characteristics.

In order B, fresh aggregates are added between RAP and fresh bitumen. The angularity of the fresh aggregate peels off the aged bitumen on the surface of RAP, increasing the surface area of the aged bitumen. This allows for the better fusion of the fresh bitumen with the aged bitumen. Additionally, since the fresh aggregates do not have fresh bitumen on their surfaces, they can break up some of the clumps in RAP, promoting the recycling of the aged bitumen by the rejuvenator, which is beneficial for compaction.

In order C, fresh bitumen is first mixed with RAP. The fresh bitumen first encapsulates the RAP, forming a fresh bitumen slurry by binding some fine particles of RAP. The addition of mineral filler further enhances the viscosity of the slurry. When the pre-mix is added, the surface lacks sufficient bitumen encapsulation, making it difficult to move freely within the RAP. This ultimately leads to an increase in VV and difficulty in compaction.

(4) Analysis of Variance (ANOVA) of the Factors

Statistical analysis was performed using IBM SPSS Statistics 21 software to analyze the importance of compaction factors based on the above experimental data. The variances analysis of compaction factors is shown in Table 10.

Table 10. Variances analysis of compaction factors.

Dependent Variable: VV	**Type III SS**	**DF**	**MS**	**F**	**Sig.**
Calibration model	46.639	8	6.133	153.313	0
Intercept	305.068	1	305.068	7626.706	0
Compaction time	0.013	4	0.003	0.083	0.985
Compaction temperature	22.142	2	11.071	276.771	0
Mixing order	0.742	2	0.371	9.274	0.008
Error	0.320	8	-	-	-
Grand total	563.630	17	-	-	-
Total correction	49.380	16	-	-	-

As shown in Table 10, a multi-way ANOVA revealed that all factors except the compaction times were significant for VV. The outcomes of the ANOVA supported the initial hypothesis. Notably, compaction temperature emerged as the most influential factor impacting VV. Consequently, to ensure optimal compaction of HIRAP, controlling the compaction temperature is recommended.

4.3. Field Evaluation

This study focuses on the HIRAM renovation of a project located in northern China. After the construction of the HIRAM, the roughness performance, anti-skid performance, water permeability, and compaction were compared before and after construction. In Figure 12, the left bar represents the results of field testing before the implementation of the HIR technique, and the right bar represents the results of field testing after implementing the HIR technique. Figure 12 shows that the original pavement had poor overall roughness performance, and after HIR, the average roughness performance of the pavement significantly decreased. This change reflects the critical role of this technology in improving pavement roughness performance, and the asphalt pavement after HIR meets the quality requirements.

Figure 12 presents the results of the field evaluation. As shown in Figure 12, regarding anti-skid performance, the pavement macrotexture depth value was more than 1.0 mm before hot in-place recycling. After implementing HIR, the asphalt pavement macrotexture depth decreased but exceeded 0.7 mm, meeting the specified performance requirements. Furthermore, the skid value of the HIRAP is greater than 50, and the calculated lateral force coefficient is greater than 56, meeting the specified requirement that the lateral force coefficient should be greater than 54. After HIR, the pavement's mean skid value increased to 73, and the mean lateral force coefficient increased to 60. Compared to the pavement before recycling, the anti-skid performance of the pavement improved, indicating enhanced anti-skid performance.

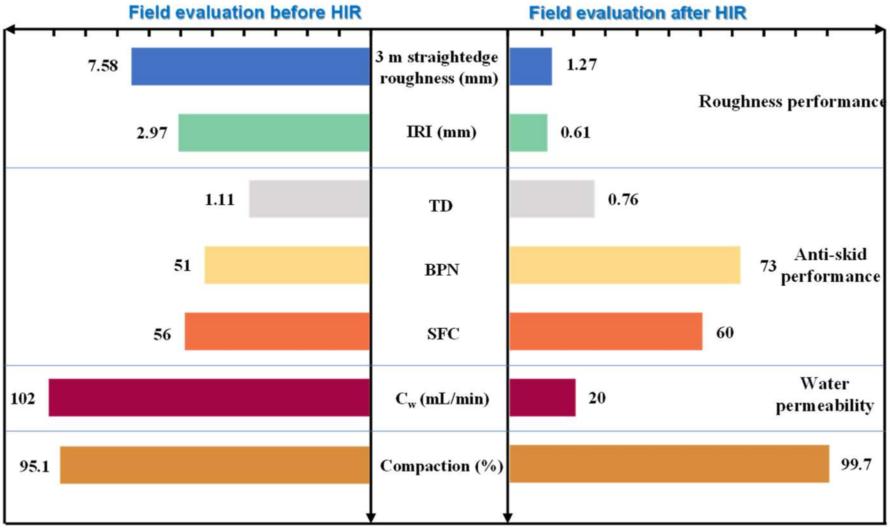


Figure 12. The results of the field evaluation.

The water permeability coefficient of the HIRAP is less than the specified requirement for SMA pavements, which should be less than 80 mL/min. After the implementation of hot in-place recycled asphalt, the water permeability coefficient of the asphalt pavement was 20, significantly improving the pavement's water-resistant performance. In addition, the compaction test data indicate that the compaction index meets the design requirements, demonstrating the excellent compatibility of the HIRAP.

5. Conclusions

This paper proposes a new method for evaluating RAP suitable for HIR. The influence of various factors on the compaction characteristics of HIRAM is analyzed. Based on the field evaluation results, HIRAM's road performance is validated. The main conclusions are as follows:

(1) Introducing a novel method for evaluating RAP, this approach employs compaction times and temperature as process parameters, with the *VV* of the formed Marshall specimens as the evaluation index. The control range for this index is comprehensively determined as being below 8.4%, considering bitumen aging and bitumen content.

(2) Mixing time has minimal impact on the *VV* of the mixture. When the RAP heating temperature is 160 °C, the *VV* shows the maximum reduction, reaching 14.3%. Similarly, when the temperature of the fresh asphalt mixture is 200 °C, the *VV* reduction is the highest, reaching 41%. For better compaction of SMA-grade mixtures, it is advisable to increase the mixture temperature. Increasing the contact area between aged and fresh bitumen promotes the compaction of the mixture.

(3) The roughness, friction coefficient, pavement compaction, and surface permeability of HIRAP meet the relevant specifications. The compaction of the recycled asphalt pavement can reach 99.7%, indicating excellent road quality.

6. Future Work

This study establishes a theoretical foundation for the further promotion of the HIR technique. A future study will include the following work:

- Future research should aim to broaden the sample scope, incorporating more engineering instances to validate the novel RAP evaluation method. Additionally, comparisons among various HIR construction processes should be conducted to meet the diverse needs of HIRAP construction under different project conditions.
- Despite the conducted field evaluation, the long-term performance and sustainability of HIRAP should be further maintained for follow-up testing to provide more basis for practical engineering applications.

- The compaction-based method is designed to facilitate widespread adoption in construction practices. Its accuracy warrants further validation, particularly in addressing the applicability issues regarding various types and sources of RAP. Developing an analytical framework that applies to diverse categories of RAP constitutes a future research trajectory.

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Appendix A

Table A1. List of abbreviations.

Abbreviations	Meaning
HIR	Hot in-place recycling
RAP	Reclaimed asphalt pavement
HIRAP	Hot in-place recycled asphalt pavement
HIRAM	Hot in-place recycled asphalt mixture
SBS	Styrene-butadiene-styrene
RTFOT	Rolling thin film oven test
PAV	Pressure aging vessel
SMA	Stone matrix asphalt
ANOVA	Analysis of variance

Table A2. List of parameters.

Parameters	Meaning
VV	Volume of voids (%)
VMA	Voids in mineral aggregate (%)
VFA	Voids filled with asphalt (%)
TD	Texture depth (mm)
IRI	International roughness index (mm)
γ_t	Theoretical maximum relative density of the asphalt mixture
γ_f	Relative density of the specimen by bulk volume
P_s	Percentage of each aggregate type to the total mass of the asphalt mixture (%)
γ_{sb}	Synthetic bulk volume relative density of the aggregates
V	The volume of sand (25 cm^3)
D	The average diameter of spread sand (mm)
BPN_{20}	Pendulum value converted to the standard temperature of 20 °C
BPN_T	Pendulum value measured at the pavement temperature
ΔBPN	Temperature correction value

Table A2. *Cont.*

Parameters	Meaning
C_W	Water permeability coefficient (mL/min)
V_1	Water quantity during the first timing (mL)
V_2	Water quantity during the second timing (mL)
t_2	Time of the first timing (s)
t_1	Time of the second timing (s)
DF	Degrees of freedom
MS	Mean square
F	F-statistic
$Sig.$	Significance level

References

1. Zhang, H.L.; Chen, Z.H.; Xu, G.Q.; Shi, C.J. Evaluation of aging behaviors of asphalt binders through different rheological indices. *Fuel* **2018**, *221*, 78–88. [CrossRef]
2. Gao, Y.M.; Zhang, Y.Q.; Yang, Y.; Zhang, J.H.; Gu, F. Molecular dynamics investigation of interfacial adhesion between oxidised bitumen and mineral surfaces. *Appl. Surf. Sci.* **2019**, *479*, 449–462. [CrossRef]
3. Ma, J.M.; Nivitha, M.R.; Hesp, S.A.M.; Krishnan, J.M. Validation of empirical changes to asphalt specifications based on phase angle and relaxation properties using data from a northern Ontario, Canada pavement trial. *Constr. Build. Mater.* **2023**, *363*, 129776. [CrossRef]
4. Alamri, M.; Lu, Q.; Xin, C. Preliminary Evaluation of Hot Mix Asphalt Containing Reclaimed Epoxy Asphalt Materials. *Sustainability* **2020**, *12*, 3531. [CrossRef]
5. Sha, A.; Jiang, W.; Shan, J.; Wu, W.; Li, Y.; Zhang, S. Pavement structure and materials design for sea-crossing bridges and tunnel: Case study of the Hong Kong–Zhuhai–Macau Bridge. *J. Road Eng.* **2022**, *2*, 99–113. [CrossRef]
6. Riccardi, C.; Losa, M. Recent advances and perspectives in circular bio-binder extender to substitute part of the fossil based binder in asphalt mixture. *Constr. Build. Mater.* **2024**, *410*, 134222. [CrossRef]
7. Pan, Y.Y.; Han, D.D.; Yang, T.; Tang, D.; Huang, Y.X.; Tang, N.X.; Zhao, Y.L. Field observations and laboratory evaluations of asphalt pavement maintenance using hot in-place recycling. *Constr. Build. Mater.* **2021**, *271*, 121864. [CrossRef]
8. Xu, X.X.; Gu, H.R.; Dong, Q.Z.; Li, J.P.; Jiao, S.J.; Ren, J. Quick heating method of asphalt pavement in hot in-place recycling. *Constr. Build. Mater.* **2018**, *178*, 211–218. [CrossRef]
9. Yu, B.; Liu, Q.; Tian, X.; Zhou, L.; Lin, M. Empirical performance models of hot in-place recycling of asphalt pavements. *Int. J. Pavement Eng.* **2017**, *18*, 1081–1088. [CrossRef]
10. Walther, A.; Büchler, S.; Cannone Falchetto, A.; Wang, D.; Riccardi, C.; Wistuba, M.P. Experimental investigation on asphalt mixtures prepared with reclaimed asphalt pavement and rejuvenators based on the BTSV method. *Road Mater. Pavement Des.* **2019**, *20*, 1695–1708. [CrossRef]
11. Wu, W.; Cavalli, M.C.; Jiang, W.; Kringos, N. Differing perspectives on the use of high-content SBS polymer-modified bitumen. *Constr. Build. Mater.* **2024**, *411*, 134433. [CrossRef]
12. Büchner, J.; Wistuba, M.P.; Remmler, T.; Wang, D. On low temperature binder testing using DSR 4 mm geometry. *Mater. Struct.* **2019**, *52*, 113. [CrossRef]
13. Renken, P.; Büchler, S.; Falchetto, A.C.; Wang, D.I.; Wistuba, M.P. Warm Mix Asphalt—A German Case Study. *Asph. Paving Technol.* **2020**, *87*, 685–716. [CrossRef]
14. Hugener, M.; Di, W.; Falchetto, A.C.; Porot, L.; De Maeijer, P.K.; Oreskovic, M.; Sa-da-Costa, M.; Tabatabaee, H.; Bocci, E.; Kawakami, A.; et al. Recommendation of RILEM TC 264 RAP on the evaluation of asphalt recycling agents for hot mix asphalt. *Mater. Struct.* **2022**, *55*, 31. [CrossRef]
15. Wang, H.P.; Zhang, H.; Liu, X.Y.; Apostolidis, P.; Erkens, S.; Skarpas, A.; Leng, Z.; Airey, G. Micromechanics-Based Viscoelasticity Predictions of Crumb Rubber Modified Bitumen Considering Polymer Network Effects. *Transp. Res. Rec.* **2022**, *2676*, 73–88. [CrossRef]
16. Jiang, W.; Zhang, M.; Ren, P.; Xing, C.; Yuan, D.; Wu, W. Development of porous asphalt mixture based on the synthesis of PTEMG and MDI polyurethane asphalt. *Constr. Build. Mater.* **2024**, *411*, 134537. [CrossRef]
17. Yu, B.; Wang, S.Y.; Gu, X.Y.; Ni, F.J.; Liu, Q. Environmental burden evaluation of hot in-place recycling of asphalt pavement based on discrete event simulation. *Transp. Res. Part D-Transp. Environ.* **2018**, *65*, 151–160. [CrossRef]
18. Zhong, H.B.; Huang, W.D.; Yan, C.Q.; Zhang, Y.; Lv, Q.; Sun, L.J.; Liu, L.Y. Investigating binder aging during hot in-place recycling (HIR) of asphalt pavement. *Constr. Build. Mater.* **2021**, *276*, 122188. [CrossRef]
19. Xu, J.; Fan, Z.; Yang, Q.; Lu, G.; Liu, P.; Wang, D. Hydrothermal carbonization of waste wood: Sustainable recycling of biomass by-products and novel performance enhancer for bitumen. *Constr. Build. Mater.* **2023**, *404*, 133307. [CrossRef]
20. Guo, X.-X.; Zhang, C.; Cui, B.-X.; Wang, D.; Tsai, J. Analysis of Impact of Transverse Slope on Hydroplaning Risk Level. *Procedia-Soc. Behav. Sci.* **2013**, *96*, 2310–2319. [CrossRef]

21. Wang, H.P.; Liu, X.Y.; Apostolidis, P.; Wang, D.; Leng, Z.; Lu, G.Y.; Erkens, S.; Skarpas, A. Investigating the High- and Low-Temperature Performance of Warm Crumb Rubber-Modified Bituminous Binders Using Rheological Tests. *J. Transp. Eng. Part B-Pavements* **2021**, *147*, 04021067. [CrossRef]
22. Wang, H.P.; Liu, X.Y.; Zhang, H.; Apostolidis, P.; Erkens, S.; Skarpas, A. Micromechanical modelling of complex shear modulus of crumb rubber modified bitumen. *Mater. Des.* **2020**, *188*, 108467. [CrossRef]
23. Jiang, W.; Li, P.F.; Sha, A.M.; Li, Y.P.; Yuan, D.D.; Xiao, J.J.; Xing, C.W. Research on Pavement Traffic Load State Perception Based on the Piezoelectric Effect. *Ieee Trans. Intell. Transp. Syst.* **2023**, *24*, 8264–8278. [CrossRef]
24. Yuan, D.D.; Jiang, W.; Sha, A.M.; Xiao, J.J.; Wu, W.J.; Wang, T. Technology method and functional characteristics of road thermoelectric generator system based on Seebeck effect. *Appl. Energy* **2023**, *331*, 120459. [CrossRef]
25. Jiang, W.; Yuan, D.D.; Shan, J.H.; Ye, W.L.; Lu, H.H.; Sha, A.M. Experimental study of the performance of porous ultra-thin asphalt overlay. *Int. J. Pavement Eng.* **2022**, *23*, 2049–2061. [CrossRef]
26. Zhang, H.L.; Duan, H.H.; Zhu, C.Z.; Chen, Z.H.; Luo, H. Mini-Review on the Application of Nanomaterials in Improving Anti-Aging Properties of Asphalt. *Energy Fuels* **2021**, *35*, 11017–11036. [CrossRef]
27. Shi, K.; Ma, F.; Fu, Z.; Song, R.; Yuan, D.; Ogbon, A.W. Enhancing aged SBS-modified bitumen performance with unaged bitumen additives. *Constr. Build. Mater.* **2024**, *412*, 134768. [CrossRef]
28. Gao, Y.M.; Zhang, Y.Q.; Gu, F.; Xu, T.; Wang, H. Impact of minerals and water on bitumen-mineral adhesion and debonding behaviours using molecular dynamics simulations. *Constr. Build. Mater.* **2018**, *171*, 214–222. [CrossRef]
29. Ma, J.M.; Hesp, S.A.M.; Chan, S.S.N.; Li, J.Z.; Lee, S.P. Lessons learned from 60 years of pavement trials in continental climate regions of Canada. *Chem. Eng. J.* **2022**, *444*, 136389. [CrossRef]
30. Sha, A.; Liu, Z.; Jiang, W.; Qi, L.; Hu, L.; Jiao, W.; Barbieri, D.M. Advances and development trends in eco-friendly pavements. *J. Road Eng.* **2021**, *1*, 1–42. [CrossRef]
31. Jia, M.; Sha, A.M.; Jiang, W.; Li, X.Z.; Jiao, W.X. Developing a solid-solid phase change heat storage asphalt pavement material and its application as functional filler for cooling asphalt pavement. *Energy Build.* **2023**, *285*, 112935. [CrossRef]
32. Wang, H.P.; Liu, X.Y.; Varveri, A.; Zhang, H.Z.; Erkens, S.; Skarpas, A.; Leng, Z. Thermal aging behaviors of the waste tire rubber used in bitumen modification. *Prog. Rubber Plast. Recycl. Technol.* **2022**, *38*, 56–69. [CrossRef]
33. Wang, T.; Jiang, W.; Xiao, J.J.; Guo, D.D.; Yuan, D.D.; Wu, W.J.; Wang, W.T. Study on the blending behavior of asphalt binder in mixing process of hot recycling. *Case Stud. Constr. Mater.* **2022**, *17*, e01477. [CrossRef]
34. Yuan, D.D.; Xing, C.W.; Jiang, W.; Xiao, J.J.; Wu, W.J.; Li, P.F.; Li, Y.P. Viscoelastic Behavior and Phase Structure of High-Content SBS-Modified Asphalt. *Polymers* **2022**, *14*, 2476. [CrossRef] [PubMed]
35. Yuan, D.D.; Jiang, W.; Xiao, J.J.; Tong, Z.; Jia, M.; Shan, J.H.; Ogbon, A.W. Assessment of the Aging Process of Finished Product-Modified Asphalt Binder and Its Aging Mechanism. *J. Mater. Civ. Eng.* **2022**, *34*, 04022174. [CrossRef]
36. Ma, Y.; Ding, Y.; Zheng, K.; Polaczyk, P.; Zhang, M.; Xiao, R.; Huang, B. Effects of Immobilized RAP Binder on Asphalt-Aggregate Interaction and Performance of 100% Recycled Asphalt Mixtures. *J. Mater. Civ. Eng.* **2023**, *35*, 04023029. [CrossRef]
37. Ali, H.; McCarthy, L.M.; Welker, A. Performance of hot in-place recycled Superpave mixtures in Florida. *Constr. Build. Mater.* **2013**, *49*, 618–626. [CrossRef]
38. Cao, R.J.; Leng, Z.; Hsu, S.C. Comparative eco-efficiency analysis on asphalt pavement rehabilitation alternatives: Hot in-place recycling and milling-and-filling. *J. Clean. Prod.* **2019**, *210*, 1385–1395. [CrossRef]
39. Huang, K.; Xu, T.; Li, G.F.; Jiang, R.L. Heating effects of asphalt pavement during hot in-place recycling using DEM. *Constr. Build. Mater.* **2016**, *115*, 62–69. [CrossRef]
40. Li, X.L.; Lv, X.C.; Zhou, Y.H.; You, Z.P.; Chen, Y.L.; Cui, Z.J.; Diab, A. Homogeneity evaluation of hot in-place recycling asphalt mixture using digital image processing technique. *J. Clean. Prod.* **2020**, *258*, 120524. [CrossRef]
41. Liu, Y.; Wang, H.N.; Tighe, S.L.; Zhao, G.Y.; You, Z.P. Effects of preheating conditions on performance and workability of hot in-place recycled asphalt mixtures. *Constr. Build. Mater.* **2019**, *226*, 288–298. [CrossRef]
42. Ma, Y.T.; Polaczyk, P.; Park, H.; Jiang, X.; Hu, W.; Huang, B.S. Performance evaluation of temperature effect on hot in-place recycling asphalt mixtures. *J. Clean. Prod.* **2020**, *277*, 124093. [CrossRef]
43. *JTG E20-2011*; Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering. Highway & Transportation Industry Standard: Beijing, China, 2011.
44. Zhang, M.; Kou, C.; Kang, A.; Xiao, P.; Hu, H. Microscopic characteristics of interface transition zones of hot mix asphalt containing recycled concrete aggregates. *J. Clean. Prod.* **2023**, *389*, 136070. [CrossRef]
45. Cai, X.; Zhang, Q.; Yu, H.; Huang, W.; Wu, K.; Yang, G.; Bao, X. Study on performance of recycled asphalt mixture based on blending state analysis of virgin and aged asphalt. *Int. J. Pavement Eng.* **2023**, *24*, 2165658. [CrossRef]
46. Yang, C.; Wu, S.; Xie, J.; Amirkhanian, S.; Zhao, Z.; Xu, H.; Wang, F.; Zhang, L. Development of blending model for RAP and virgin asphalt in recycled asphalt mixtures via a micron-Fe3O4 tracer. *J. Clean. Prod.* **2023**, *383*, 135407. [CrossRef]
47. *JTG 3450-2019*; Field Test Methods of Highway Subgrade and Pavement. Highway & Transportation Industry Standard: Beijing, China, 2019.
48. Nizamuddin, S.; Baloch, H.A.; Jamal, M.; Madapusi, S.; Giustozzi, F. Performance of waste plastic bio-oil as a rejuvenator for asphalt binder. *Sci. Total Environ.* **2022**, *828*, 8. [CrossRef]
49. Vazquez, V.F.; Garcia-Hoz, A.M.; Teran, F.; Gil-Abarca, A.; Paje, S.E. Functional characterization of a Cold-In place-Recycled pavement at different stages of the curing process. *Sci. Total Environ.* **2021**, *789*, 9. [CrossRef] [PubMed]

50. Kumar, A.; Choudhary, R.; Kandhal, P.S.; Julaganti, A.; Behera, O.P.; Singh, A.; Kumar, R. Fatigue characterisation of modified asphalt binders containing warm mix asphalt additives. *Road Mater. Pavement Des.* **2020**, *21*, 519–541. [CrossRef]
51. Zhu, Y.J.; Ma, T.; Xu, G.J.; Fan, J.W.; Zhang, Y.M.; Wu, M. Study of the Mixing between Asphalt and Rejuvenator in Hot In-Place Recycled Layer. *J. Transp. Eng. Part B-Pavements* **2023**, *149*, 04023005. [CrossRef]
52. Bouraima, M.B.; Zhang, X.H.; Rahman, A.; Qiu, Y.J. A comparative study on asphalt binder and mixture performance of two traffic lanes during hot in-place recycling (HIR) procedure. *Constr. Build. Mater.* **2019**, *223*, 33–43. [CrossRef]
53. Pan, Y.Y.; Liu, G.Q.; Tang, D.; Han, D.D.; Li, X.G.; Zhao, Y.L. A rutting-based optimum maintenance decision strategy of hot in-place recycling in semi-rigid base asphalt pavement. *J. Clean. Prod.* **2021**, *297*, 126663. [CrossRef]
54. Ma, D.C.; Lan, F. Numerical simulation analysis on multi-layer low-temperature heating method of asphalt pavement in hot in-place recycling. *J. Cent. South Univ.* **2020**, *27*, 3793–3806. [CrossRef]
55. Pan, Y.Y.; Yang, T.; Chen, A.Q.; Li, X.G.; Zhao, Y.L. Determination of Virgin Asphalt Mixture Content in Hot In-Place Recycling Based on Field Rutting Depth Variability. *J. Mater. Civ. Eng.* **2023**, *35*, 05023002. [CrossRef]
56. Liu, Z.M.; Sun, L.J.; Zhai, J.H.; Huang, W.Q. A review of design methods for cold in-place recycling asphalt mixtures: Design processes, key parameters, and evaluation. *J. Clean. Prod.* **2022**, *370*, 133530. [CrossRef]
57. Han, D.D.; Zhao, Y.L.; Pan, Y.Y.; Liu, G.Q.; Yang, T. Heating process monitoring and evaluation of hot in-place recycling of asphalt pavement using infrared thermal imaging. *Autom. Constr.* **2020**, *111*, 103055. [CrossRef]
58. Schwettmann, K.; Nytus, N.; Radenberg, M.; Stephan, D. Ageing behaviour of naturally and artificially aged bitumen samples after the addition of rejuvenators. *Road Mater. Pavement Des.* **2023**, *24*, 471–485. [CrossRef]
59. Purohit, S.; Panda, M.; Das, A.K. Performance of waste polyethylene modified bituminous paving mixes containing reclaimed asphalt pavement and recycled concrete aggregate. *Constr. Build. Mater.* **2022**, *348*, 16. [CrossRef]
60. Hettiarachchi, C.; Hou, X.D.; Xiang, Q.; Yong, D.; Xiao, F.P. A blending efficiency model for virgin and aged binders in recycled asphalt mixtures based on blending temperature and duration. *Resour. Conserv. Recycl.* **2020**, *161*, 12. [CrossRef]
61. Goli, A.; Ziari, H.; Amini, A. Influence of Carbon Nanotubes on Performance Properties and Storage Stability of SBS Modified Asphalt Binders. *J. Mater. Civ. Eng.* **2017**, *29*, 9. [CrossRef]
62. Boom, Y.J.; Enfrin, M.; Grist, S.; Giustozzi, F. Recycled plastic modified bitumen: Evaluation of VOCs and PAHs from laboratory generated fumes. *Sci. Total Environ.* **2022**, *832*, 13. [CrossRef]