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EFFECT OF RAP CONTENT ON THE PERFORMANCE OF WARM MIX STONE MATRIX ASPHALT

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Abstract. The incorporation of reclaimed asphalt pavement (RAP) into warm mix stone matrix asphalt (WSMA) has attracted increasing attention due to its potential to reduce natural resource consumption, energy demand, and environmental impacts associated with asphalt pavement construction. However, the use of RAP in SMA mixtures may significantly influence the balance between rutting resistance and cracking performance because of the stiffening effect of aged binder. Therefore, this study investigates the influence of RAP content on the mechanical performance of WSMA mixtures. Four mixtures containing 0%, 10%, 20%, and 30% RAP were designed using a warm mix additive, a bio-based rejuvenator, and cellulose fiber. The performance of the mixtures was evaluated through IDEAL-RT and IDEAL-CT tests to characterize rutting and cracking resistance, respectively. The results indicated that increasing RAP content significantly improved rutting resistance, as reflected by higher shear strength and RTIndex values. However, the cracking resistance gradually decreased with increasing RAP content due to the increased stiffness and brittleness of the aged binder system. Among the investigated mixtures, the WSMA containing 20% RAP exhibited the most balanced mechanical performance, providing substantial rutting improvement while maintaining acceptable cracking resistance.

Keywords: reclaimed asphalt pavement, warm mix stone matrix asphalt, bio-based rejuvenator, cellulose fiber, rutting tolerance index, cracking tolerance index.

1. INTRODUCTION

Stone Matrix Asphalt (SMA) is a high-performance asphalt mixture widely used for pavements subjected to heavy traffic volumes and high axle loads due to its stone-on-stone aggregate skeleton, which is formed by a high coarse aggregate content and a binder-rich mastic phase. This unique internal structure provides SMA with superior rutting resistance, durability, and skid resistance [1]. Along with the growing demand for high-performance pavement structures, increasing concerns regarding sustainability and circular economy have driven the wider use of Reclaimed Asphalt Pavement (RAP) in asphalt mixtures. RAP is currently considered a strategic material resource because it reduces the consumption of virgin aggregates and asphalt binder, lowers construction costs, and significantly mitigates environmental impacts [2, 3]. Several life cycle assessment studies have confirmed that RAP incorporation can substantially reduce energy consumption and CO_2 emissions [4, 5]. However, the use of RAP in SMA mixtures is more challenging than in dense-graded asphalt mixtures because SMA strongly relies on a carefully designed coarse aggregate skeleton and a relatively high binder content to ensure structural stability and durability [6, 7]. The binder contained in RAP is generally stiffer and more brittle due to oxidation and changes in the asphaltene–maltene balance, which may significantly affect mixture workability, cracking resistance, and moisture durability [8, 9]. Previous studies have shown that increasing RAP content generally improves high-temperature stiffness and rutting resistance, but may reduce fatigue life and low-temperature cracking resistance if not properly controlled [10-12]. In SMA mixtures, excessive RAP content may also disrupt the stone-on-stone contact and alter the composition of the mastic phase, thereby reducing mixture durability and increasing the risk of cracking [6, 13].

Warm Mix Asphalt (WMA) technology has been increasingly adopted to address the limitations associated with the high production temperatures of conventional Hot Mix Asphalt (HMA) and SMA mixtures. By using organic additives, chemical surfactants, or foaming techniques, WMA allows mixing and compaction at temperatures approximately 20–40°C lower than those of HMA, resulting in lower fuel consumption, reduced emissions, improved construction conditions, and less binder aging [14-16]. Previous studies have shown that the use of WMA in SMA mixtures can improve workability and compactability, while maintaining or even enhancing rutting resistance [17, 18]. The combined use of RAP and WMA is particularly attractive from both technical and environmental perspectives, since WMA may help offset the reduced workability and increased stiffness caused by the aged binder in RAP [19]. Several studies have indicated that WMA facilitates the incorporation of higher RAP contents by improving aggregate coating and binder blending, thereby enhancing constructability without significantly compromising performance [20, 21]. Nevertheless, the extent of blending between virgin binder and aged RAP binder remains uncertain and is influenced by factors such as RAP particle size, mixing temperature, mixing conditions, and additive type [8]. In SMA mixtures, these interactions are even more complex because of the gap-graded structure and the high mineral filler content, both of which strongly influence the formation and rheological behavior of the mastic phase. The incorporation of aged RAP binder may alter the filler-to-binder ratio, increase mastic viscosity, and affect the risk of binder drain-down [7]. In addition, WMA additives may interact with both virgin and aged binders, thereby modifying the microstructural arrangement of the mastic and the interfacial bonding between aggregates and binder [17, 22]. These combined effects are expected to significantly influence the rutting resistance, cracking resistance, and moisture susceptibility of SMA mixtures containing RAP and WMA. To maintain satisfactory performance in SMA mixtures, previous studies have suggested that moderate RAP contents (e.g., 10–30%) can be incorporated without significantly compromising rutting resistance, and in some cases may even improve high-temperature performance because of the increased stiffness of the binder system [23]. However, higher RAP contents are often associated with a reduction in fatigue and cracking resistance. Similarly, WMA technology has been reported to improve the moisture resistance and compactability of SMA mixtures, although the effectiveness strongly depends on the additive type and mixture design [24–26]. Despite the increasing interest in RAP and WMA, research specifically addressing their combined influence in SMA mixtures remains limited. Most previous studies have focused either on RAP in dense-graded asphalt mixtures or on WMA in conventional SMA, while only a few have systematically examined the role of RAP content in WSMA systems [2, 22]. Therefore, this study aims to systematically evaluate the influence of RAP content on the performance of SMA mixtures produced using WMA technology. The outcomes of this study are expected to provide a scientific basis for the design and application of warm recycled SMA mixtures, thereby supporting the development of more sustainable pavement solutions.

2. MATERIALS OF WARM MIX STONE MATRIX ASPHALT WITH RECLAIMED ASPHALT PAVEMENT

2.1. Aggregate Mixture

The aggregates used in this study were produced from neutral igneous rock obtained from the Tan Cang, Dong Nai Province, Vietnam. The aggregate system consisted of 12.5–19 mm, 9.5–12.5 mm, 0–4.75 mm fractions, and mineral filler. The properties of these materials satisfied the requirements of TCCS 36: 2021 in the Table 1.

Table 1. Properties of aggregate materials.

Properties	*Agg. 12.5-19*	*Agg. 6-12.5*	*Agg. 0-4.75*	*Filler*
Bulk specific gravity	2.73	2.727	2.703	2.711
Effective specific gravity	2.752	2.750	2.742	-
Water absorption (%)	0.21	0.37	0.52	-
Dust and clay content (%)	0.36	0.68	-	-
Los Angeles abrasion loss (%)	23.5	-	-	-

2.2. Reclaimed Asphalt Pavement (RAP)

The RAP material was obtained from an existing asphalt pavement through milling and was subsequently processed by sieving to obtain the 6–12.5 mm size fraction, as shown in. The binder in the RAP material was extracted by the centrifuge extraction method and subsequently recovered using the Abson recovery procedure, following AASHTO T164 and AASHTO R59, respectively. The properties of the RAP in Table 2.

Table 2. Characteristics of RAP material.

Properties	Results	Criteria
Theoretical maximum specific gravity of RAP	2.614	-
Binder content in RAP (%)	2.8	-

Physicomechanical properties of the binder extracted from RAP:		
Penetration at 25°C (0.1 mm)	25.3	Min 20
Softening point (°C)	64.5	-
Viscosity at 135°C (Pa·s)	32145	-
G*/sinδ at 82°C (kPa)	1.08	-

2.3. Asphalt binder

A virgin asphalt binder with a penetration grade of 60/70 was used in this study in accordance with ASTM D946M. The fundamental properties of the binder are summarized in Table 3.

Table 3. Physicomechanical properties of the virgin asphalt binder.

Properties	Results	Criteria
Penetration at 25°C (0.1 mm)	63.4	60-70
Dynamic viscosity at 60°C (Pa·s)	210.0	Min 180
Ductility at 25°C (cm)	> 100	Min 100
Softening point (°C)	49.6	Min 46
G*/sinδ at 64°C (kPa)	1.82	Min 1.0
Bulk specific gravity at 25°C	1.03	-

2.4. Additives

Rejuvenator. A rejuvenating agent was introduced to restore the stiffness of the aged asphalt binder present in RAP, thereby enhancing its interaction and compatibility with the virgin binder. In this research, a bio-derived rejuvenator supplied by Hansoo Road Co., Ltd. was utilized. The detailed characteristics of this additive are presented in Table 4, and all obtained values satisfied the specifications outlined in ASTM D4552M-20.

Table 4. Physicochemical characteristics of the rejuvenator.

Properties	Results
Viscosity at 25°C (cP)	1934
Specific gravity at 25°C	0.943
Physical state at room temperature	Liquid
Color	Yellow
Flash point (°C)	244

Warm mix additive. A warm-mix technology was adopted in this investigation to enable reductions in both mixing and compaction temperatures of the asphalt mixture. Specifically, a commercially produced additive, designated as Zero-M, was selected for this purpose. This additive is predominantly based on Styrene–Butadiene–Styrene (SBS) and incorporates a range of proprietary chemical constituents designed to enhance workability at reduced temperatures. The corresponding physicochemical properties of the additive are summarized in Table 5.

Table 5. Physical properties of the warm mix additive.

Properties	Results	Specification
Solidification temperature (°C)	100	DIN-ISO 2207
Softening point (°C)	150-160	ASTM D3954
Flash point (°C)	285	-
Density at 25°C (kg/m³)	950	DIN 51 757
Viscosity at 135°C (mm²/s)	-	DIN 51 562

Fiber additives. Cellulose fiber was used as the stabilizing additive in this study. The fiber, classified as an organic stabilizing material, was supplied by JRS, Germany. The cellulose fiber used in this study is a commercially available stabilizing material, and its engineering properties meet the requirements specified in UFGS-32 12 15.16, as shown in Table 6 [14].

Table 6. Properties of ArboCel cellulose fiber.

Properties	*Results*
pH	6±1
Average fiber diameter (µm)	45 µm
Average length of fiber	1100 µm
Cellulose content	85±5%

2.5. Composition of Warm Stone Matrix Asphalt (WSMA)

The mixture design of the Warm Mix Stone Matrix Asphalt (WSMA) was developed following a performance-oriented framework, in which the aggregate skeleton was established based on the target gradation curve illustrated in Figure 1. Simultaneously, the mixture was proportioned to meet the specified engineering performance criteria summarized in Table 7, while ensuring appropriate volumetric characteristics, including air voids content, voids in mineral aggregate (VMA), and optimum binder content.

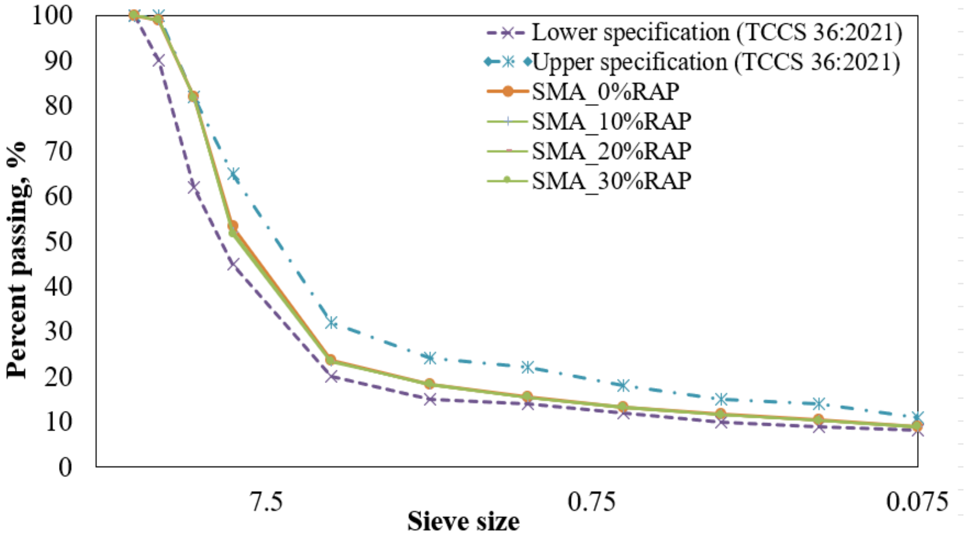


Figure 1. Aggregate gradation of the WSMA mixtures.

Table 7. Design properties of the SMA mixture.

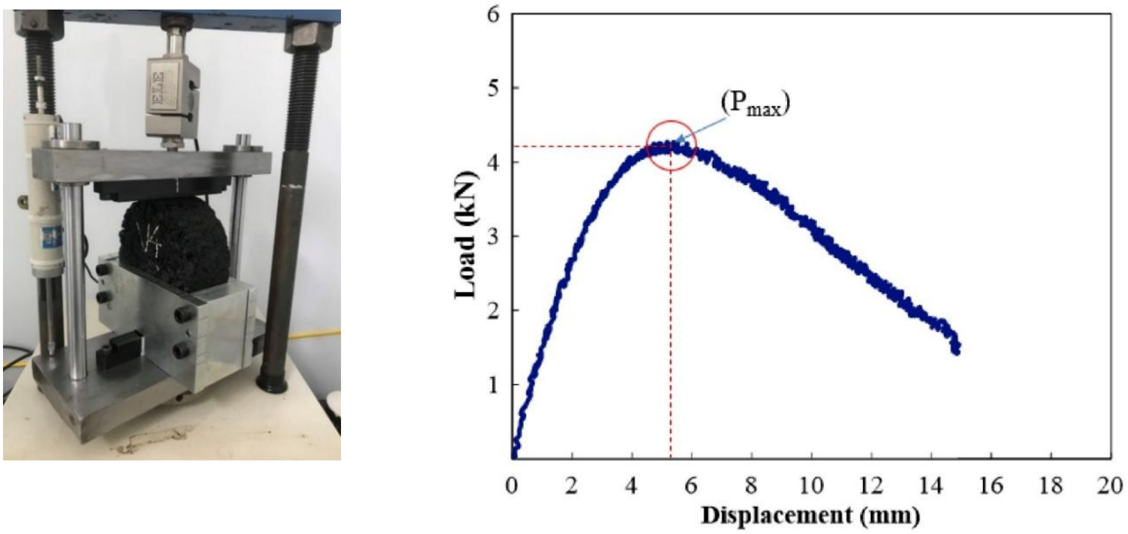
Properties	**Results for mixtures containing varying RAP contents**				**Criteria**
	0%	10%	20%	30%	
Bitumen content, %	6.3	6.1	6.1	6.1	Min 6
Warm mix additive, %	0.7	0.7	0.7	0.7	-
Rejuvenator, %	0	0.05	0.05	0.05	-
Cellulose fiber, %	0.3	0.3	0.3	0.3	0.2-0.4
Marshall Stability, kN	7.11	7.62	8.74	9.81	Min 6.2
Marshall Flow, mm	3.8	3.9	3.7	3.1	2 ÷ 4
Air voids, %	3.89	3.54	3.62	3.26	3 ÷ 4
VMA, %	19.3	18.4	19.1	18.6	Min 17
VCA$_{MIX}$, %	Lower VCA$_{DR}$	Lower VCA$_{DRC}$	Lower VCA$_{DRC}$	Lower VCA$_{DRC}$	Lower VCA$_{DRC}$
Draindown, %	0	0	0	0	Max 0,3

All design properties of the WSMA mixture satisfied the requirements of TCCS 36: 2021.

3. PERFORMANCE EVALUATION TESTS

3.1. Rutting Resistance Test

The rutting resistance of the asphalt mixtures was evaluated using the Rutting Tolerance Index (RTIndex) in accordance with ASTM D8360. Testing was performed at a temperature of 50°C under a constant loading rate of 50 mm/min. Cylindrical specimens (150 mm in diameter and 62 mm in height) were prepared using a Superpave gyratory compactor to achieve a target air void content of 7 ± 0.5%. Three replicate specimens were tested for each mixture. The experimental setup and a typical specimen after testing are illustrated in Figure 2.



(a) (b)

Figure 2. RTIndex test: (a) specimen and test apparatus; (b) load–displacement curve obtained from the test.

The rutting resistance was quantified in terms of the RT_{Index}, which was calculated using Equations (1) and (2).

$$\tau_f = 0{,}356 \times \frac{P_{max}}{t \times w} \quad (1)$$

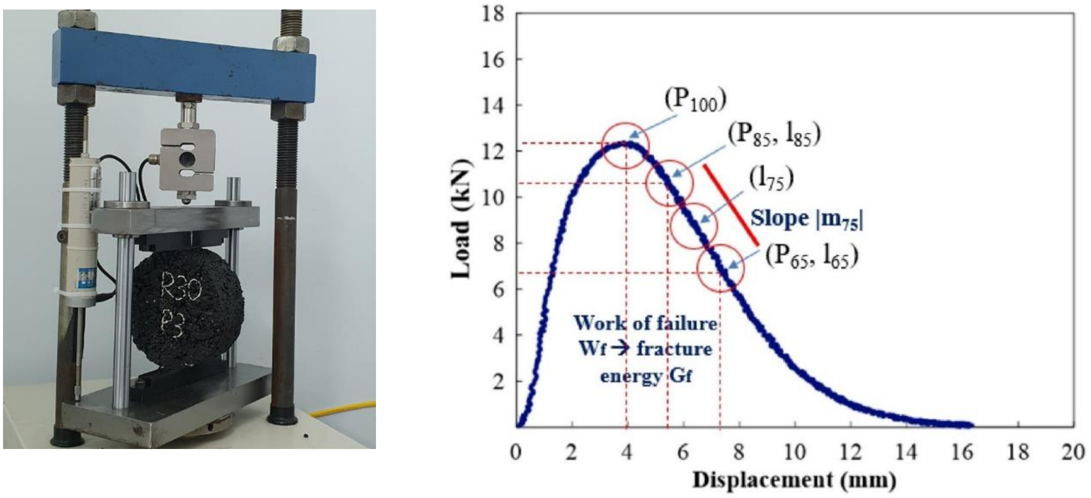
where τf represents the shear strength (Pa); Pmax corresponds to the maximum load attained during testing (N); t denotes the specimen height (mm); and w is the width of the upper loading strip applied to the specimen (w = 0.0191 m). Subsequently, the RTIndex was calculated based on the obtained shear strength using Equation (2).

$$RT_{Index} = 6{,}618 \times 10^{-5} \times \frac{\tau_f}{1Pa} \quad (2)$$

A higher RT_{Index} indicates better rutting resistance of the asphalt concrete mixture.

3.2. Cracking Resistance Test

The Indirect Tensile Asphalt Cracking Test (IDEAL-CT) is widely recognized as an effective method for evaluating the cracking resistance of asphalt mixtures and has been adopted as a rapid assessment tool for mixture design and quality control [27]. The testing procedure followed ASTM D8225, conducted at a temperature of 25°C under a monotonic loading rate of 50 mm/min, as illustrated in Figure 3. Cylindrical specimens with a diameter of 150 mm and a height of 62 mm were prepared with a target air void content of 7 ± 0.5%. The cracking resistance was characterized using the CT_{Index}, which was determined according to Equation (3). This index reflects the fracture energy dissipation and post-peak load–displacement behavior of the mixture, thereby providing insight into its resistance to crack initiation and propagation.



(a) (b)

Figure 3. IDEAL-CT method for cracking assessment.

$$CT_{Index} = \frac{G_f}{|m_{75}|} \times \left(\frac{l_{75}}{D}\right) \quad (3)$$

where:

t– thickness of the test specimen (mm);

G_f – fracture energy (J/m²);

$|m_{75}|$ – peak slope of the load–displacement curve at 75% of the maximum compressive load (kN/mm);

D – diameter of the test specimen (mm);

l_{75} – displacement corresponding to 75% of the maximum compressive load (mm).

According to the specifications adopted by different State Departments of Transportation in the United States, the minimum required CT_{Index} generally ranges from 50 to 100 [28].

4. RESULTS AND DISCUSSION

4.1 Effect of RAP content on rutting resistance

The results of the IDEAL-RT_{Index} test are presented as load–displacement curves in Figure 4.

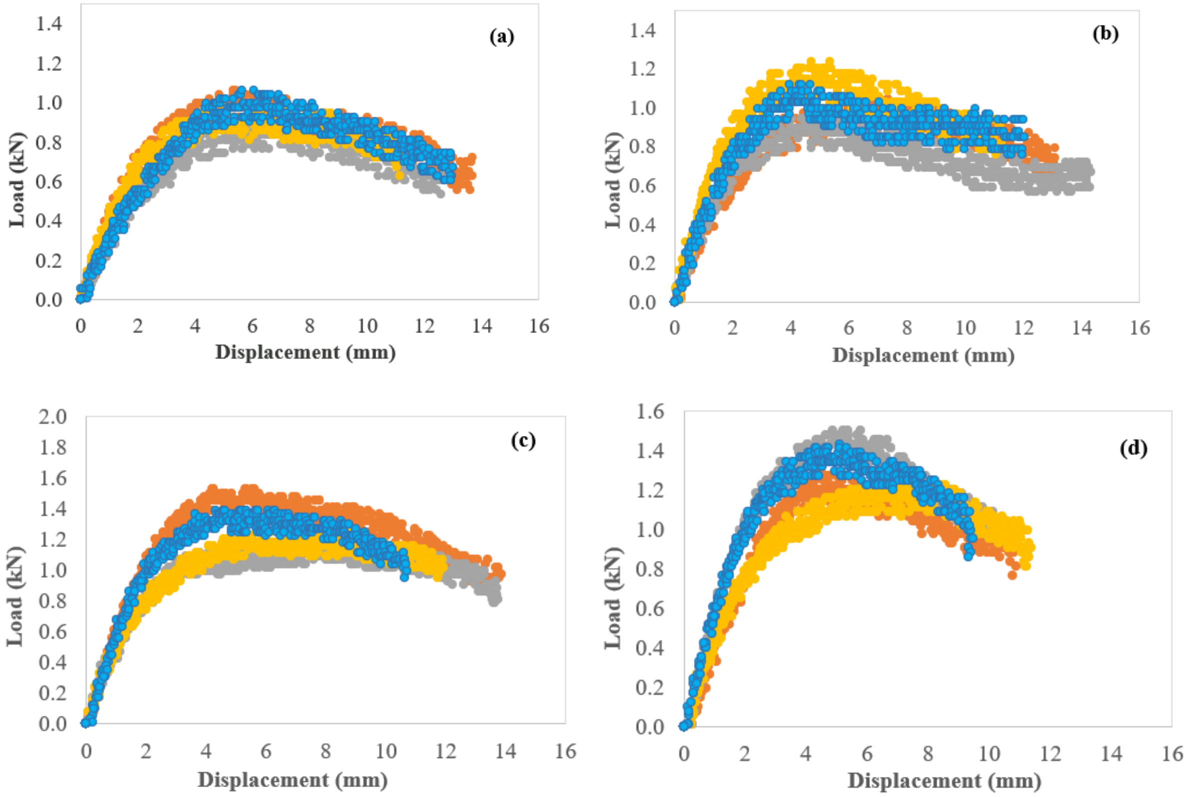


Figure 4. Load–displacement curves of the IDEAL-RTIndex test: (a)-SMA_0%RAP, (b)-SMA_10%RAP, (c)-SMA_20%RAP, (d)-SMA_30%RAP.

Based on the recorded load–displacement response, the shear strength and RT_{Index} were calculated using Equations (1) and (2), respectively. The resulting values are illustrated in Figures 5 and 6.

Figure 5 illustrates the variation in shear strength of the SMA mixtures with increasing RAP content. The results show that the shear strength increased markedly as the RAP content increased from 0% to 30%. The control mixture, SMA_0%RAP, exhibited an average shear strength of 0.3 MPa, whereas the mixtures containing 10%, 20%, and 30% RAP achieved values of approximately 0.33 MPa, 0.40 MPa, and 0.41 MPa, respectively. Compared with the control mixture, the incorporation of RAP significantly improved the shear resistance of the SMA mixtures, with the mixture containing 30% RAP showing an increase of approximately 37% in shear strength.

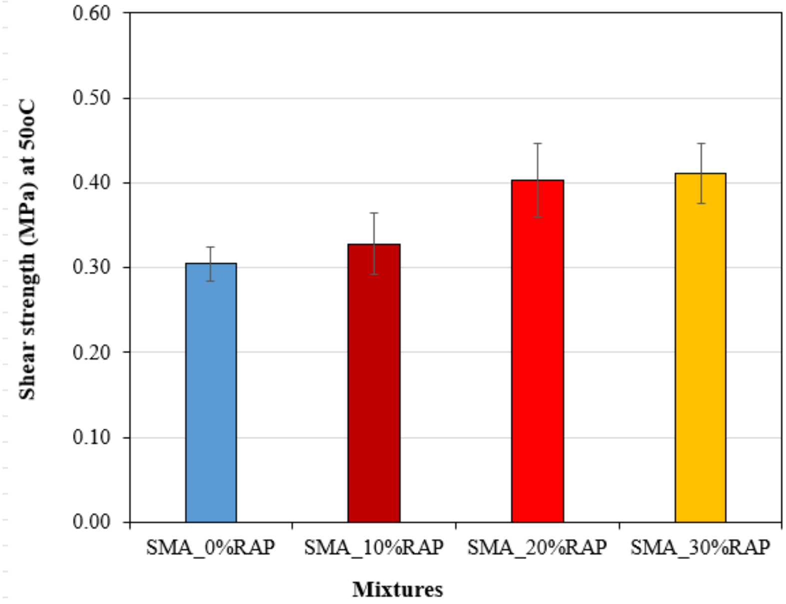


Figure 5. Shear strength of the mixtures.

A notable improvement was observed when the RAP content increased from 10% to 20%, where the shear strength increased by nearly 0.07 MPa, corresponding to approximately 22.8%. This substantial increase suggests that RAP plays an important role in enhancing the load-bearing capacity of the SMA structural skeleton at moderate replacement levels. However, the results also indicate that the increase in shear strength became marginal when the RAP content increased from 20% to 30%, with an improvement of only about 2–3%. This trend suggests the onset of a saturation effect, where the contribution of RAP tends to stabilize at higher replacement levels. Excessive RAP content may render the binder system overly stiff, thereby limiting stress redistribution and reducing the efficiency of load transfer within the mixture.

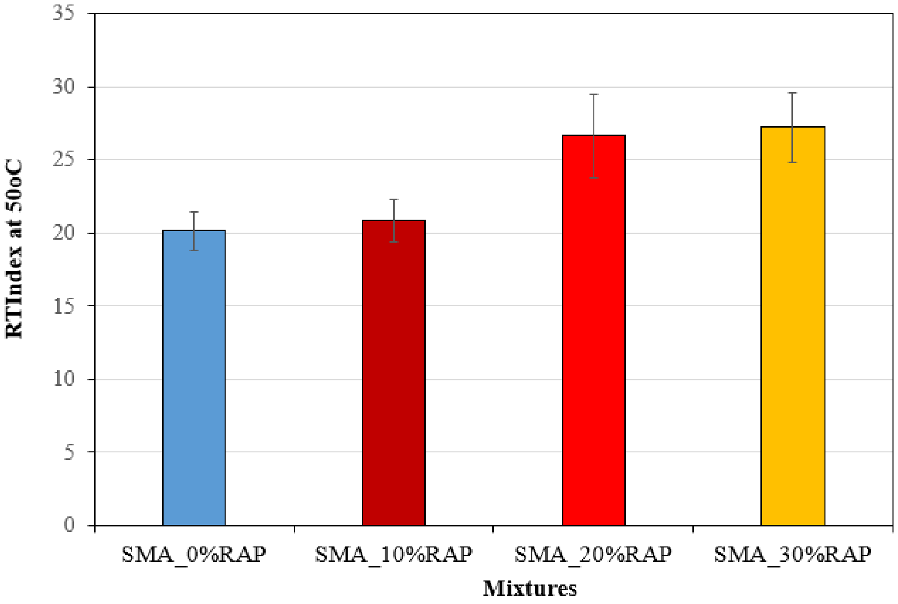


Figure 6. Rutting Tolerance Index (RTIndex) of the mixtures.

The results presented in Figure 6 show that the Rutting Tolerance Index (RT_{Index}) of the SMA mixtures increased as the RAP content increased from 0% to 30%. Relative to the control mixture, the inclusion of RAP led to a pronounced improvement in the rutting resistance of the SMA mixtures. In particular, increasing the RAP content from 0% to 20% resulted in an approximate 35% increase in RT_{Index}, demonstrating a substantial enhancement in resistance to permanent deformation. This behavior is primarily associated with the presence of aged binder within the RAP, which exhibits higher stiffness compared to virgin binder. The increased stiffness of the asphalt mastic limits shear deformation and reduces the potential for aggregate slippage under repeated loading. Furthermore, RAP aggregates are generally coated with a stiffened asphalt film, which enhances interparticle friction and promotes a more stable stone-on-stone skeleton structure in SMA mixtures.

When the RAP content increased from 10% to 20%, the RT_{Index} increased by approximately 22.8%, suggesting that the reinforcing effect of RAP on the internal structure of the mixture became more pronounced at moderate RAP contents. However, when the RAP content increased from 20% to 30%, the improvement in RTIndex became marginal, indicating the onset of a mechanical plateau. This phenomenon may be associated with an excessively stiff binder system at high RAP contents, which reduces the ability of the mixture to redistribute stress effectively. Overall, these results demonstrate that the use of RAP in SMA mixtures can significantly enhance rutting resistance, with a RAP content of approximately 20% appearing to be a reasonable level for achieving a balance between mechanical performance and material recycling objectives.

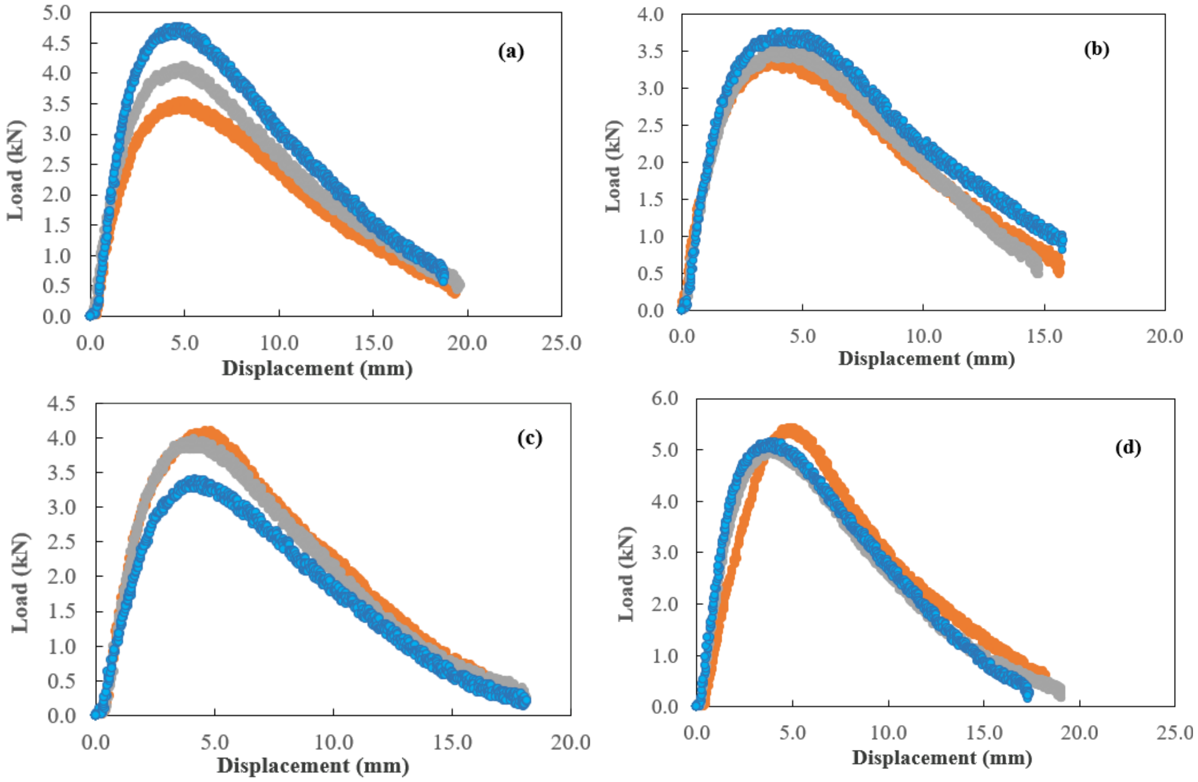


Figure 7. Load–displacement curves from the IDEAL-CT test: (a)-SMA_0%RAP, (b)-SMA_10%RAP, (c)-SMA_20%RAP, (d)-SMA_30%RAP.

4.2. Effect of RAP content on cracking resistance

The cracking test results, expressed in terms of IDEAL-CT_{Index}, are illustrated by the corresponding load–displacement curves shown in Figure 7.

Based on the test data presented in Figure 7, the characteristic parameters representing the cracking resistance of the mixtures were calculated according to Equation (3). The results are shown in Figures 8 and 9.

The $l_{75}/|m_{75}|$ ratio serves as an indicator of the ductile-to-brittle response of asphalt mixtures under intermediate temperature conditions. Higher values of this ratio are associated with improved resistance to crack propagation and a more ductile mechanical behavior, whereas lower values signify a transition toward brittle response. As illustrated in Figure 8, the SMA mixture containing 10% RAP exhibited the highest $l_{75}/|m_{75}|$ value (25.70), slightly exceeding that of the control mixture without RAP (24.64).

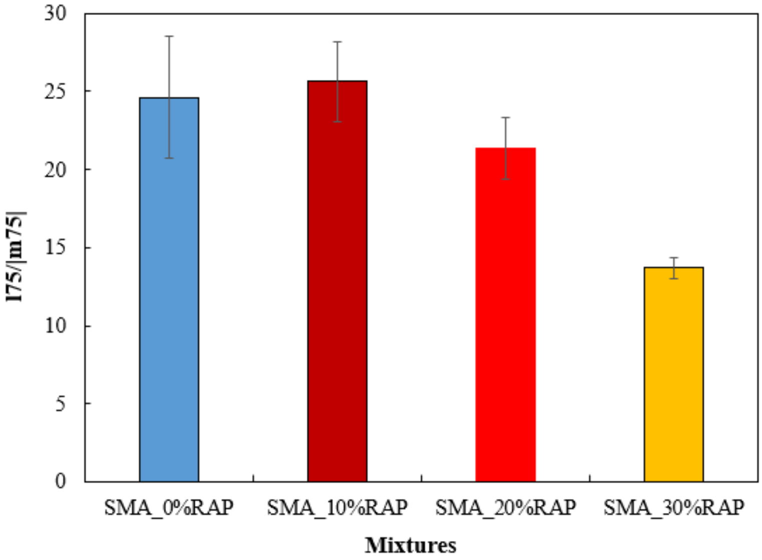


Figure 8. The $l_{75}/|m_{75}|$ ratio of the mixtures.

This observation suggests that a moderate incorporation of RAP may enhance cracking resistance, likely due to the combined effects of aged binder and RAP aggregates in reinforcing the aggregate skeleton stiffness. However, a further increase in RAP content to 20% led to a reduction of the ratio to approximately 21, indicating a shift toward more brittle behavior. This trend became more evident at 30% RAP, where the ratio dropped significantly to around 14. Overall, these findings demonstrate that excessive RAP content can adversely affect mixture ductility and reduce resistance to crack propagation.

The influence of RAP content on the cracking resistance of SMA mixtures was evaluated using the CT_{Index} obtained from the IDEAL-CT test, as presented in Figure 9. The control mixture, SMA_0%RAP, exhibited the highest CT_{Index} value (approximately 880), indicating excellent resistance to crack propagation. With the incorporation of 10% RAP, the CT_{Index} decreased to approximately 630, corresponding to a reduction of about 28% relative to the RAP-free mixture. When the RAP content increased to 20%, the CT_{Index} further declined to approximately 540, representing a reduction of about 39% compared with the control mixture. The lowest CT_{Index} value was observed for the SMA_30%RAP mixture, at approximately 480, which corresponds to a reduction of about 45% relative to SMA_0%RAP. The observed decline indicates that elevated RAP contents have a detrimental effect on the cracking resistance of SMA mixtures. This response is largely governed by the characteristics of the aged binder within RAP, which contributes to increased stiffness while simultaneously diminishing ductility and limiting the mixture's capacity for fracture energy dissipation during crack propagation. In addition, at higher RAP levels, the interaction and blending between the aged and virgin binders may be incomplete, further compromising the overall resistance to cracking.

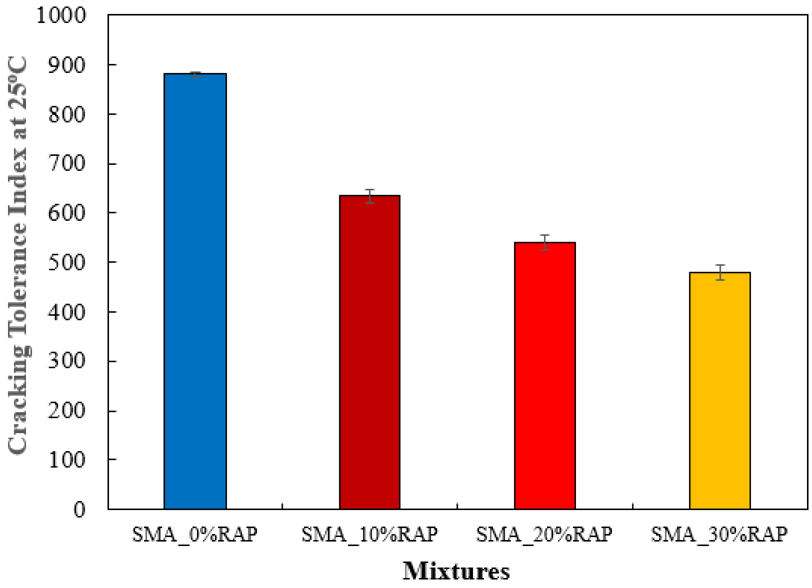


Figure 9. Cracking Tolerance Index (CT_{Index}) of the mixtures.

5. CONCLUSION

This study provides a comprehensive evaluation of the influence of RAP incorporation on the rutting and cracking performance of WSMA. Based on the obtained results, the following key conclusions are drawn:

1. The incorporation of higher RAP contents contributed to a pronounced improvement in rutting resistance of WSMA, as demonstrated by the increased values of shear strength and RT_{Index}.
2. The beneficial effect of RAP on rutting performance was most pronounced up to 20% RAP, while the improvement became marginal beyond this level, indicating a mechanical plateau.
3. In contrast, increasing RAP content resulted in a continuous reduction in cracking resistance, as reflected by the decrease in CT_{Index} and the reduction in the $l_{75}/|m_{75}|$ ratio.
4. The results suggest that 20% RAP may be considered an optimum or balanced RAP level for WSMA, providing substantial rutting improvement while maintaining an acceptable cracking performance.
5. The combination of WMA technology and RAP shows strong potential for developing more sustainable asphalt mixtures, although careful control of RAP content is necessary to avoid excessive brittleness.

6. Further studies are recommended to investigate moisture susceptibility, fatigue resistance, binder blending behavior, and long-term durability to support practical implementation.

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