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Rheological and Performance Evaluation of Reclaimed Asphalt Pavement (RAP) in Flexible Pavement Construction

A Comprehensive Experimental and Sustainability Assessment

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Abstract- reinforced Growing demand for sustainable infrastructure has intensified interest in recycled construction materials, particularly Reclaimed Asphalt Pavement (RAP). RAP offers environmental and economic advantages by reducing demand for virgin aggregates and bitumen; however, aged binder stiffening and reduced flexibility can increase fatigue and cracking susceptibility if not properly managed. This study presents a laboratory evaluation of asphalt mixtures incorporating RAP at replacement levels of 0%, 10%, 20%, 30% and 40%, with binder contents between 5.0% and 7.0%. Testing included conventional binder characterisation (penetration, softening point, flash and fire point), Marshall stability and flow analysis, volumetric evaluation (air voids, VMA and VFA) and microstructural/chemical assessment using SEM, XRD and XRF.

Results indicate that moderate RAP inclusion increases mixture stiffness and improves rutting resistance while maintaining acceptable durability indicators. At higher RAP contents, oxidative aging effects become dominant, increasing brittleness and raising fatigue-cracking risk. The study concludes that RAP can serve as both a sustainability intervention and a performance-enhancing material when proportioned optimally and supported by appropriate binder selection and quality control, aligning flexible pavement construction with circular economy objectives.

Keywords: Reclaimed asphalt pavement; RAP; Asphalt recycling; Marshall stability; Rheology; Binder aging; Volumetric properties; Sustainability; Rutting resistance; Fatigue performance.

1. Introduction

Flexible pavement construction remains one of the most material-intensive activities in civil engineering, relying heavily on virgin aggregates and bituminous binder. Both materials require energy-intensive extraction and processing, and their supply is increasingly shaped by environmental regulation, cost volatility and sustainability targets. These pressures have accelerated the adoption of recycling strategies that reduce embodied carbon and conserve natural resources.

Reclaimed Asphalt Pavement (RAP) is among the most viable options in pavement engineering because it contains high-quality aggregates and aged binder recovered from milled or reconstructed asphalt layers. When correctly processed and blended with virgin materials, RAP reduces consumption of newly quarried aggregates and can partially replace virgin binder demand. This creates direct cost savings and delivers measurable environmental benefit through reduced extraction and reduced bitumen production impacts.

The engineering challenge lies in the rheological condition of the aged binder. Oxidative aging increases stiffness, raises viscosity and reduces ductility. While increased stiffness can enhance rutting resistance under high temperatures, it may also reduce strain tolerance and increase thermal and fatigue cracking risk. For this reason, RAP mixtures require robust volumetric control and performance-informed testing rather than relying solely on traditional empirical criteria.

This study evaluates how RAP percentage and binder content influence mixture performance and identifies a practical RAP range that maximises benefits without compromising durability.

2. Background and Theoretical Context

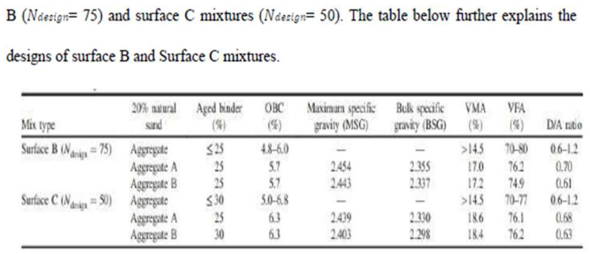
Sustainable construction increasingly adopts circular economy principles that keep materials in productive use for longer. RAP aligns strongly with this approach because it reintegrates a high-value pavement material into new asphalt production rather than directing it to landfill. In addition to reducing aggregate mining, RAP can reduce the demand for virgin binder, which is among the most carbon-intensive components in asphalt mixtures.

However, sustainability gains must be achieved without reducing pavement life. Where RAP increases brittleness and shortens fatigue life, any carbon and cost benefits may be offset by earlier rehabilitation. A performance-based approach is therefore necessary to balance stiffness improvement against cracking risk, particularly in climates or traffic regimes where fatigue loading is dominant.

3. Methodology

A factorial laboratory programme was adopted to evaluate both the independent and interactive effects of RAP content and binder content. Seventy-five specimens were prepared across RAP replacement levels of 0%, 10%, 20%, 30% and 40%, and binder contents of 5.0%, 5.5%, 6.0%, 6.5% and 7.0%. RAP was sourced from the Julius Berger KM 38 Yard in Shagamu, Lagos, and was processed to ensure consistent gradation and removal of oversized contaminants. Virgin aggregates, binder and mineral filler were characterised to confirm suitability for mixture production.

Binder recovered from RAP was extracted using solvent-based procedures and compared against virgin binder to determine stiffness changes attributable to aging. Aggregate gradation was checked through sieve analysis and adjusted to maintain mixture stability and adequate void structure. Marshall compaction and testing were performed at 60°C to evaluate stability, flow and associated volumetric properties. To strengthen interpretation beyond empirical results, microstructural and chemical techniques (SEM, XRD, XRF) were used to assess morphology, mineral composition and binder–aggregate interaction characteristics, with particular focus on indicators of aging-related densification and adhesion variation.

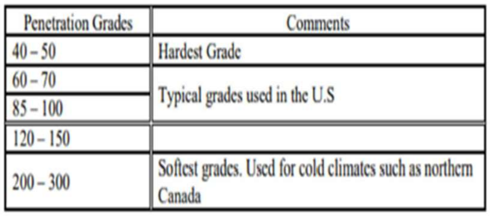


B (N_{design}= 75) and surface C mixtures (N_{design}= 50). The table below further explains the designs of surface B and Surface C mixtures.

Mix type	20% natural sand	Aged binder (%)	OBC (%)	Maximum specific gravity (MSG)	Bulk specific gravity (BSG)	VMA (%)	VFA (%)	D/A ratio
Surface B (N_{design} = 75)	Aggregate	≤25	4.8–6.0	—	—	>14.5	70–80	0.6–1.2
	Aggregate A	25	5.7	2.454	2.355	17.0	76.2	0.70
	Aggregate B	25	5.7	2.443	2.337	17.2	74.9	0.61
Surface C (N_{design} = 50)	Aggregate	≤30	5.0–6.8	—	—	>14.5	70–77	0.6–1.2
	Aggregate A	25	6.3	2.439	2.330	18.6	76.1	0.68
	Aggregate B	30	6.3	2.403	2.298	18.4	76.2	0.63

Figure 3: Mix Designs of Surfaces B and C Mixtures

- **Calculation**



Penetration Grades	Comments
40 – 50	Hardest Grade
60 – 70	Typical grades used in the U.S
85 – 100	
120 – 150	
200 – 300	Softest grades. Used for cold climates such as northern Canada

Figure 1: AASHTO M20 and ASTM D946 Penetration Grades

4. Results and Discussion

Marshall stability increased with RAP content up to approximately 30%, indicating enhanced stiffness and improved resistance to rutting. This is consistent with the presence of oxidised binder in RAP, which increases mixture modulus and improves load-bearing capacity at elevated temperatures. At 40% RAP, the stability gain was accompanied by reduced flexibility indicators, suggesting that stiffness benefits begin to trade off against cracking susceptibility as aged binder becomes more dominant in the blended system.

Volumetric results show that RAP influences both binder distribution and void structure. With appropriate binder contents, VFA levels indicated improved moisture resistance potential; however, higher RAP contents reduced effective VMA in some combinations, producing denser mixtures that may be more vulnerable to cracking under repeated strain. This confirms that volumetric optimisation is essential and that binder content cannot be treated as a constant across RAP levels.

Rheological interpretation from binder tests and chemical observations indicated oxidative aging effects, including increased viscosity and reduced maltene fraction, consistent with stiffened binder behaviour. Moderate RAP blends exhibited a workable balance between rut resistance and strain tolerance, whereas high RAP contents were more likely to show brittle response characteristics unless mitigated through softer binder selection or rejuvenator use.

Overall, the results suggest an optimal RAP range typically between 20% and 30% for conventional wearing course applications under moderate to high traffic, subject to local climate and binder grade selection.

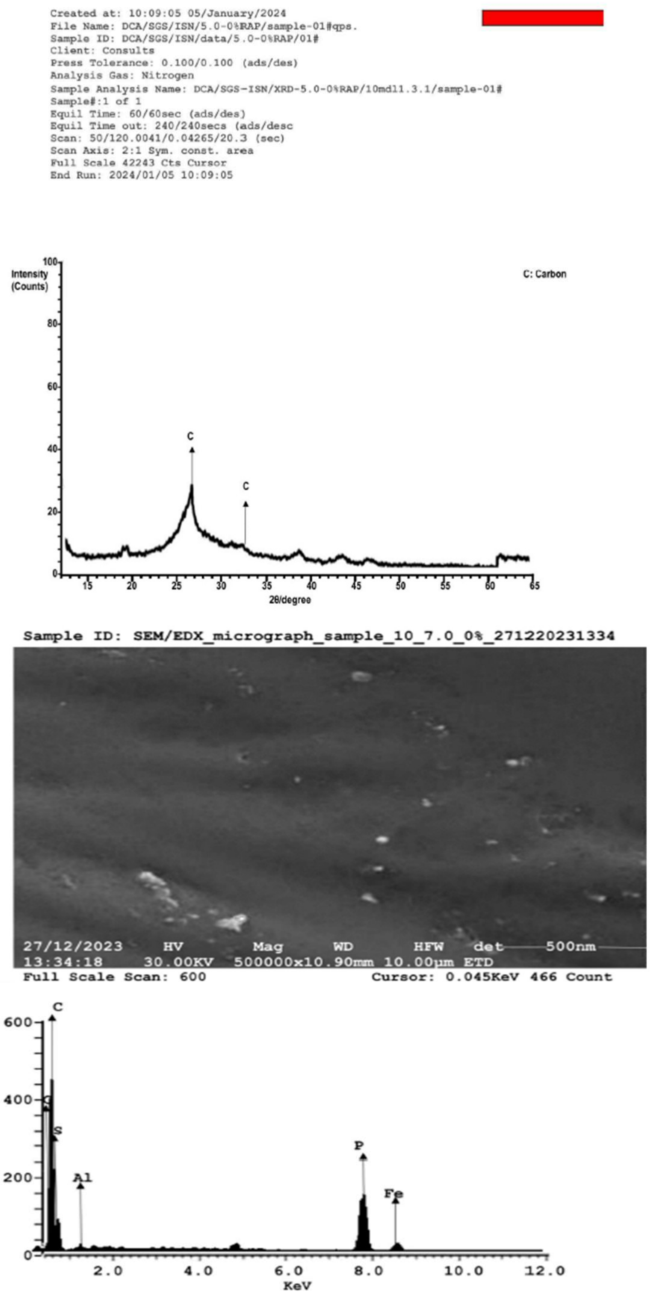


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Fig 17: Scanning electron microscope result for 7.0 BC, 0% RAP

5. Engineering and Industry Implications

From a practical implementation perspective, RAP contents in the range of 10% to 30% can deliver both performance improvements and sustainability gains without requiring major redesign of conventional production processes, provided quality control ensures consistent RAP gradation, moisture management and controlled blending. At higher RAP contents, performance can still be achieved but typically requires additional interventions such as rejuvenators, softer binder grades, or stricter control of effective binder activation and blending efficiency.

For developing regions, RAP offers significant cost reduction potential while supporting durable pavement construction when integrated into performance-informed mix design procedures.

6. Conclusion

This study confirms that RAP is not solely a recycled substitute but can function as a performance-influencing component in asphalt mixtures when properly proportioned. Moderate RAP levels improve stiffness and rutting resistance, but excessive RAP content increases brittleness and elevates cracking risk. Rheological assessment remains essential for identifying acceptable blending ranges and selecting suitable binder strategies. RAP therefore supports sustainable pavement development without compromising structural integrity when engineered using appropriate volumetric control and performance evaluation.

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