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RESEARCH ARTICLE

Performance analysis of sustainable asphalt mixes containing reclaimed asphalt pavement and crumb rubber

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Abstract - Due to the increased demand for aggregates in road construction, intensifying environmental issues including soil erosion, water pollution, and ecosystem degradation caused by aggregate extraction. To mitigate these impacts, this study utilized recycled materials such as reclaimed asphalt pavement (RAP) and crumb rubber (CR) as partial aggregate replacements, incorporating 40% RAP and 2–6% CR in the mix. Marshall stability, resilient modulus, and dynamic creep tests were performed to assess load-bearing capacity, stiffness, and deformation behaviour under different conditions. The Marshall test results also provided insights into the relationship between stability, flow, and stiffness. Additionally, based on existing literature and current findings, the study identifies key limitations, discusses practical applications, and proposes directions for future research. The test results showed that recycled mixes, particularly RAP40 and RAP40CR2, performed better than traditional hot mix asphalt (HMA) in the Marshall test. In the resilient modulus test, both RAP40 and RAP40CR2 outperformed the control mixture, with RAP40CR2 achieving the greatest values 42.23% and 69.9% higher at 25°C and 40°C, respectively. Similarly, dynamic creep results revealed that mixtures containing RAP40, RAP40CR2, and RAP40CR6 exhibited enhanced resistance to permanent deformation compared to the control, with RAP40CR2 providing the most significant stability improvement. Overall, the study concludes that combining RAP and CR helps mitigate environmental impacts by incorporating waste materials, while also performing well across different temperatures and loading conditions.

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1. Introduction

With the rapid growth of urban areas and extensive infrastructure endeavours, developing nations face a heightened demand for natural aggregate to keep pace with the expanding infrastructure. The production of traditional hot mix asphalt (HMA) requires a large volume of high-quality virgin aggregates and asphalt binder, both of which have considerable environmental impacts due to activities such as quarrying, transportation, and emissions-intensive production methods. However, the extensive use of natural aggregates in large-scale pavement construction and maintenance worldwide runs counter to the key goal of sustainable infrastructure development [1]. Thus, a wide range of research has been conducted to utilise the waste product in pavement construction with the objective of mitigating concerns related to environmental sustainability and fiscal viability [2]-[5]. According to the literature, the worldwide annual disposal of waste materials contributes about 3–4% of total GHG emissions to the atmosphere [6]. In addition, it incurs a substantial management cost of USD 205.4 per ton, which is anticipated to increase fivefold by 2030. These waste materials have a serious impact on landfills [7]. In pavement construction, integrating recycled waste materials not only mitigates the environmental risks associated with inadequate waste disposal but also reduces dependence on increasingly depleted natural aggregates, promoting more sustainable practices in pavement engineering [8]. Sustainable pavement technologies increasingly promote the use of reclaimed asphalt pavement (RAP) and crumb rubber (CR) because both materials reduce the consumption of virgin aggregates and help divert waste tyres from landfills. Consequently, the use of recycled materials in highway pavement construction offers considerable benefits both environmentally and economically [9] RAP, as a substitute for a portion of aggregates in HMA, offers a financially advantageous and environmentally sustainable approach that reduces the need for waste transportation and disposal, reduces reliance on landfills, preserves natural aggregate resources, and decreases the energy consumption associated with the extraction and transportation of raw materials [10]. According to the National Asphalt Pavement Association's 2021 industry survey, the average RAP content in recycled asphalt mixtures reached 22%, reflecting a growing interest in RAP utilisation; in total, 85.3 million tons of RAP were used, conserving approximately 4,134 million litres of asphalt binder and replacing more than 80.3 million tons of virgin aggregate [11]. Moreover, incorporating RAP materials into HMA significantly reduces the paving costs of asphalt pavements [12]. Several studies highlight the potential to incorporate high RAP contents in recycled asphalt mixtures without compromising pavement performance. RAP typically contains around 4% aged asphalt binder, enabling substantial binder replacement in HMA. For example, increasing RAP content from 15% to 40% can raise fresh binder savings from approximately 10% to 30% [11]. Cost reductions of up to 14% have been observed with recycled asphalt mixtures compared to conventional mixtures [13]. RAP has been found to enhance workability and reduce viscosity at

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lower temperatures [14]. Although earlier research reported that high RAP contents may increase mixture stiffness and heighten cracking susceptibility [15], more recent work demonstrates that the use of rejuvenators can effectively restore aged RAP binders and improve the overall performance of RAP-containing mixtures [16]-[18]. Recent research has focused on evaluating the rutting resistance, and dynamic modulus of asphalt mixtures incorporating varying proportions of RAP [19]-[21]. When RAP is used in an asphalt mixture, the high viscosity and hardness of the aged binder reduce the mixture's low-temperature cracking resistance [22]. Another study by Wang et al. [20] evaluated the rutting resistance of HMA with RAP content from 0% to 60%, showing increased rut resistance of 25–39%, while raising the low-frequency dynamic modulus and reducing low-temperature cracking performance by only 10–20%, confirming the feasibility of high-RAP mixtures. According to the literature, 40% of RAP replacement, as an overall aggregate, shows better resistance to fatigue cracking, rutting, and moisture damage [23], [24].

CR, which is generated from waste tyres, is another waste product that has raised concern for environmental scientists. In recent decades, notable progress has occurred in the transportation and automotive industries, leading to a marked uptick in the utilisation of rubber tyres. Consequently, there has been a rapid accumulation of scrap tyres stemming from a diverse range of vehicles [25]. Around 1 billion tires are discarded as solid waste each year, and this is projected to rise to 1.2 billion by 2030 [26] [27]. In 2023, the global CR market was valued at $1,040 million and is expected to grow to $1,378.8 million by 2030, reflecting a Compound Annual Growth Rate of 3.9% from 2024 to 2030 [28]. Despite this market growth, improper disposal of waste tyres presents a major environmental issue. Tyres are highly flammable due to their volatile components, posing a significant fire risk and releasing toxic smoke harmful to human health [29]. Moreover, their combustion can emit styrene, a hazardous gas that contributes to air pollution and poses serious health risks [30]. As a result, tyre disposal has become a pressing environmental concern, leading to bans on landfill disposal. Open-air disposal of tires leads to water being trapped within them, creating an environment conducive to breeding various insects and pests [31], [32]. To solve this problem, scholars have suggested a practical method of grinding tyres into fragments or crumbs and reusing them in asphalt pavement as a partial replacement for aggregate [33]-[35]. Zeleke and Tsegaye [36] found that 3% CR replacement increases pavement thickness; however, it reduces stability, indirect tensile strength, and bulk specific gravity. A mechanistic evaluation was conducted by Souliman et al. [37] to understand the long-term performance of HMA incorporating rubber. The results showed that asphalt rubber mixtures fabricated by replacing fine aggregates increase fatigue life by 6 times in new pavements and 40 times in overlays, improve rutting life, and deliver better cost-effectiveness than conventional HMA. Moreover, most CR particles maintain a solid form within the asphalt, creating a network structure. This modification in asphalt composition, including CR particles, has notably enhanced the base asphalt performance [38].

Despite the extensive literature on only RAP mixtures or CR-modified mixtures, very few studies have examined their combined use within the same mix design. Existing RAP and CR studies rely on field-extracted pavement cores with uncontrolled ageing histories; for example, the Islamabad–Lahore motorway investigation used fixed levels of 15% RAP and 7% CR but lacked laboratory control over mix variables [39]. Studies on CR-RAP or reclaimed asphalt rubber pavement (RARP) primarily address the recyclability of aged, rubberised materials rather than evaluating performance when RAP and CR are introduced simultaneously into fresh HMA mixtures. Furthermore, binder contents and mix gradations vary substantially across the literature, making it difficult to isolate the true interaction between RAP stiffness and the elastic response contributed by CR. There is no systematic study evaluating high RAP content combined with low and moderate CR levels under identical binder content, identical gradation, and identical mixture preparation conditions. This study aims to understand the feasibility of using a combination of RAP and CR in HMA by conducting a laboratory-controlled evaluation with fixed RAP contents and varying CR contents. By controlling RAP at a high, practical value and systematically varying CR content, the study isolates the interaction between RAP-induced stiffness and CR-induced elasticity under a fully controlled laboratory mix design, enabling a clearer understanding of their combined influence on asphalt performance.

2. Materials and Methods

Following AC14 standards [40], waste derived from RAP and CR were substituted, by weight, for a specific portion of the aggregate. This section provides a detailed explanation of the material properties and the research methodology used in this study. An overview of the adopted research approach is presented in Figure 1. The flowchart illustrates the process of preparing and testing HMA using natural aggregates, RAP, and CR. After collecting materials, different mix proportions were selected, including a control sample and three RAP–CR combinations. Based on the literature, this research utilises a fixed 40% RAP with varying CR contents because 40% represents the upper limit at which RAP can be incorporated without significantly compromising mixture workability, moisture resistance, or compaction, while still providing substantial binder replacement and environmental benefits [41]. At the same time, using 2% and 6% CR allows evaluation of low and moderate modification levels that have been widely reported in the literature to improve elasticity, rutting resistance, and resilient modulus without causing excessive air voids or workability issues [42]. These mixtures were then used to prepare HMA, followed by Marshall and resilient modulus and dynamic creep tests to evaluate performance.

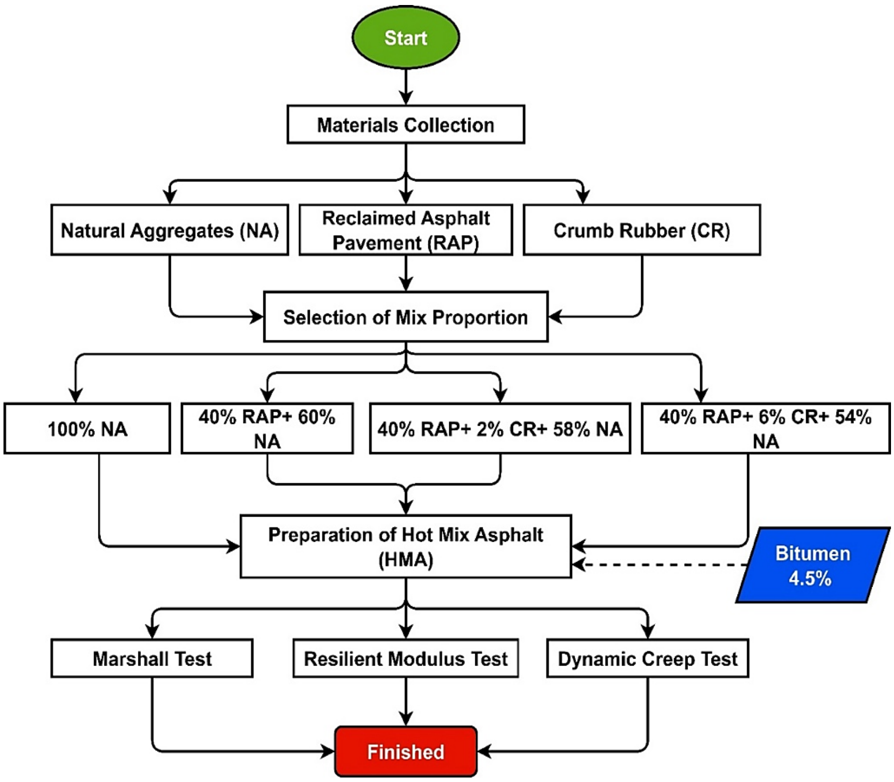

Figure 1. Research flow diagram

2.1 Aggregates

The aggregate gradation applied in this study followed the standards set by Malaysia's Public Works Department [43]. The particle size distribution of the aggregates is shown in Figure 2. This study requires particles to pass through a 14 mm sieve. These particles were sourced from East Rock Quarry Sdn. Bhd., Malaysia. Subsequently, all samples were sieved to achieve the appropriate particle size for incorporation into the HMA mixture. Table 1 presents the weight of natural aggregates used, in accordance with the AC14 specification [40].

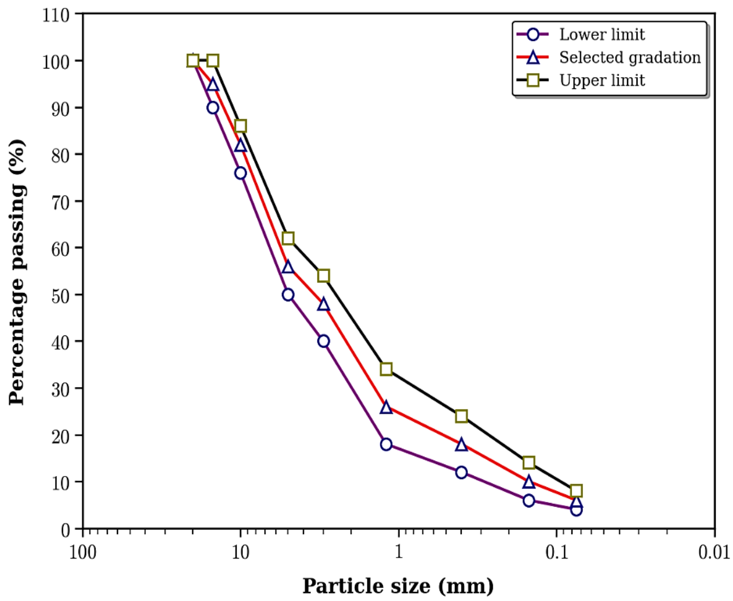

Figure 2. Sieve analysis size distribution

2.2 Reclaimed Asphalt Pavement

RAP is obtained from the removal of existing HMA surfaces during rehabilitation or resurfacing works. Its composition is similar to that of conventional HMA, containing both coarse and fine aggregate particles. The specific gravity of the aggregates ranges from 2.26 to 2.63, while the binder has a specific gravity of approximately 1.0-1.1 [44]. In this study, untreated RAP initially undergoes sieving to ensure passage through a 5 mm sieve. The RAP was collected from Plateau Enterprise Sdn. Bhd., located at Kuantan, Pahang, Malaysia. Subsequently, the specimens were sieved to attain the requisite sizes for the HMA mixture, following the specifications outlined in Table 1. RAP was collected in three size fractions (5 mm, 3.35 mm, and 1.18 mm), with a 40% replacement level used as a substitute for natural aggregates.

2.3 Crumb Rubber

CR is made by grinding used tyres into small particles, typically under 4.75 mm, for use in asphalt or other applications. Its specific gravity ranges from 0.53 to 1.17, thereby enhancing asphalt properties such as elasticity and durability [45]. This research selected a particle size of 0.150 mm, with the material sourced from the online marketplace Shopee, Malaysia. The CR content was adjusted by incorporating 2% and 6% of the total aggregate weight per sample, as detailed in Table 1.

Table 1. Particle size gradation of used aggregates.

Sieve size (mm), AC14	Passing (%)	Sample weight (g)	Replacement material (g)		
			40% RAP	2% CR	6% CR
14	90 – 100	56.90	-	-	-
10	76 – 86	159.32	-	-	-
5	50 – 62	284.50	284.50	-	-
3.35	40 – 54	102.42	102.42	-	-
1.18	18 – 34	238.98	68.28	-	-
0.425	12 – 28	91.04	-	-	-
0.150	6 – 14	91.04	-	22.76	68.28
0.075	4 – 8	45.52	-	-	-
Pan		68.28	-	-	-
Total		1138.00	455.20	22.76	68.28

2.4 Bitumen

According to JKR, the standard optimum binder content for AC-14 is 4-6% [46]. Based on prior studies, this research used a 60/70 PEN-grade bitumen at a proportion of 4.5% by weight of the aggregate[47], [48]. The bitumen was sourced from the highway laboratory at the Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), Malaysia. The testing procedure involved diluting the bitumen and maintaining it at 40°C for 24 hours. The properties of the bitumen are summarised in Table 2.

Table 2. Bitumen properties

Properties	ASTM code	Specifications	Obtained value
Specific gravity (g/cc)	ASTM D 70 − 82	1.01 – 1.06	1.03
Penetration (1/10 mm)	ASTM D 5 − 86	60 – 70	63
Flash point (ºC)	ASTM D 92 −05	230 ºC Minimum	321 ºC
Fire point (ºC)	ASTM D 92 – 05	–	334 ºC
Loss on heat (%)	ASTM D 6 – 95	<1%	0.95%
Solubility	ASTM D 4	95% Minimum	97.82%
Ductility (cm)	ASTM D 113 − 99	100 cm Minimum	100 + cm

2.5 Mix Design

Once the materials such as aggregate, RAP, and CR were prepared, the sieves were arranged in descending order, with the largest openings at the top and the smallest at the bottom. The natural aggregates, RAP, and CR were proportioned as previously described before being mixed with 60/70 grade bitumen. Samples were prepared according to the laboratory mould size of 100 mm diameter and 74 mm height. The test principle involved using diluted bitumen, heated to 40°C for 24 hours. The materials were mixed using a dry mixing method, with the temperature kept between 150°C and 155°C throughout the process. Subsequently, 75 blows were applied to the mould using the Marshall Compactor. Following AC14 standards [40], RAP and CR were used as aggregate replacements in asphalt samples, as shown in Table 3.

Table 3. Particle size gradation of used aggregates

Mix	Natural aggregate (gm)	Reclaimed asphalt pavement (gm)	Crumb rubber (gm)	Bitumen (gm)
Control	1138.00	−	−	45.52
RAP40	682.80	455.20	−	45.52
RAP40CR2	660.04	455.20	22.76	45.52
RAP40 CR6	614.52	455.20	68.28	45.52

2.6 Methods

2.6.1 Marshall stability test

The experiment was conducted on 12 asphalt samples, with three specimens prepared for each mix type: Control, RAP40 (40% RAP and 0% CR), RAP40CR2 (40% RAP and 2% CR), and RAP40CR6 (40% RAP and 6% CR), in accordance with the ASTM D6927 standard [47]. Each sample was weighed and placed into a mould measuring 101.6 mm in diameter and 76.2 mm in height, fitted with a base plate and extension collar. The samples were then oven-heated at temperatures between 160°C and 165°C for 24 hours. Prior to testing, they were conditioned in a water bath at 60°C for 30 minutes. Following this, the samples were tested using a Marshall testing machine to measure their stability and deformation. The bulk density of each compacted HMA sample was also determined by calculating its specific gravity, defined as the ratio of the sample's weight to the weight of an equal volume of water, in accordance with ASTM D2726 [48].

2.6.2 Resilient modulus test

In this research, the testing was conducted using a Universal Testing Machine (UTM) at controlled temperatures of 25°C and 40°C, following the ASTM D4123 standard [42]. A peak load of 1000 N was applied vertically along the diametral axis of cylindrical specimens, and the resulting horizontal deformation was recorded. As specified in ASTM D4123, the load should fall between 10% and 50% of the specimen's tensile strength [42]. In this study, the applied load corresponded to 15% of the direct tensile strength. Each specimen was tested in two orientations: 0° and 90°.

2.6.3 Dynamic creep test

The purpose of this test was to evaluate the rutting susceptibility of the asphalt mixture using a UTM in conjunction with specialised computer software to analyse permanent deformation. Prior to testing, the sample was conditioned within the machine at a temperature of 40°C. During the initial setup phase, a fixed delay of 30 minutes was programmed, during which no stress was applied. Once the test began, continuous loading pulses were administered, and two Linear Variable Displacement Transducers (LVDTs) were used to monitor the resulting strain. The test lasted approximately one hour and thirty minutes, involving 1800 loading cycles at a stress level of 10 kPa, after which the software generated the deformation data.

3. Results and Discussion

3.1 Marshall Stability

3.1.1 Bulk density

Bulk density is a fundamental property of HMA, as it is essential for calculating other key parameters such as air voids, voids in mineral aggregates (VMA), and maximum theoretical density. As shown in Figure 3**,** the bulk density of the control mix was recorded at 2.28 g/cm³. For the modified mixtures RAP40, RAP40CR2, and RAP40CR6, the values were 2.32 g/cm³, 2.23 g/cm³, and 2.09 g/cm³, respectively. The results demonstrate that incorporating 40% RAP increased the bulk density of asphalt pavement. This is because its aged binder creates thin coating films that let the aggregates fit together more closely. Moreover, RAP's dense, well-graded particle structure reduces air voids, resulting in a higher compacted density [49]. In contrast, the addition of CR led to a reduction in bulk density. Specifically, the mix containing 40% RAP and 6% CR showed a 9.1% decrease in bulk density compared to the control. This reduction is attributed to CR particles creating additional voids in the asphalt matrix, thereby lowering the overall density [50]. Moreover, CR has a much lower specific gravity than the aggregates and binder it replaces. Its irregular shape can hinder particle packing during compaction, increasing air voids in the mixture and ultimately reducing the overall bulk density [51], [52]. A reduction in bulk density is observed with increasing CR at a given bitumen content [53].

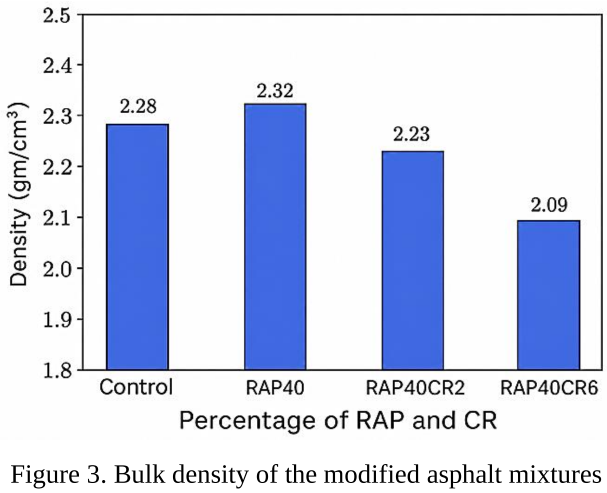

Figure 3. Bulk density of the modified asphalt mixtures

3.1.2 Stiffness

Measuring stiffness is a common technique for understanding the structural behaviour of bituminous mixtures in road construction [54]. Figure 4 presents the stiffness values of asphalt mixtures modified with RAP and CR. The recorded stiffness for the control mixture, RAP40, RAP40CR2, and RAP40CR6 was 3115.88 MPa, 6078 MPa, 5677.53 MPa, and 3192.53 MPa, respectively. Based on the results, it is conspicuous that RAP40-modified asphalt was 95% stiffer, while RAP40CR2-modified asphalt was 82% stiffer than the control sample. The addition of RAP40 mixture exhibited the greatest stiffness because incorporating RAP introduces aged binder that is significantly harder and more brittle than virgin binder. This binder has undergone substantial physical and chemical changes during its previous service life, resulting in a noticeably stiffer asphalt mixture [55], [56]. The stiffness modulus values of RAP40CR2 and RAP40CR6 declined due to the further injection of CR with the RAP. The probable reason for this reduction in the stiffness modulus with increasing CR content might be insufficient bond in the binder [57]. Additionally, all asphalt mixtures modified with RAP and CR met the minimum standard requirement of 2 kN as specified by JKR. Mixtures with higher stiffness values exhibit greater resistance to creep deformation and are more effective in distributing applied loads [58].

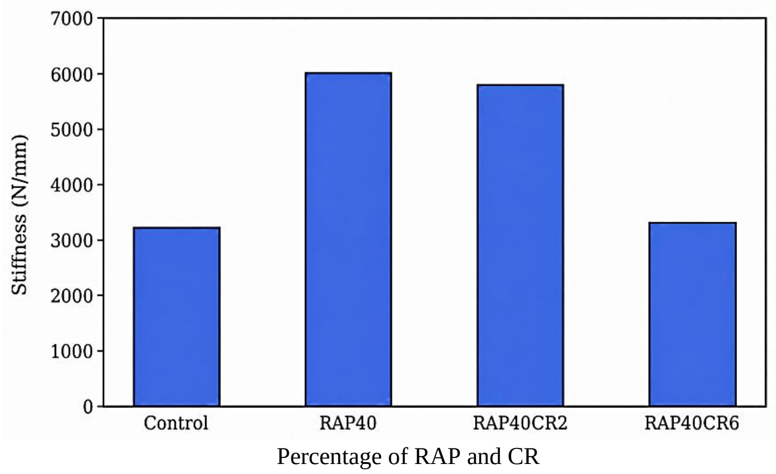

Figure 4. Stiffness of the modified asphalt mixtures

3.1.3 Stability

The stability of the asphalt mixture was affected by the addition of RAP and CR, as well as the consistency of the asphalt binder. Figure 5 presents the stability test results, revealing a notable trend. Stability initially rose by incorporating RAP40, which was higher than other mixes. The RAP40 mixture achieved a stability value of 20,744.58 N, which is approximately 77% higher than that of the control mixture, which had a stability of 11,718.5 N. This is because incorporating RAP introduces aged, stiff binder that strengthens the mixture, increasing its stiffness and viscosity when blended with new binder. As a result, the pavement exhibits improved high-temperature performance, greater resistance to heavy loads, and reduced susceptibility to permanent deformation, such as rutting [59]. On the contrary, the stability values had declined with the addition of different percentages of CR (2% and 6%). Incorporating CR aggregates into an asphalt mix resulted in lower stability at 4.5% binder content, which corresponds to increased CR content [60]. The inclusion of CR reduces pavement stability by decreasing the contact between coarse aggregates, which softens the mixture and makes it more susceptible to deformation. CR absorbs lighter oils from the binder, causing the rubber particles to swell—sometimes three to five times their original size—which increases binder viscosity and flexibility while reducing the mixture's resistance to loading and flow [61]. At higher contents, this effect further diminishes overall stability and durability [62].

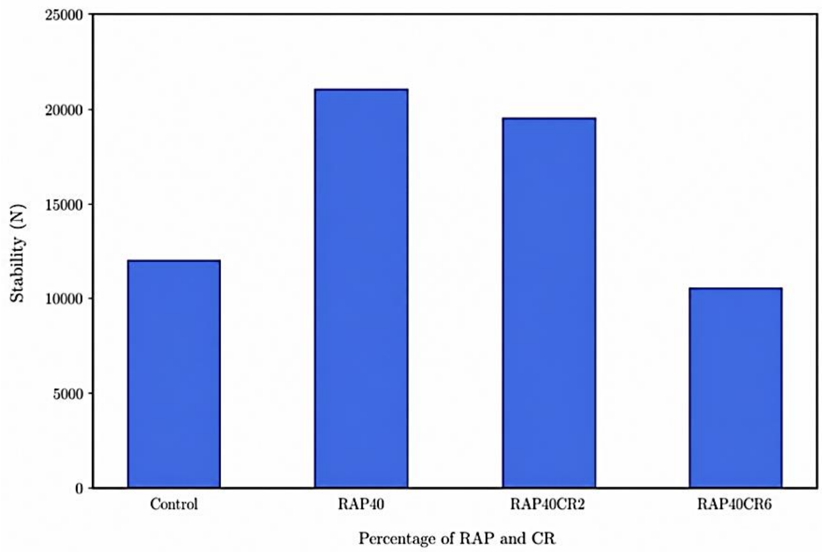

Figure 5. Stability of the modified asphalt mixtures

3.1.4 Flow test

Flow value reflects the flexibility of asphalt mixtures. As shown in Figure 6, the flow values of the modified mixtures decreased compared to the control mix. Specifically, the RAP40 and RAP40CR2 mixtures recorded flow values of 3.42 mm and 3.37 mm, respectively, whereas the control sample showed a flow value of 3.77 mm. The incorporation of RAP and a small amount of CR reduce pavement flow, which represents permanent deformation, by increasing the mixture's stiffness and elasticity. This improvement enhances the pavement's durability, allowing it to better withstand traffic loads and high temperatures [63]. However, a slight increase in flow was noted for the RAP40CR6 mixture. The addition of excessive CR increases the flow value because these materials contribute to a higher binder content and improved flexibility, leading to increased deformation under loading [64]. Importantly, all mixture results meet the standard specification requirements, stipulating a flow range of 2.0 mm to 4.0 mm for road applications [58]. This variation in flow values can be attributed to the different content compositions in the mixture. Higher flow values may indicate the potential for permanent deformations such as rutting or shoving during pavement service life, while excessively low values may lead to cracking under heavy loads.

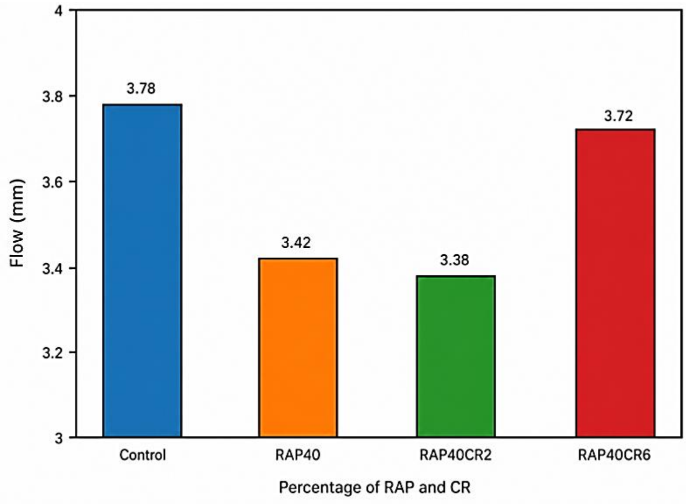

Figure 6. Flow of the modified asphalt mixtures

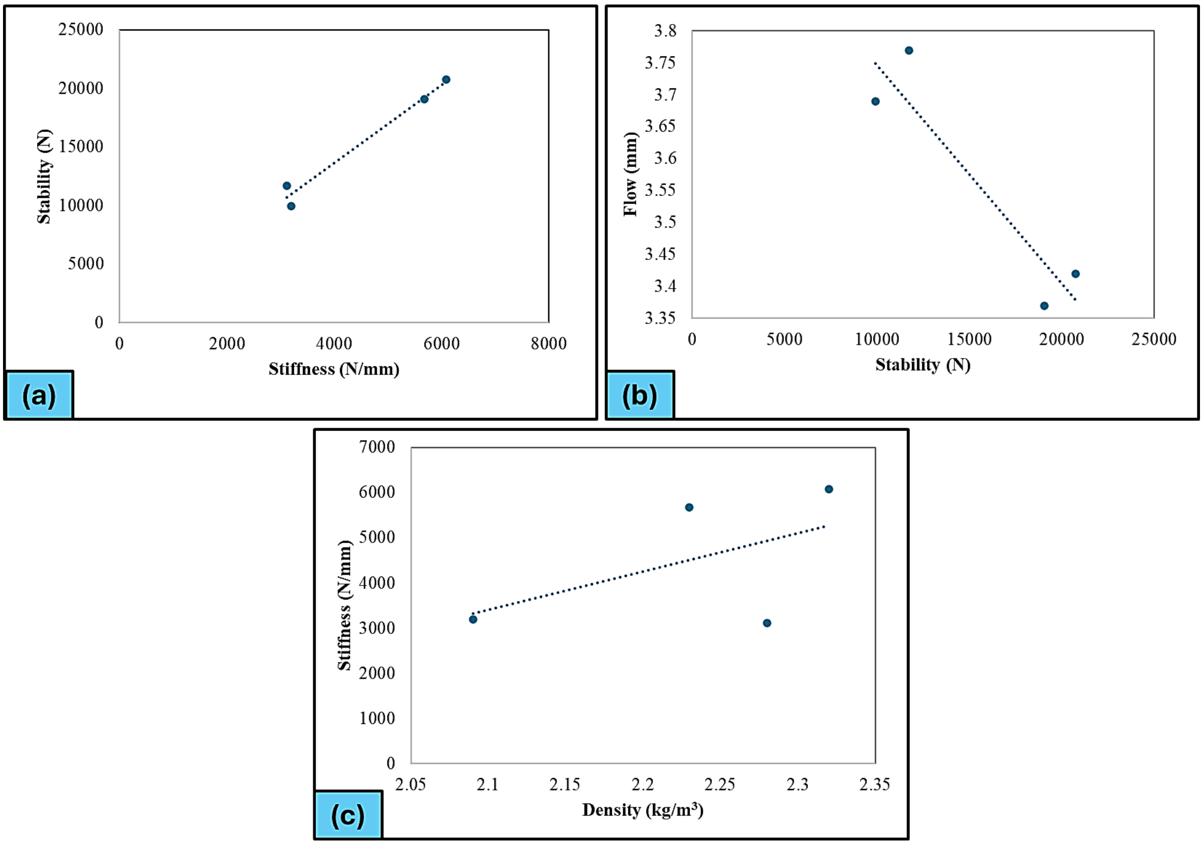

Figure 7. Correlation of RAP and CR modified asphalt mixture

3.2 Relationship of Volumetric Properties of Reclaimed Asphalt Pavement and Crumb Rubber

The results of the Marshall test reveal a relationship between stability, flow, and stiffness in the asphalt mixtures. Correlation analysis was conducted to evaluate the strength and direction of these relationships based on varying percentages of RAP and CR, as shown in Figure 7. Figure 7(a) illustrates the correlation between stability and stiffness. Both parameters increased with higher RAP and CR content, demonstrating a strong positive linear relationship. This is supported by a correlation coefficient (r-value) of 0.987, which is very close to 1.0, indicating a strong positive correlation. The combined use of RAP and a small amount of CR enhances pavement stiffness and stability by strengthening the asphalt binder and increasing resistance to permanent deformation. RAP contributes aged binder and aggregates, while CR improves the binder's viscoelastic properties [65]. Figure 7(b) presents the correlation between stability and flow. As the RAP and CR content increased, stability improved while flow decreased. This is because the aged, stiffer binder in RAP and the swelling of CR particles both increase the overall stiffness and internal friction of the asphalt mixture. The stiffer RAP binder enhances load-bearing capacity (higher stability), while CR absorbs lighter oils, swells, and increases binder viscosity and elasticity, limiting excessive deformation and plastic flow under load [66]. This inverse relationship is represented by a strong negative linear correlation, with an r-value of 0.9276, again indicating a strong association between the two variables. Meanwhile, Figure 7(c) shows the relationship between stiffness and density. An increase in RAP and CR percentages led to higher values in both stiffness and density, suggesting a positive linear correlation. This effect is attributed to the aged, hardened binder in RAP, while the small amount of CR increases stiffness through its elastic properties and interaction with the binder. Together, these materials create a denser pavement structure, enhancing overall performance and durability [67]. However, the correlation coefficient here is 0.537, which indicates a moderate relationship, as the value is relatively distant from 1.0.

3.3 Resilient Modulus

Figure 8 displays the resilient modulus values of the asphalt mixtures containing RAP and CR, as well as the control mix, tested at temperatures of 25°C and 40°C. At 25°C, the RAP40CR2 mixture found the highest resilient modulus at 6567 MPa, followed by RAP40 at 4652.50 MPa, and the control mix at 4617 MPa. These results indicate that the mixture containing 40% RAP and 2% CR exhibited superior recoverability after loading at medium and high temperatures. This is attributed to the combined effect of increased stiffness from the aged RAP binder and improved elasticity from the CR particles at intermediate temperatures [65]. Furthermore, the RAP40CR2 mixture showed a higher complex shear modulus (G) and a lower phase angle (δ) with the bitumen, resulting in the greatest rutting resistance, while the reduced phase angle at low temperatures enhanced its resistance to fatigue cracking [68].

On the other hand, at 40°C, the resilient modulus decreased across all samples, with values of 3596 MPa for RAP40CR2, 2763 MPa for RAP40, 2116.50 MPa for the control mix, and the lowest value of 1378 MPa for RAP40CR6. An increase in heating temperature reduces the resilient modulus due to variations in the coefficients α and β [69]. Additionally, CR increases the binder's viscosity, making the asphalt mix stiffer and more durable. Because of its increased stiffness, the pavement can withstand heavy loads without changing shape, reducing the risk of rutting [70]. At both temperature points, RAP40 and RAP40CR2 showed greater robust modulus values than the control mix. However, RAP40CR6 showed lower resilient modulus values than the control mixes at both temperatures. The strong connection and high adhesiveness between RAP and CR enabled the formation of the aggregate particle [56]. The development of the RAP40CR2 asphalt mixture's stiffness and elasticity improved the mixture's resistance performance.

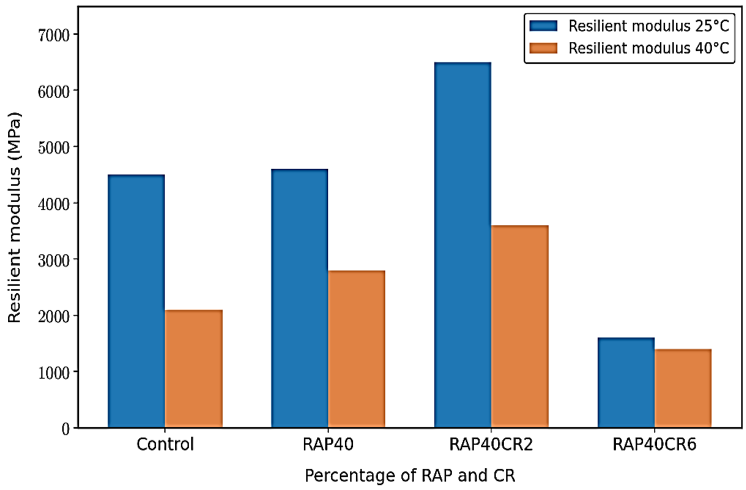

Figure 8. Resilient modulus of modified asphalt mixtures

3.4 Dynamic Creep

Dynamic creep tests assess permanent strain and deformation in asphalt mixtures. At 40 °C, the total permanent strain of the control mix was lower compared with that of the RAP and CR-modified HMA mixtures. As shown in Figure 9, incorporating RAP and CR did not lead to a substantial improvement in rutting resistance relative to the control mixture. Li et al. [71] showed that using RAP in HMA yields higher dynamic modulus values than in control specimens. The

RAP40 thus properly complies with the proven experiments in terms of dynamic strain. Among the modified mixtures, RAP40CR2 exhibited the highest permanent strain compared to RAP40 and RAP40CR6. Since permanent strain directly influences permanent deformation, this had a notable impact on the mixture's performance. The graph shows that asphalt mixtures containing RAP and CR underwent greater permanent deformation up to failure when compared to the control mixture. Notably, the deformation curves for RAP40 and RAP40CR2 overlapped at around 1800 cycles, after which RAP40 consistently showed lower deformation than RAP40CR2, indicating the higher susceptibility of RAP40CR2 to strain-induced deformation. This is because the permanent strain values of RAP40 and RAP40CR6 are similar. It is noteworthy to mention that all samples exhibited the tertiary zone, indicating a high level of resistance to irreversible deformation.

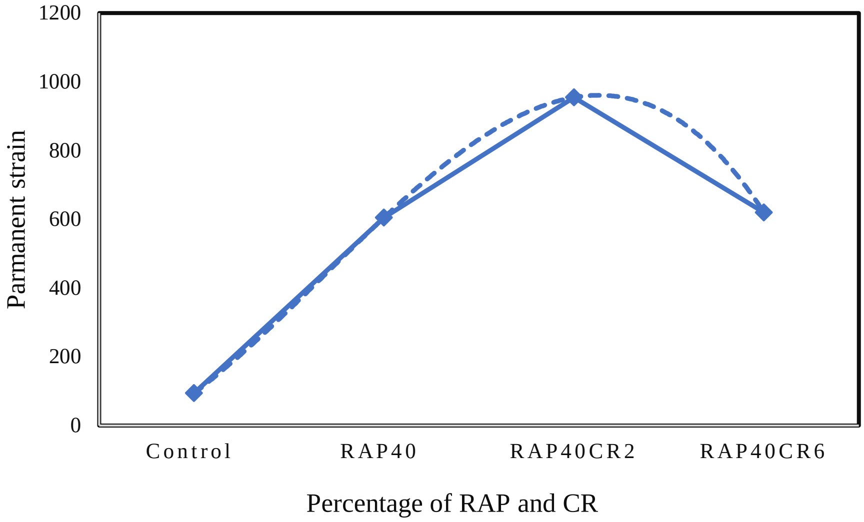

Figure 9. Permanent strain of RAP and CR modified asphalt mixture

Figure 10 presents the progression of permanent deformation as a function of loading cycles for the control and RAP-modified asphalt mixtures incorporating different crumb rubber contents. The observed differences in strain accumulation are governed by the combined effects of binder rheology, aggregate structure, and viscoelastic energy dissipation mechanisms introduced by the modification of RAP and CR [72]. The control mixture exhibits the lowest permanent deformation throughout the loading history, which can be attributed to its relatively higher effective binder content and more uniform binder coating, allowing for improved stress redistribution and reduced localised shear deformation [39]. In contrast, the incorporation of 40% RAP introduces a stiffer aged binder, which restricts stress relaxation and increases susceptibility to irreversible strain accumulation, particularly during the early loading cycles. All mixtures exhibit a rapid increase in permanent deformation during the initial loading stage, corresponding to the primary strain accumulation zone. This is followed by a gradual and stable deformation rate associated with the secondary zone, suggesting enhanced internal resistance to shear flow [72]. The absence of an abrupt acceleration in deformation at higher cycles indicates a delayed or suppressed tertiary flow region, highlighting the mixtures' ability to withstand long-term repetitive loading [73].

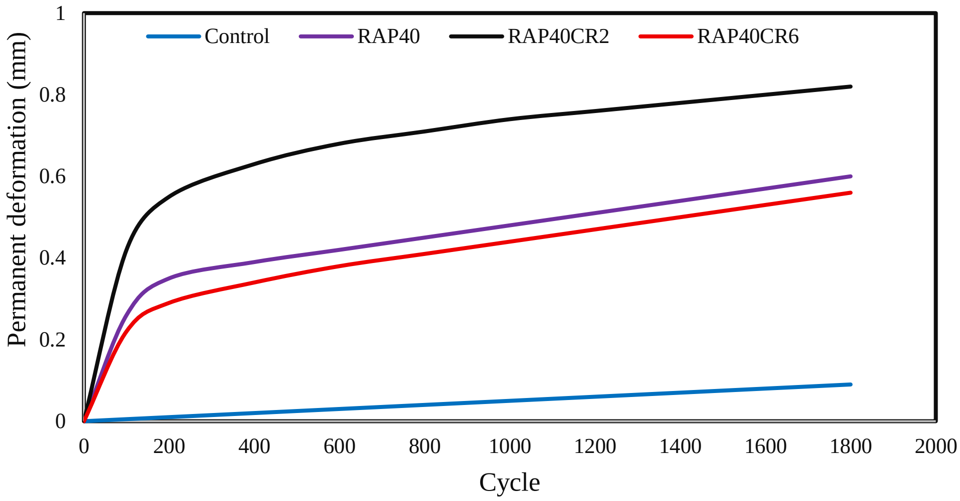

Figure 10. Permanent deformation of RAP and CR modified asphalt mixture

Creep stiffness values for the tested mixtures are presented in Figure 11. The results indicate that incorporating RAP and CR generally reduced creep stiffness compared to the control mixture. However, the inclusion of CR slightly increased the stiffness within the modified mixtures. This is because the rubber particles swell and absorb lighter components of the asphalt binder. This raises the binder's viscosity and elasticity, producing a more resilient material that resists deformation and offers higher high-temperature stiffness, thereby improving rutting resistance [74]. Among all samples, RAP40 showed the highest stiffness, followed by RAP40CR2 and then RAP40CR6. Incorporating RAP significantly increases a mixture's creep stiffness because RAP contains a hardened, aged asphalt binder [75]. This indicates that while the presence of CR enhances stiffness to some extent, the RAP40 mixture without CR demonstrated the greatest stiffness overall, with the stiffness decreasing as the CR content increased in the RAP-modified mixtures. The analyses showed that the RAP40 and RAP40CR2 modified can increase the permanent deformation of the asphalt mixture.

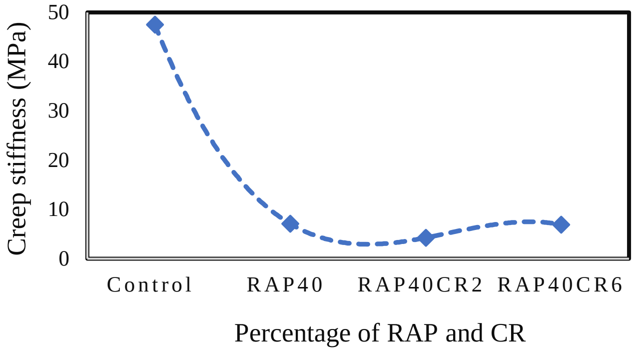

Figure 11. Creep stiffness of RAP and CR modified asphalt mixture

4. Conclusions

This research examined the performance of asphalt mixes containing RAP and varying amounts of CR used as aggregate replacements. The incorporation of 40% RAP resulted in enhanced Marshall stability, exceeding that of the control samples. Furthermore, the addition of 2% and 6% CR further improved stability and stiffness while reducing flow values compared to the control mixtures. Among all the mixtures, RAP40CR2 exhibited the lowest flow value as well as the highest stability and stiffness, and it met the requirements specified by the standard specifications. In addition, the correlation analysis of Marshall stability revealed a strong relationship between RAP–CR–modified asphalt mixtures. The resilient modulus increased at both 25 °C and 40 °C with the incorporation of RAP and CR, indicating an improved ability of the asphalt mixtures to recover their original shape after deformation. Notably, the mixture containing RAP40CR2 demonstrated the highest resistance to permanent deformation, highlighting the importance of bitumen elasticity in enhancing recovery performance. According to the dynamic creep test results, the permanent deformation behaviour, strain characteristics, and creep stiffness of both the control and RAP–CR–modified asphalt mixtures were effectively evaluated. Compared with the control samples, mixtures containing 40% RAP, RAP40CR2, and RAP40CR6 exhibited superior resistance to failure. However, due to its lower creep stiffness, RAP40CR2 showed relatively higher strain and deformation. Nevertheless, RAP40CR2 had a significant impact on improving stability. The findings of this study demonstrate that RAP–CR–modified asphalt mixtures can be successfully produced to meet the required volumetric and performance standards. Therefore, incorporating RAP and CR into asphalt mixtures represents a practical, cost-effective, and environmentally sustainable alternative.

The study effectively met its goals by examining the material's resilience and recoverable strain under repeated stress after adding coarse RAP and CR particles to HMA. Therefore, adding RAP and CR to the asphalt mix could be a practical, economical, and environmentally beneficial alternative. The study on HMA incorporating RAP and CR presents several limitations, such as the potential variability in the quality and characteristics of the RAP and CR materials, which can affect consistency in performance. Additionally, the long-term durability and performance of the modified asphalt under varying environmental and traffic conditions require further investigation. Practical applications of this research could include enhanced sustainability in asphalt pavement design by reducing the need for virgin materials and promoting recycling. Future research should focus on optimising the proportion of RAP and CR for different climate zones, evaluating the economic feasibility of large-scale implementation, and exploring alternative additives to improve the overall performance and lifespan of the modified asphalt.

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Declaration of Competing Interests

The authors declare no conflicts of interest.

Credit Authorship Contribution Statement

K. Hasan (Methodology; Formal analysis; Writing—original draft; Writing – review and editing)
R. Ferdaus (Methodology; Data curation; Software; Writing – review and editing)
A. Chowdhury (Methodology; Data curation, Software; Writing – review and editing)
S. S. Toha (Methodology; Formal analysis; Software; Writing – review and editing)
S. Ghosh (Methodology; Conceptualization, Supervision; Writing – review and editing)
R. P. Jaya (Analysis; Supervision; Conceptualization; Writing – review and editing)
F. M. Yahaya (Investigation; Validation; Supervision; Funding acquisition; Writing – review and editing)

Availability of Data and Materials

The data supporting this study's findings are available on request from the corresponding author.

Ethics Declarations

This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Declarations

The authors claim that artificially intelligent-assisted technologies, such as generative AI, were not used to generate content, ideas, or theories. We have just utilised AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

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