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ECO-FRIENDLY SOLUTION FOR UTILIZATION OF RECLAIMED ASPHALT PAVEMENT MATERIAL

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Abstract- Although Reclaimed Asphalt Pavement (RAP) is commonly used in road construction, research on its detailed laboratory and field performance is still limited. This study focused on evaluating the fundamental properties of RAP and identifying the optimal content for sustainable asphalt mixtures through a two-phase experimental approach. Key performance aspects such as rutting, cracking resistance, and moisture susceptibility were assessed. Results indicated that mixtures containing 40% RAP achieved the best balance of durability and sustainability. The Cooper wheel tracking test showed rut depths under 2.5 mm after 10,000 cycles, and the SCB test confirmed good fracture resistance at various temperatures. Moisture tests, including rolling bottle and boiling water methods, showed strong binder-aggregate adhesion with coverage above 85%. These findings suggest that with proper design, RAP can enhance pavement performance, reduce environmental impact, and lower the need for virgin aggregates by up to 40%.

Keywords- Fracture Resistance, Recycled Asphalt Pavement, Permanent Deformation, Moisture Damage

1 Introduction

Reclaimed Asphalt Pavement (RAP), obtained through the milling of aged pavements, has gained widespread use in road construction due to its durability and environmental advantages [1], [9], [15]. Though RAP naturally degrades over time from environmental exposure and traffic loads, its reuse in new asphalt mixtures significantly reduces the need for virgin aggregates and bitumen, contributing to lower material consumption, reduced landfill waste, and a more sustainable circular economy [9], [10], [15]. The RAP used in this study was sourced from the M-2 Motorway and had been in service for 15 years, highlighting its potential for reuse in infrastructure projects while decreasing greenhouse gas emissions and energy demands associated with material production and transportation.
Previous studies have demonstrated that RAP improves stiffness and load-bearing capacity due to the presence of aged binder [1], [5], [22]. However, excessive RAP content can compromise flexibility and increase the likelihood of cracking [6], [13], [21]. Optimal RAP content is often recommended in the range of 30–40% to achieve a balance between performance and sustainability [5], [12], [13]. To mitigate the adverse effects of aged binder, various rejuvenators such as sunflower oil, used cooking oil, and Cereclor have been successfully employed to restore flexibility, fatigue resistance, and aging durability in RAP binders [2]–[4]. Recent advancements in machine learning have further supported the optimization of mechanical properties like Indirect Tensile Strength (ITS) in rejuvenated RAP mixtures [18], [19].

Despite these developments, high RAP contents continue to present challenges such as incomplete blending with virgin binder and reduced coating efficiency, leading to inconsistent performance [20], [21]. Therefore, a performance-based approach is essential to optimize RAP dosage and binder properties for reliable pavement design. This study aims to evaluate the physical and mechanical characteristics of RAP through proper mix design and a series of laboratory tests—including wheel tracking, Semi-Circular Bend (SCB), boiling water, and rolling bottle tests—to identify the optimal RAP content for cost-effective, durable, and environmentally friendly asphalt pavement mixtures.

2 Research Methodology

2.1 Laboratory Testing Program

A detailed laboratory program was conducted in two phases to assess RAP suitability, as outlined in Table 1 and illustrated in Figure 1. In Phase 1, RAP from the M-2 Motorway was tested for binder content (3.8%) using the Centrifuge Extraction Method (ASTM D2172) and analyzed for gradation under NHA Class B limits. It was blended with 80/100-grade virgin bitumen, and trial mixes were designed to meet Marshall criteria for stability, air voids, VMA, VFA, and flow. Mixtures with 0%, 25%, 50%, and 100% RAP were prepared to determine the optimum bitumen content. Phase 2 involved performance-based testing of these mixtures, summarized in Table 2, to evaluate mechanical behavior and durability. Using a softer 80/100 binder effectively restored aged RAP binder properties, enhancing flexibility and blending without chemical rejuvenators. Results showed that moderate RAP levels (25–50%) maintained good moisture resistance and durability, while higher RAP contents increased stiffness, reduced binder coating, and raised moisture susceptibility.

Table 1: Laboratory Tests Matrix

Test Name	Standard	Input Parameters	Output Parameters
Bitumen Extraction Test	ASTM D 2172	Solvent: 1000 mL CCl_4, Extraction time: 45-60 minutes, Temperature 120 °C	Optimum Bitumen Content
Marshall Stability	ASTM D-6927	Loading rate: 50 mm/min, Test temperature 60 °C, Core Diameter: 4 inches, Height: 2.5 inches,	Stability values (kg)
Bulk Specific Gravity	ASTM D-2726	25 °C, Weight measurement nearest to 0.01 g in water, air and SSD states	Bulk specific gravity (Gmb)
Cooper Wheel Tracker Test	EN 12697-22	10000 passes, Frequency: 26.5 rpm Load: 720 N, Terminal Rut Depth: 12.5 mm	Permanent Deformation/Rutting Depth
Rolling Bottle Test	EN 12697-11	Temperature:50°C, 60°C, 70°C, Rotation Speed15 rpm, 20 rpm	Durability
Semi Circular Bend	ASTM D 8044-16	Temperature: 40°C to 50°C; Frequency: 1 Hz	Cracking resistance under repeated loading.
Boiling Water Best	ASTM D3626	Temperature (around 100°C or 212°F).Time up to 10 minutes.	Moisture damage

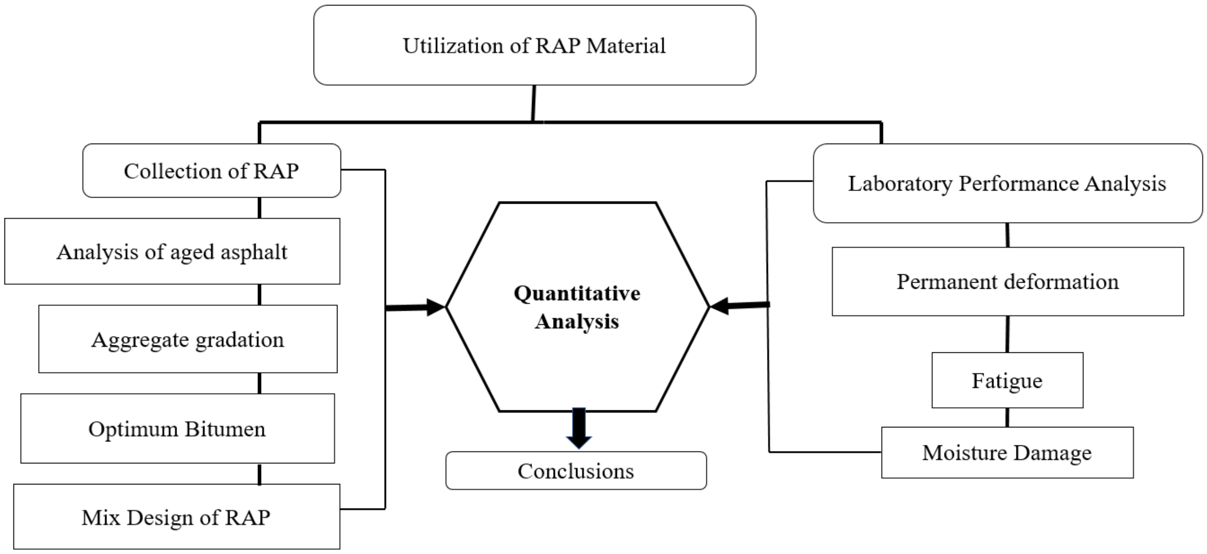

Figure 1: Flow chart of the experimental plan

Table 2: Marshal Parameters Determined For RAP Mix

RAP Contents (%)	Stability (Kg)	Flow (mm)	Unit Weight (Kg/m^3)	VA (%)	VMA (%)	VFA (%)
0	1150	12.7	2340.1	5.60	14.90	68.20
25	1121	11.2	2351.2	5.20	14.40	70.20
50	1230	10.77	2363.0	4.20	13.30	72.40
100	1280	9.2	2336.5	4.00	12.96	73.90

2.2 Aggregate Gradation

Aggregate gradation was performed on RAP aggregate under the NHA class B limitations, and a gradation curve was obtained by plotting the percentage passing versus the corresponding sieve size, as shown in Figure 2.

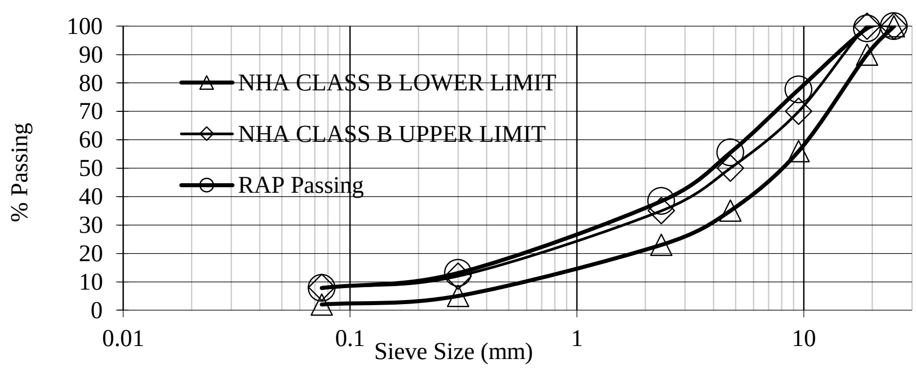

Figure 2: Gradation Curve for RAP Aggregates

2.3 Performance Testing of Asphalt Mixtures

These tests, aligned with international standards, provided a comprehensive understanding of the rutting, cracking, and moisture resistance performance of RAP-containing mixtures.

i. Cooper Wheel Tracking Test (BS EN 12697-22): Used to evaluate rutting resistance under simulated traffic loading. Rectangular slab specimens were tested at 50°C with 10,000 cycles, and rut depths were recorded at predefined intervals.
ii. Semi-Circular Bend (SCB) Test (ASTM D8044-16): Assessed fracture resistance and cracking potential at low temperatures. Semi-circular specimens (150 mm diameter, 62 mm thick) with a notch depth of 19–20 mm were tested to determine fracture energy from load-displacement behavior.
iii. Rolling Bottle Test (EN 12697-11): Evaluated binder-aggregate adhesion under moisture conditioning. 150 g of aggregate (6.3–8 mm) was rotated in 400 ml of water at 60 rpm, and binder coverage was visually assessed after 24, 48, and 72 hours.
iv. Boiling Water Test (ASTM D3626): Measured moisture susceptibility by immersing 250 g of loose asphalt mixture in boiling water for 10 minutes, followed by visual evaluation of binder stripping.

3 Results

3.1 Cooper Wheel Tracking Test

The test results show valuable insights from Cooper Wheel Tracking into the rutting resistance of the RAP material under repeated traffic load at high temperature. The curves show that higher RAP contents show higher resistance to permanent deformation after 10,000 wheel cycles. Mixture with (0% RAP) showed that the rut depth of 5.8mm, and the RAP material with 100% showed a rut depth of 1.9 mm. The RAP of 25% and 50% showed 4.1 mm and 2.2 mm, respectively, as shown in Figure 4.

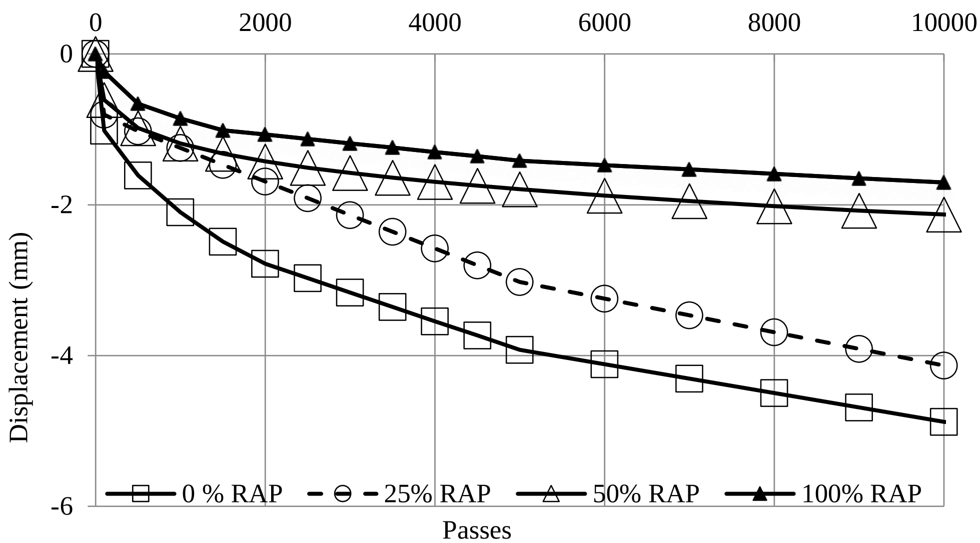

Figure 4: Influence of wheel passes on rut depth at different RAP percentages

Figure 4 demonstrates that rutting decreased as RAP content increased. The mix with 0% RAP showed a displacement of 5.88 mm, exceeding the AASHTO limit of 4 mm, whereas mixtures with 25%, 50%, and 100% RAP recorded rut depths of 4.13 mm, 2.25 mm, and 1.91 mm, respectively—all within acceptable limits. These results align with previous findings that attribute improved rutting resistance to the stiffness of aged binder in RAP mixtures [22], [18]. However, excessive RAP content can compromise flexibility, increasing the risk of cracking [21].

3.2 Semi-Circular Bend Test

The Semi-Circular Bend (SCB) test, conducted according to ASTM D8044, evaluated the fracture resistance of RAP mixtures. At intermediate temperatures, mixes with 25–40% RAP showed fracture energy comparable to or slightly exceeding the control (510 N), with 25% and 50% RAP yielding 570 N and 350 N, respectively. However, at 100% RAP, fracture energy dropped to 242 N, indicating increased brittleness and a higher risk of cracking at elevated RAP levels, as shown in Table 3.

Table 3: Fracture Resistance (N) of asphalt mixtures at different RAP percentages.

Sample	0% RAP	25% RAP	50% RAP	100% RAP
Fracture Resistance N	510 N	570 N	350 N	242 N

3.3 Rolling Bottle Test

This test is used to assess the stripping or loss of adhesion between asphalt binder and aggregate in the presence of water. It provides insight into the moisture damage that may occur in asphalt mixtures under wet conditions. Figure 5 shows the percentage of binder coverage remaining after different conditioning periods (24, 48, and 72 hours) for various RAP percentage

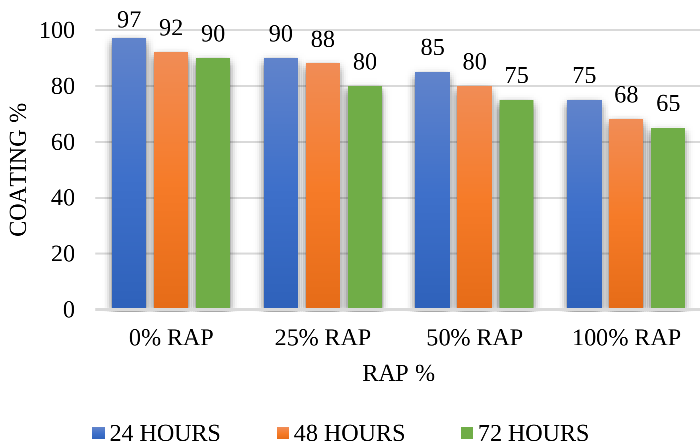

Figure 5: Effect of conditioning time and RAP percentages on binder coating

3.4 Boiling Water Test

The Boiling Water test (ASTM D3626) showed over 90% coating retention for RAP contents up to 40%, and 80–85% for higher RAP levels. This indicates good moisture resistance at moderate RAP use, but potential durability concerns at higher contents, as shown in Figure 6.

3.5 Equations

The aged binder in RAP improves stiffness and rutting resistance but reduces flexibility, increasing cracking risk. Poor blending at high RAP levels can weaken bonding and performance. To achieve balanced properties, RAP content was optimized using a performance-based method.

$$\text{Performance Index} = \frac{\text{Fracture Resistance} \times \text{Moisture Resistance}}{\text{Rut Depth}} \quad (1.0)$$

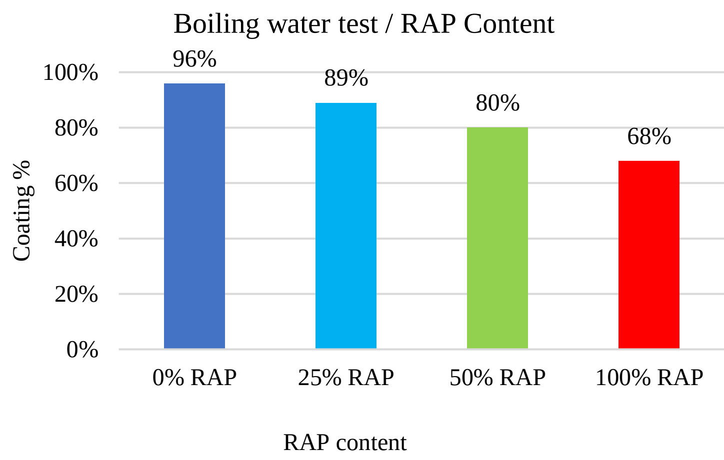

Figure 6: Effect of RAP percentage on binder coating

Table 4: Performance testing results of asphalt mixtures

Permanent Deformation test Rut Depth mm	**0% RAP**	**25%RAP**	**50%RAP**	**100%RAP**
Rut Depth mm	5.8	4.1	2.2	1.9
Fracture Resistance N	510	570	350	242
AVG OF Boiling Water and Rolling Bottle test	95%	90%	82%	70%

Table 5: Performance index for optimum asphalt content

0% RAP	**25% RAP**	**50%RAP**	**100%RAP**
83.5	125.1	130.5	89.2

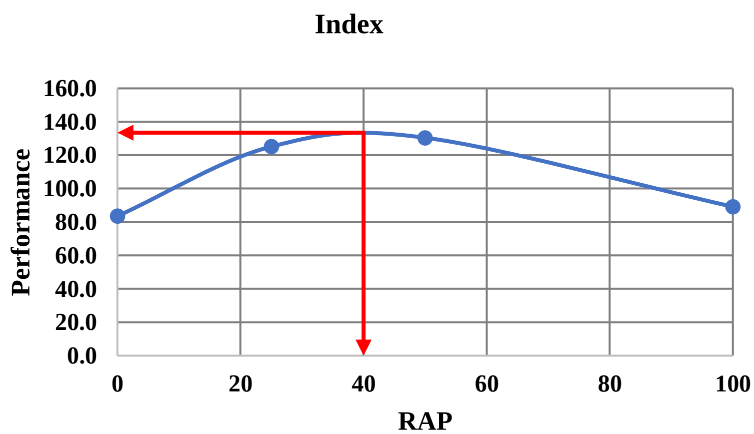

Figure 6: Optimum asphalt content based on performance index

4 Conclusion

This study identified 40% RAP as the optimal content for balanced asphalt performance, offering good rutting resistance, fracture energy, and binder coating. Mixes with 25–50% RAP showed strong durability and moisture resistance, while higher contents improved rutting but reduced fracture strength due to aged binder. The findings support cost-effective, eco-friendly pavement design and quality control through performance testing. However, results are based on lab conditions, excluding long-term factors like traffic and climate. Future research should include field trials and binder analysis. Challenges such as binder variability, limited blending at high RAP levels, and inconsistent standards hinder widespread adoption. Performance-based design and methods like Super pave are recommended for better control.

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