

Performance Recovery of Aged Asphalt in RAP Mixtures Using Sugarcane Bagasse Bio-Rejuvenator: Moisture Susceptibility and Rutting Behaviour Analysis

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ABSTRACT

The incorporation of Reclaimed Asphalt Pavement (RAP) into hot mix asphalt offers substantial environmental and economic advantages; however, the presence of aged asphalt binder often leads to excessive stiffness, reduced durability, and limited workability, necessitating the use of rejuvenating agents to restore performance. This study investigates the potential of a sugarcane bagasse-based bio-rejuvenator to enhance the mechanical and durability characteristics of AC-WC mixtures containing varying RAP contents. Three mixtures were prepared at their respective optimum asphalt contents and evaluated through Marshall Stability, Marshall Immersion, and wheel tracking tests to assess structural integrity, moisture susceptibility, and resistance to permanent deformation. The incorporation of the bio-rejuvenator consistently improved the performance indicators across all RAP levels, demonstrating its capability to restore binder functionality, enhance mixture cohesion, and strengthen resistance against moisture-induced damage. Furthermore, the rejuvenated mixtures exhibited improved deformation resistance under repeated loading, indicating a more stable internal structure and better long-term rutting performance. These findings indicate that sugarcane bagasse bio-rejuvenator not only restores workability but also significantly enhances moisture resistance and rutting performance of RAP asphalt mixtures.

Keywords: Sugarcane bagasse, Bio-rejuvenator, Bio-asphalt, Reclaimed asphalt pavement (RAP).

INTRODUCTION

The increasing use of Reclaimed Asphalt Pavement (RAP) in asphalt mixtures is driven by the need to reduce construction costs, conserve natural aggregates, and promote circular economy practices (Poulikakos L. D. et al., 2017; Mantalovas K. et al., 2019; Peduzzi A. et al., 2023; Xiao F. et al., 2019). However, the aged asphalt contained in RAP typically exhibits increased stiffness, oxidation, and brittleness, which worsens mixture workability and leads to premature distresses such as moisture damage and rutting. Previous studies have shown that oxidative aging alters the viscoelastic behavior of asphalt binder, making rejuvenation essential to restore its functional properties (Yang et al., 2017).

Bio-based rejuvenators have gained significant attention as sustainable alternatives to petroleum-derived softening agents. Bio-oils derived from biomass contain natural aromatic compounds, ketones, and light fractions capable of diffusing into aged asphalt and restoring its colloidal balance (Li et al., 2021). Several researchers have reported that bio-oils can effectively recover penetration, reduce stiffness, and improve fatigue and rutting resistance of aged binders (Zhang et al., 2019). The chemical effectiveness is strongly influenced by the functional group composition of bio-oils, particularly the presence of oxygenated species and low-molecular-weight

components (Li et al., 2021; Yang et al., 2017). Sugarcane bagasse, an abundant agricultural waste in tropical countries, has emerged as a promising feedstock for bio-oil production. Hydrothermal liquefaction and sub-supercritical processing of bagasse can generate bio-oils rich in phenolic and aliphatic compounds, which are suitable for rejuvenating oxidized binders (Baloch et al., 2018; Nunes et al., 2021). These chemical constituents enhance rejuvenation effectiveness by improving molecular mobility and facilitating diffusion into aged asphalt structures. Compared with other biomass-derived rejuvenators, sugarcane bagasse offers advantages in terms of availability, low cost, and renewable origin, making it highly relevant for sustainable pavement engineering applications.

While numerous studies have explored biomass-derived rejuvenators, limited research has focused specifically on the performance of RAP mixtures incorporating sugarcane bagasse bio-rejuvenator with comprehensive evaluation under moisture susceptibility and rutting performance. Previous works have demonstrated that bio-oils can improve binder aging indices and mixture stability, but their influence on durability indicators such as retained stability and dynamic stability remains underexplored, especially for RAP contents above 20% (Nizamuddin et al., 2022; Zhang et al., 2019). Therefore, a performance-oriented evaluation is essential to quantify the restoration efficiency of sugarcane bagasse bio-rejuvenator when applied to RAP mixtures.

The performance of asphalt pavements is influenced by the characteristics of the mixture, particularly its stability, durability, and resistance to permanent deformation. In the context of improving sustainability, the use of reclaimed asphalt pavement (RAP) and biomass-based rejuvenating agents has become one of the most widely explored strategies. Sugarcane bagasse-based bio-asphalt is considered a promising candidate because it contains lignocellulosic components capable of restoring part of the aromatic fractions lost in aged asphalt (Jiang et al., 2023; Al-Khateeb et al., 2024; Albayati et al., 2024; Musco et al., 2024). To evaluate the mechanical behavior of asphalt mixtures incorporating RAP and bio-asphalt, several standardized test methods are employed. The Marshall Test provides information on the stability and flow of the mixture under static loading. The Marshall Immersion Test assesses the mixture's resistance to moisture-induced damage, whereas the Wheel Tracking Test measures its resistance to permanent deformation (rutting) under repetitive loading (Xiao Z. et al., 2019; Wang, W. H. et al., 2020). This evaluation is essential to determine whether the combination of RAP, Pen 60/70 asphalt, and sugarcane bagasse bio-asphalt can meet established technical specifications and deliver satisfactory field performance (Jiang et al., 2023; Musco et al., 2024).

This study investigates the mechanical recovery of RAP mixtures incorporating sugarcane bagasse bio-rejuvenator through Marshall stability, Marshall immersion, and wheel tracking tests. The objective is to assess how bio-rejuvenation influences strength, moisture resistance, and rutting behavior, particularly in mixtures with medium to high RAP content. The results contribute to expanding scientific insight into biomass-derived rejuvenators and support the development of more sustainable pavement rehabilitation strategies.

METHODS

This research was conducted as a controlled laboratory experimental study designed to evaluate the rejuvenation effectiveness of sugarcane bagasse-derived bio-asphalt for improving the performance of RAP-containing asphalt mixtures. The investigation followed a systematic experimental framework in which mixture properties and functional performance parameters were assessed through standardized specimen testing. All laboratory procedures were performed in accordance with the specifications and testing protocols outlined in widely recognized asphalt standards, ensuring the technical rigor and repeatability of the results. Furthermore, the experimental data were analyzed and interpreted with reference to current scholarly literature to substantiate scientific accuracy and contextual relevance.

The materials used in this study included 60/70 penetration-grade asphalt as the base binder and sugarcane bagasse bio-asphalt, produced from lignocellulosic agricultural residues, which served as the rejuvenating agent for RAP binders. The mixtures were prepared using a hot-mix asphalt (HMA) process and designed according to the gradation requirements of Asphalt Concrete–Wearing Course (AC-WC). RAP material was incorporated at predetermined proportions, and the bio-rejuvenator was added at optimized dosages to achieve effective restoration of the aged binder. All specimens were subjected to performance evaluations including Marshall stability, moisture susceptibility, and wheel-tracking tests to comprehensively assess the influence of the bio-rejuvenator on the mechanical and durability characteristics of the mixtures.

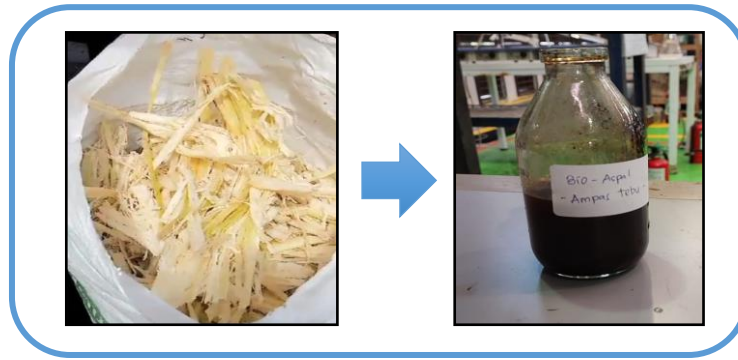


Figure 1. Sugarcane Bagasse Bio-Rejuvenator

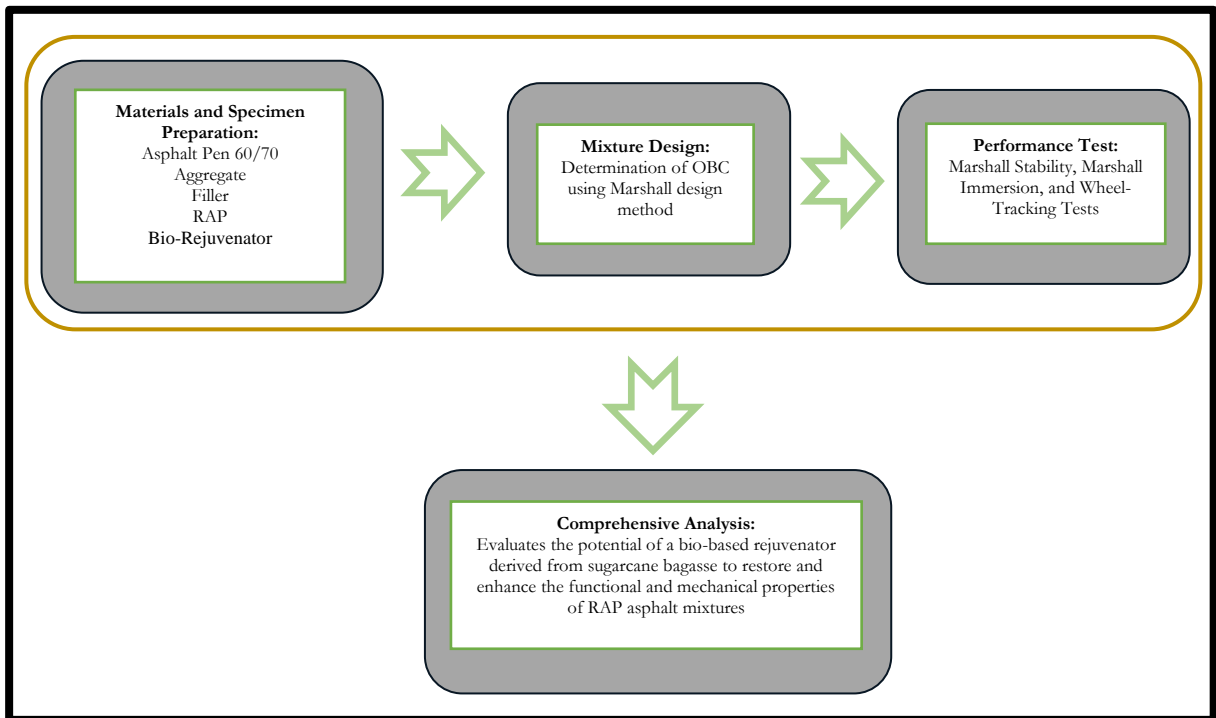


Figure 2. Research and Analysis Stages

RESULT AND DISCUSSION

Test results in the Table 1 indicate that the incorporation of Reclaimed Asphalt Pavement (RAP) combined with bio-asphalt noticeably influences Marshall performance parameters. Overall, increasing the RAP content from 0% to 40% with the addition of bio-asphalt leads to a significant increase in stability, from 1395.00 kg to 1625.00 kg. This improvement suggests that RAP contributes to strengthening the mixture due to the presence of aged binder with higher stiffness, while the bio-asphalt functions as a rejuvenating agent that maintains mixture flexibility. The Marshall Quotient (MQ) also increases markedly from 365.18 kg/mm to 432.18 kg/mm, indicating higher stiffness and improved resistance to permanent deformation (rutting).

In terms of volumetric properties, the results show that VIM decreases from 4.50% to 4.00%, while VFA increases from 73.80% to 76.10%. This trend indicates better binder absorption and improved void filling due to the interaction between RAP and bio-asphalt, resulting in a denser and more stable mixture. The density also increases slightly (from 2.269 to 2.286 t/m³), consistent with the reduction in air voids and the addition of RAP. Meanwhile, the flow values decrease slightly (from 3.82 mm to 3.76 mm), suggesting increased mixture stiffness, although the values remain within the acceptable range for AC-WC mixtures.

Table 1. Marshall Parameter Values In AC-WC Mixture Variations

| Criteria | RAP 0% | RAP 20% + Bio-asphalt | RAP 40% + Bio-asphalt |
|----------|--------|-----------------------|-----------------------|
|----------|--------|-----------------------|-----------------------|

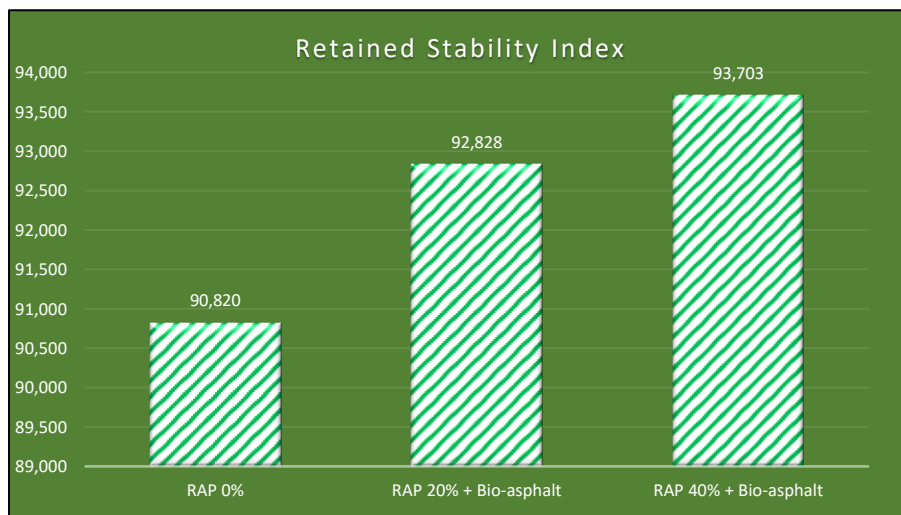
| | | | |
|-----------------------------|---------|---------|---------|
| Optimum Asphalt Content (%) | 5.80 | 5.85 | 6.00 |
| Stability (kg) | 1395.00 | 1606.50 | 1625.00 |
| Flow (mm) | 3.82 | 3.78 | 3.76 |
| VMA (%) | 17.40 | 16.80 | 16.40 |
| VFA (%) | 73.80 | 75.00 | 76.10 |
| VIM (%) | 4.50 | 4.25 | 4.00 |
| Density (t/m ³) | 2.269 | 2.281 | 2.286 |
| Marshall Quotient (kg/mm) | 365.18 | 425.00 | 432.18 |

The Marshall immersion test results presented in Table 2 and Figure 3 provide insight into the moisture susceptibility and durability of AC-WC mixtures incorporating various proportions of RAP and bio-asphalt. The wet stability values measured after 30 minutes of immersion show a consistent increase with the addition of RAP and bio-asphalt, from 1420.08 kg for the control mixture (0% RAP) to 1698.15 kg for the mixture containing 40% RAP and bio-asphalt. All stability values exceed the minimum specification of 800 kg, indicating that each mixture possesses adequate initial resistance to moisture-induced weakening. This improvement in short-term immersion stability suggests that the combination of aged binder from RAP and rejuvenating bio-asphalt enhances the binder-aggregate adhesion and structural integrity of the mixture.

A similar trend is observed in the 24-hour immersion stability results, where the retained stability progressively increases from 1289.71 kg in the control mixture to 1591.22 kg in the 40% RAP mixture. Although a reduction in stability after prolonged immersion is expected due to moisture infiltration, the mixtures containing RAP exhibit a smaller proportional loss in strength. This is further supported by the Immersion Index of Stability (IKS), which increases from 90.82% to 93.70% across the mixture variations. Since all mixtures surpass the minimum requirement of 90%, the results confirm that the incorporation of RAP and bio-asphalt improves resistance to moisture damage and stripping. The enhanced IKS values imply more effective binder rejuvenation, improved coating of aggregates, and increased tolerance to prolonged water exposure. Overall, the findings demonstrate that mixtures with higher RAP content and corresponding bio-asphalt modifications exhibit superior moisture durability compared to conventional mixtures. The mixture containing 40% RAP and 25.5% bio-asphalt provides the best performance in terms of both short-term and long-term immersion stability, suggesting its potential suitability for pavement applications in areas with high rainfall or frequent moisture exposure.

Table 2. Marshall Immersion Test Results for AC-WC Mixture Variations

| Criteria | Specification | RAP 0% | RAP 20% + Bio-asphalt | RAP 40% + Bio-asphalt |
|-----------------------------------|---------------|---------|-----------------------|-----------------------|
| Standard Immersion Stability (kg) | ≥800 | 1420.08 | 1600.50 | 1698.15 |
| 24-Hour Immersion Stability (kg) | – | 1289.71 | 1485.72 | 1591.22 |
| Retained Stability Index (%) | ≥90 | 90.82 | 92.83 | 93.70 |



The Wheel Tracking test results in Table 3 indicate that the incorporation of RAP combined with bio-asphalt has a significant effect on improving the resistance of AC-WC mixtures to permanent deformation (rutting). The

mixture without RAP experienced substantially greater deformation compared to the two mixtures containing RAP. At the 60-minute mark, the deformation of the RAP 0% mixture reached 4.30 mm, whereas the RAP 20% + bio-asphalt mixture reached only 1.87 mm, and the RAP 40% + bio-asphalt mixture showed an even lower value of 1.49 mm. This difference demonstrates that RAP contributes to increasing the stiffness of the mixture, while bio-asphalt helps maintain flexibility and enhances binder adhesion, resulting in a mixture that is more stable against rut formation.

The initial deformation (DO) values show a similar trend, decreasing from 2.14 mm in the RAP 0% mixture to 1.27 mm in the RAP 20% mixture and 1.13 mm in the RAP 40% mixture. This reduction in DO indicates that mixtures containing RAP are better able to resist deformation from the early stages of loading. Rutting resistance is also reflected in the deformation rate (RD) values, where the RAP 0% mixture exhibits an RD of 0.0360 mm/min, much higher than the RAP 20% (0.0100 mm/min) and RAP 40% (0.0060 mm/min) mixtures. Lower RD values indicate that the progression of rutting in RAP-containing mixtures occurs at a much slower rate.

The parameter that best characterizes rutting performance is Dynamic Stability (DS). The results show a substantial increase in DS, from 1166.67 passes/mm in the RAP 0% mixture to 4200 passes/mm in the RAP 20% mixture and reaching the highest value of 7000 passes/mm in the RAP 40% mixture. This increase in DS confirms that the use of RAP and bio-asphalt provides significant improvement in permanent deformation resistance, making the mixture more stable under repeated loading and high-temperature conditions. Overall, the Wheel Tracking test results demonstrate that mixtures with higher RAP content, combined with the addition of bio-asphalt, exhibit far superior rutting performance compared to mixtures without RAP. The mixture containing 40% RAP + bio-asphalt shows the highest performance among all variations and can therefore be recommended for pavement applications with high traffic volumes or environments prone to extreme temperature conditions and repeated loading.

Table 3. Wheel Tracking Test Results for AC-WC Mixture Variations

| Criteria | RAP 0% | RAP 20% + Bio-asphalt | RAP 40% + Bio-asphalt |
|-----------------------------------|---------|-----------------------|-----------------------|
| Initial Deformation, DO (mm) | 5.80 | 5.85 | 6.00 |
| Rutt Depth, RD (mm/min) | 0,0360 | 0,0100 | 0,0060 |
| Dynamic Stability, DS (passes/mm) | 1166,67 | 4200,00 | 7000,00 |

CONCLUSION

The results indicate that incorporating RAP in combination with bio-asphalt consistently enhances the performance of AC-WC mixtures. Increasing RAP content up to 40% with the addition of bio-asphalt improves Marshall stability, MQ values, and volumetric parameters, indicating a denser and more stable mixture. The Marshall immersion test further demonstrates better resistance to moisture-induced damage, with higher immersion stability and retained stability values, all meeting specification limits. These findings confirm that the interaction between aged binder in RAP and the rejuvenating properties of bio-asphalt improves adhesion and reduces susceptibility to stripping.

The Wheel Tracking test reinforces that RAP-modified mixtures exhibit superior rutting resistance compared with mixtures without RAP. Reduced deformation, lower deformation rates, and significantly higher dynamic stability indicate improved resistance to permanent deformation under repetitive loading and elevated temperatures. Overall, the mixture containing 40% RAP combined with sugarcane bagasse bio-asphalt shows the best performance across all parameters and is recommended as a sustainable mixture with high structural integrity and durability for heavy-traffic pavement applications.

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