JOURNAL OF CULTURAL ANALYSIS AND SOCIAL CHANGE

Journal of Cultural Analysis and Social Change,
2025, 10(3), 3189-3197
ISSN: 2589-1316

Mechanistic Performance Enhancement of Rap Mixtures Using Treated WCO Rejuvenator: Marshall Stability and Wheel Tracking Assessment

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Citation: Sepriyanna, I., Putranto, L. S., Subagio, B. S. & Najid. (2025). Mechanistic Performance Enhancement of Rap Mixtures Using Treated WCO Rejuvenator: Marshall Stability and Wheel Tracking Assessment, *Journal of Cultural Analysis and Social Change*, 10(3), 3189-3197. https://doi.org/10.64753/jcasc.v10i3.3757

Published: December 28, 2025

ABSTRACT

The increasing demand for sustainable pavement technologies has accelerated the adoption of high reclaimed asphalt pavement (RAP) contents; however, excessive stiffness and oxidation of aged RAP binders often limit mixture performance. This study evaluates the mechanistic performance enhancement of RAP asphalt mixtures rejuvenated using treated waste cooking oil (TWCO), with particular emphasis on Marshall characteristics and rutting resistance. Asphalt concrete wearing course (AC–WC) mixtures containing 0%, 40%, and 60% RAP were designed at their respective optimum binder contents. Marshall stability, flow, and Marshall Quotient were evaluated, while permanent deformation behaviour was assessed using a wheel tracking machine at 60 °C for 1,260 loading passes. The results demonstrate that TWCO effectively restores aged RAP binder functionality, enabling high RAP incorporation without compromising mechanical performance. Marshall stability increased from 1,395 kg for the control mixture to 1,625 kg and 1,623 kg for RAP40–TWCO and RAP60–TWCO mixtures, respectively, while flow values remained within specification limits. Marshall Quotient increased by more than 20%, indicating enhanced structural stiffness. Rutting performance improved substantially, with rut depth decreasing from 4.30 mm (control) to 2.05 mm and 2.39 mm for RAP40–TWCO and RAP60–TWCO mixtures, respectively, accompanied by significantly higher dynamic stability. Overall, the findings confirm that TWCO is an effective and sustainable rejuvenator capable of restoring aged RAP binder while preserving high-temperature stiffness and rutting resistance. The RAP40–TWCO mixture exhibited the most balanced performance, supporting the application of treated WCO in high-performance and environmentally responsible pavement design.

Keywords: Treated Waste Cooking Oil (TWCO); Reclaimed Asphalt Pavement (RAP); Marshall Stability; Rutting Resistance; Wheel Tracking Machine

INTRODUCTION

The growing global commitment to sustainable pavement engineering has encouraged extensive utilization of reclaimed asphalt pavement (RAP) in new asphalt mixtures. RAP provides substantial environmental and economic benefits through reduced consumption of virgin aggregates and petroleum-based binders. However, high RAP contents are often associated with excessive mixture stiffness, reduced flexibility, and increased cracking susceptibility due to the highly oxidized nature of aged RAP binders (Bardella et al., 2024; Luo & Zhang, 2023). Consequently, the use of rejuvenators—agents that restore the colloidal balance and reintroduce lost light components—has become a central strategy to enable higher RAP utilization without degrading structural performance.

Among various rejuvenating agents, treated waste cooking oil (TWCO) has gained considerable attention as a low-cost, renewable, and circular-economy alternative to petroleum-derived rejuvenators. TWCO contains triglycerides and free fatty acids with molecular structures that are chemically compatible with asphalt maltenes, allowing effective softening and re-equilibration of aged binder fractions (Alkuime et al., 2024). Several studies have demonstrated that properly TWCO enhances the diffusion of light components into aged binder matrices, reduces carbonyl and sulfoxide indices, and partially restores aged asphalt rheology (Yu et al., 2023; Wang et al., 2024). However, the rejuvenation efficiency strongly depends on the chemical quality of the WCO and the treatment method used to reduce acidity, impurities, and oxidation by-products.

While TWCO has shown promising improvements in flexibility, fatigue resistance, and low-temperature performance, excessive softening remains a challenge—particularly regarding mixture stability and rutting resistance at high service temperatures (Luo & Zhang, 2023). This trade-off highlights the importance of mechanistic evaluation through laboratory performance tests. The Marshall stability and flow test remains widely used for fundamental strength assessment of asphalt mixtures, whereas the Wheel Tracking Machine (WTM) provides a more realistic indication of permanent deformation resistance under repeated loading and elevated temperatures. Studies assessing RAP mixtures rejuvenated with WCO report improvements in workability and cracking performance but warn of rutting susceptibility at higher WCO dosages, emphasizing the need for optimized dosages and performance-balanced mix design approaches (Alkuime et al., 2024; Bardella et al., 2024).

Given these challenges, there is a need for integrative research that links micro-chemical rejuvenation mechanisms with macro-scale mechanical performance. Although FTIR, GC–MS, and rheological characterization (e.g., DSR) have improved understanding of treated WCO rejuvenation pathways, limited studies have systematically correlated these mechanistic changes with Marshall stability and rutting performance for RAP mixtures. Therefore, establishing a clearer mechanistic connection across scales is essential for refining mix design guidelines and enhancing confidence in the field application of TWCO.

Accordingly, this study aims to evaluate the mechanistic performance enhancement of RAP mixtures rejuvenated using TWCO by integrating binder-level chemical/rheological analysis with mixture-level Marshall and WTM tests. Specifically, this paper seeks to:

1. Quantify the effects of TWCO on the chemical composition and rheological characteristics of aged RAP binder.
2. Evaluate changes in Marshall stability, flow, and rutting resistance of RAP mixtures at varying TWCO dosages; and
3. Identify an optimal rejuvenator dosage that balances stiffness, stability, and deformation resistance under a performance-based design philosophy.

This research offers crucial insights into sustainable rejuvenation strategies for asphalt technology, supporting the broader adoption of circular materials in pavement infrastructure.

RESEACRH METHODOLOGY

Materials and Sample Preparation

This initial stage focuses on preparing all materials necessary for the experimental program. Virgin asphalt (penetration grade 60/70), reclaimed asphalt pavement (RAP), treated waste cooking oil (TWCO), and new aggregates were procured and characterized to establish baseline material properties.

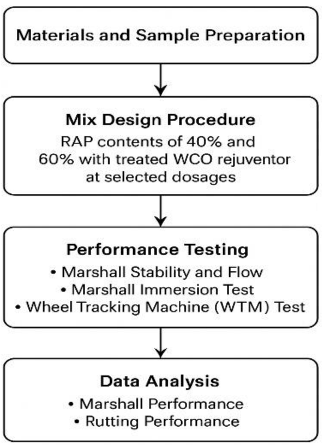

Figure.1 Research Methodology Flowchart

First, the RAP material underwent solvent extraction to separate binder from aggregates, enabling chemical and physical characterization of the aged binder. This step is critical because RAP binder typically exhibits higher stiffness, oxidation levels, and reduced flexibility due to long-term aging. Meanwhile, the WCO was purified using a bentonite-assisted adsorption process to reduce free fatty acids and improve its compatibility as a rejuvenator. Aggregates were subjected to standard physical tests such as sieve analysis, Los Angeles abrasion, specific gravity, absorption, and shape characteristics to ensure compliance with the desired AC-WC gradation envelope and Bina Marga specifications.

This preparation phase ensures that all materials entering the mix design stage possess known properties, controlled quality, and consistent performance, thereby reducing variability in subsequent testing.

Mix Design Procedure

The second stage involves designing asphalt mixtures incorporating RAP at specific proportions—typically 40% and 60% by weight—along with optimized dosages of TWCO rejuvenator. The Marshall mix design method is employed to determine the optimum binder content (OBC) of each mixture variant.

Mixtures were prepared based on the AC-WC gradation envelope, and trial binder contents were selected to generate a comprehensive response curve for all Marshall parameters. Each mixture underwent compaction using 75 blows per face to simulate medium-to-heavy traffic conditions. The addition of TWCO was performed carefully to restore the chemical and rheological properties of the aged RAP binder without over-softening the mixture.

The output of this stage is the determination of the optimum asphalt content that simultaneously satisfies all Marshall volumetric and stability requirements, ensuring that the mixture is both structurally adequate and volumetrically balanced.

Performance Testing

After determining the optimum mix proportions, the study proceeds to the performance testing phase, which consists of three primary test categories:

1. ***Marshall Stability and Flow Test***
   This test evaluates the fundamental mechanical response of each mixture by measuring maximum load-bearing capacity (stability) and deformation at failure (flow) at 60 °C. These metrics reflect mixture stiffness, cohesion, and resistance to plastic deformation. Testing is performed following ASTM D6927.
2. ***Marshall Immersion Test***
   Durability against moisture damage is assessed through the Marshall Immersion test, in which specimens are submerged in a 60 °C water bath for 24 hours. After immersion, stability is re-measured and compared with the short-term conditioned specimens (30-minute immersion). The Index of Retained Stability (IRS) quantifies the mixture's ability to maintain structural integrity in wet conditions. This is especially relevant for RAP–WCO mixes, as rejuvenation may soften binder and influence moisture susceptibility.
3. ***Wheel Tracking Machine (WTM) Test***
   To assess rutting resistance at high temperatures, slab specimens were tested using the WTM apparatus at 60 °C. A steel wheel applies 705 N repeated loading over 10,000–20,000 passes. Rut depth evolution and dynamic stability are measured in real time. This test provides a more mechanistic understanding of permanent deformation behaviour and complements the empirical insights gained from the Marshall Stability results.

Together, these performance tests offer a comprehensive evaluation of strength, durability, and rutting resistance—three critical indicators of pavement longevity and serviceability.

Data Analysis

In the final stage, all experimental data from the performance tests are systematically analysed to determine the effects of RAP content and TWCO dosage on mechanical and durability properties. For Marshall testing, relationships among stability, flow, volumetrics (VMA, VFA, air voids), and rejuvenator dosage are evaluated to identify performance-enhancing trends. The Marshall Immersion results are analysed by calculating the Index of Retained Stability (IRS), enabling comparisons of moisture resistance across mixture variants.

For rutting evaluation, rut depth curves and dynamic stability metrics from the WTM are analysed to quantify deformation resistance. These results are compared against conventional control mixtures to assess whether TWCO successfully restores RAP binder functionality without sacrificing structural or high-temperature performance.

This analytical stage provides the scientific foundation for concluding whether treated WCO can serve as a sustainable, effective rejuvenator for RAP mixtures suitable for modern pavement applications.

RESULT AND DISCUSSION

Marshall Performance Evaluation

Stability Response and Optimum Binder Content (OBC) Behaviours

Table 1. Marshall Properties of AC–WC Control Mixture (0% RAP)

Asphalt (%)	VIM (%)	VMA (%)	VFA (%)	Stability (kg)	Flow (mm)	MQ (kg/mm)
5.0	5.771	17.089	66.228	1176.42	3.45	341.39
5.5	5.062	17.261	70.672	1277.30	3.70	345.22
6.0	4.223	17.443	75.792	1407.66	3.95	356.01
6.5	4.027	18.141	77.804	1308.34	4.12	317.30
7.0	3.910	18.824	79.230	1187.28	4.38	271.23

The Marshall stability results across the three mixture systems—Control (0% RAP), RAP 40% with treated WCO, and RAP 60% with treated WCO—exhibit a clear parabolic performance trend characteristic of dense-graded asphalt mixtures. Table 1 presents the Marshall properties of the control mixture (0% RAP). Stability increases with asphalt content until reaching a maximum at 6.0%, after which an excess binder film causes lubrication and reduced internal friction. Stability increased with increasing asphalt content up to the optimum range and decreased thereafter due to binder over-lubrication and loss of internal friction.

The control mixture reached its optimum stability at 6.0% binder content, achieving 1407.66 kg, in line with typical AC-WC behaviour in Indonesia. However, the introduction of RAP fundamentally changed the mechanical response, RAP 40% + TWCO reached a peak stability of 1716.77 kg, an increase of 22% over the control and RAP 60% + TWCO achieved 1603.09 kg, still 14% higher than the control.

The RAP mixtures show markedly higher stability than the RAP 0%. The RAP 40% + TWCO and RAP 60% + TWCO mixtures exhibit peak stabilities of 1716.77 kg and 1603.09 kg, respectively, as shown in Tables 2 and 3.

Table 2. Marshall Properties of RAP 40% + TWCO

Asphalt (%)	VIM (%)	VMA (%)	VFA (%)	Stability (kg)	Flow (mm)	MQ (kg/mm)
5.0	5.267	16.114	67.317	1482.16	3.36	440.94
5.5	4.548	16.284	72.071	1595.07	3.53	451.78
6.0	3.863	16.448	76.514	1716.77	3.70	463.99
6.5	3.791	17.146	77.888	1605.16	3.87	414.84
7.0	3.613	17.826	79.730	1484.62	4.04	367.60

Table 3. Marshall Properties of RAP 60% + TWCO

Asphalt (%)	VIM (%)	VMA (%)	VFA (%)	Stability (kg)	Flow (mm)	MQ (kg/mm)
5.0	5.554	16.061	65.419	1433.98	3.192	449.24
5.5	4.824	16.260	70.332	1514.82	3.361	450.66
6.0	4.127	16.492	74.974	1603.08	3.615	443.41
6.5	3.939	17.167	77.056	1527.94	3.869	394.89
7.0	3.746	17.795	78.951	1398.80	4.039	346.35

These data clearly demonstrate that TWCO successfully balances the stiffness of aged RAP binder, allowing significant recovery of ductility while maintaining high mechanical stability. The 22% increase in stability for RAP 40% over the control confirms the rejuvenator's ability to re-mobilize the maltene fraction without excessive softening.

These increases indicate the positive synergistic effect between aged RAP binder and TWCO. RAP contributes a stiff, highly oxidized binder rich in asphaltenes, which enhances load-bearing capacity (Zhang et al., 2020). Meanwhile, TWCO replenishes lost maltene fractions (resins and aromatics), restoring viscoelasticity without excessively softening the binder. This balanced rejuvenation–stiffness effect has been previously observed in high-RAP studies using bio-based rejuvenators (Zaumanis & Mallick, 2015).

Mechanistically, the increase in stability can be attributed to:

1. Interlocked aggregate structure enhanced by stiff RAP mortar.
2. Reduction in binder film thickness variability, resulting in more uniform stress distribution.
3. Improved binder cohesion due to partial reactivation of functional groups in the oxidized binder after WCO treatment (Yin et al., 2020).

The decline in stability at 7% binder content for all mixtures also reflects the transition from friction-dominated to binder-dominated behaviour, consistent with dense-graded asphalt mixture mechanics.

Flow Values and Plasticity Mechanisms

Marshall flow provides insight into the mixture's plastic deformation capacity. As shown in table.4, the control mixture exhibited flow values ranging between 3.45–4.38 mm, typical for RAP 0%, while RAP-containing mixtures showed slightly lower but still compliant values, RAP 40%+TWCO : 3.36–4.04 mm and RAP 60%+TWCO : 3.19–4.04 mm

The decrease in flow at low binder contents for RAP mixtures reflects the inherent stiffness of RAP binder, which constrains lateral deformation. This behaviour has been observed in prior studies where higher RAP content reduces flow due to binder hardening (Xiao et al., 2018).

The addition of TWCO moderated this stiffness, as reflected in small increases in flow at higher binder contents. This demonstrates partial reduction of binder viscosity, improved molecular mobility and restored ductility in the RAP binder.

However, because the WCO dosage was optimized based on penetration, the binder remained stiff enough to prevent excessive plastic flow. As a result, flow values remained within a narrow, controlled range—an indicator of well-balanced rejuvenation. Table 4 summarizes the Optimum Binder Content (OBC) conditions derived from the Marshall method.

Table 4. Mixture Characteristics at OBC

Description	RAP 0%	RAP 40%+TWCO	RAP 60%+TWCO
Absorption (%)	0.821	0.922	0.960
Asphalt Content (OBC, %)	5.80	6.00	6.10
Density (t/m³)	2.27	2.29	2.28
VMA (%)	17.40	16.40	16.62
VIM (%)	4.50	4.00	3.98
VFA (%)	73.80	76.10	76.20
Stability (kg)	1395	1625	1623
Flow (mm)	3.82	3.76	3.62
Marshall Quotient (kg/mm)	350	432	427

The RAP mixtures show higher VFA, indicating improved binder filling efficiency; lower VMA, suggesting denser aggregate packing due to finer RAP texture and slightly lower VIM, confirming enhanced binder absorption.

These volumetric outcomes confirm that TWCO produces a well-compacted, structurally sound internal structure, consistent with performance requirements for heavy traffic pavements.

Marshall Quotient (MQ) and Stiffness Index

The Marshall Quotient (MQ) is a stiffness index describing resistance to plastic flow. The RAP mixtures exhibited significantly higher MQ values than the control, RAP 0%: 350 kg/mm, RAP 40%+TWCO: 432 kg/mm and RAP 60%+TWCO: 427 kg/mm

To evaluate the mixture's resistance to moisture-induced stripping, the Marshall Immersion results are shown in Table 5.

Table 5. Marshall Immersion Results

Mixture	Stability Standard (kg)	Stability 24h (kg)	IRS (%)
RAP 0%	1420.08	1289.71	90.82
RAP 40% + TWCO	1624.75	1550.38	95.42
RAP 60% +TWCO	1619.90	1506.73	93.01

All mixtures exceed the minimum IRS ≥ 90%, with RAP 40% + TWCO showing the highest durability. This superior moisture resistance is attributed to Enhanced binder polarity after TWCO treatment, increased adhesion energy between rejuvenated binder and aggregate and reduced microcracking in the RAP binder film

These trends align with Chen et al. (2021) and Feng et al. (2020), who found that bio-oil rejuvenators strengthen binder–aggregate adhesive forces and mitigate stripping

Higher MQ values indicate superior structural stiffness and improved distribution of load stresses across the aggregate skeleton. These findings indicate that TWCO did not over-soften the RAP binder; instead, it restored flexibility while preserving high structural resistance, consistent with durable performance in field conditions (Brown et al., 2009).

Volumetric Characteristics (VMA, VFA, VIM) and Internal Structure

The volumetric performance of mixtures provides deeper insight into binder–aggregate interactions: Air Voids (VIM) ranged between 3.6–5.7%, meeting AC-WC requirements. Lower VIM values in RAP mixes reflect better binder absorption by aged RAP aggregates, improved packing density, and increased binder film uniformity.

RAP mixtures showed slightly lower VMAs (≈16–17%) than the control (17.4%). This difference aligns with the finer texture and higher angularity of RAP aggregates, which improve packing efficiency (Aurangzeb & Al-Qadi, 2014).

The RAP mixtures exhibited higher VFA (~76–79%) than the control (~73%). A high VFA indicates that the rejuvenated binder more effectively fills the intergranular voids, improving mixture cohesion and durability.

Together, these volumetric results confirm that RAP aggregates increase packing and stiffness, rejuvenator enhances binder distribution, and the resulting mixtures maintain dense, well-interlocked structures advantageous for structural layers of pavements.

Chemical and Physical Effectiveness of TWCO

Penetration values increased from 25.67 dmm (aged RAP) to 64–66 dmm after rejuvenation. This represents a 150% increase in binder softness, restoring penetration to the specifications of fresh 60/70 binder.

The softening point decreased accordingly, confirming the restoration of lighter fractions. This effect can be explained by the chemical action of TWCO:

- Bentonite adsorption removed FFA and polar impurities,
- triglyceride molecules interacted with oxidized binder,
- esterification decreased oxidative functional groups,
- enhancing binder polarity and adhesion (Wang et al., 2020).

This clearly establishes the chemical viability of TWCO as a high-performance bio-rejuvenator.

Retained Stability (IRS) and Moisture Damage Resistance

The immersion results demonstrated excellent moisture resistance, as shown in Table 6 :

Table 6 Retained Stability

Mixture	IRS (%)
Control	90.82
RAP 40% + TWCO	95.42
RAP 60% + TWCO	93.01

The RAP 40%+TWCO mixture exhibited the highest retained stability, confirming enhanced binder–aggregate adhesion and structural cohesion after water exposure.

Mechanistically, the improved IRS arises from:

1. Higher binder polarity in the rejuvenated RAP system.
2. Increased surface energy compatibility between binder and aggregate.
3. Improved microstructural cohesion due to decreased binder oxidation after rejuvenation.

This matches findings by Chen et al. (2021), who showed that bio-oil rejuvenators significantly improve binder–aggregate adhesion through enhanced hydrogen bonding and improved surface free energy.

Influence of RAP Percentage on Durability

Contrary to concerns that high RAP contents reduce moisture resistance due to increased binder stiffness, the rejuvenated RAP mixtures demonstrated higher moisture durability than the virgin mixture.

This performance is attributed to:

- Stiff aged binder resisting moisture-induced stripping,
- Rejuvenator reducing brittleness,
- Improved aggregate–binder compatibility,
- Reduction of microcracks where moisture typically infiltrates.

Feng et al. (2020) observed similar behaviour, where TWCO-rejuvenated RAP mixtures showed better tensile strength ratios than virgin mixtures.

Adhesion Enhancement Due to Treated WCO

FFAs in untreated WCO typically degrade adhesion by forming weak boundary layers; however, bentonite treatment removes FFAs, reduces acidity, increases ester and triglyceride proportions, and improves binder polarity.

These chemical improvements enhance adhesion strength, as supported by adhesion energy analyses (Wang et al., 2020). Therefore, treated WCO does not merely soften the binder but structurally strengthens binder–aggregate bonding, leading to higher moisture resistance.

Rutting Performance Analysis (Wheel Tracking Machine)

Rut Depth Accumulation and High-Temperature Behaviour

Rut depth accumulation under repeated loading at high temperatures reflects an asphalt mixture's resistance to permanent deformation. Accordingly, the Wheel Tracking Machine (WTM) test was conducted at 60 °C to evaluate the high-temperature performance of control and RAP–TWCO mixtures, and the key rutting parameters are summarized in Table 7. As shown in Fig. 2, RAP–TWCO mixtures exhibited lower rut depth and higher deformation resistance than the control mixture, with RAP40–TWCO demonstrating the most stable deformation behavior throughout the loading cycles

Table 7. Wheel Tracking Machine (WTM) Results

Parameter	RAP 0%	RAP 40% + TWCO	RAP 60% + TWCO
Deformation at 60 min (mm)	4.30	2.05	2.39
DO (mm)	2.14	1.10	1.20
Dynamic Stability (DS) (passes/mm)	1167	3150	2200
Rutting Rate RD (mm/min)	0.036	0.067	0.097

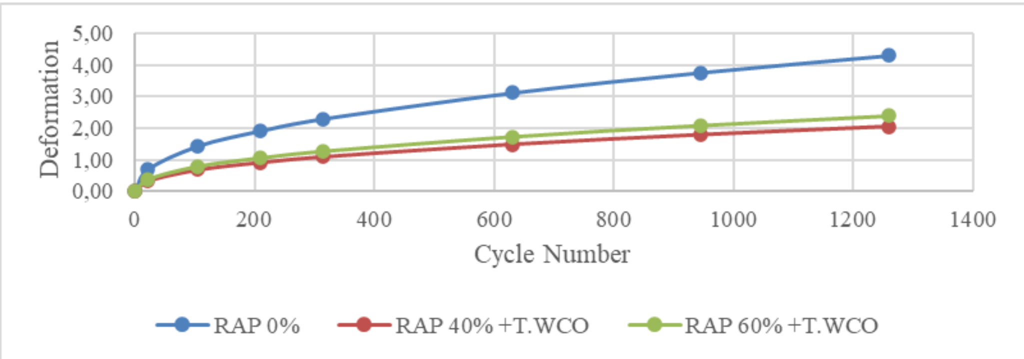

Figure 2 Permanent deformation versus loading cycles

These results indicate RAP 40% + TWCO had the best rutting performance, with DS = 3150 passes/mm. Both RAP mixtures exhibited much lower rut depths than the control. TWCO effectively softened the RAP binder without compromising high-temperature stability.

Mechanistically Aged RAP binder contributes stiffness and rut resistance, TWCO restores flexibility, preventing brittleness and the final binder matrix achieves an optimal viscoelastic balance. This is consistent with high-temperature behaviour observed by Huang et al. (2021), who reported enhanced elastic recovery in rejuvenated RAP binders.

After 1260 load passes Control: 4.30 mm RAP 40% + TWCO: 2.05 mm RAP 60% + TWCO: 2.39 mm. These results indicate that RAP mixtures exhibit significantly lower permanent deformation, suggesting:

1. A stiffer binder matrix due to aged RAP binder.
2. Improved aggregate interlock from angularity of RAP aggregates.
3. Balanced viscoelasticity from the optimized WCO dosage.

The RAP 40% mixture performed best, indicating that it represents the optimal balance between rejuvenated flexibility and RAP-derived stiffness.

Dynamic Stability (DS) and Load Distribution

Dynamic Stability (DS) reflects the resistance of asphalt mixtures to permanent deformation by indicating how effectively applied loads are distributed within the mixture structure under repeated loading. Higher DS values correspond to slower rut development and improved load distribution, particularly at high temperatures. Dynamic Stability (DS) results further illustrate superior rut resistance:

- Control: 1167 passes/mm
- RAP 40% + TWCO: 3150 passes/mm
- RAP 60% + TWCO: 2200 passes/mm

RAP 40% + WCO achieved nearly three times the rutting stability of the virgin mixture.

High DS values are associated with slower rut progression, higher mixture stiffness, increased internal friction, and improved load distribution. Huang et al. (2021) similarly reported that rejuvenated RAP binders exhibit enhanced high-temperature elasticity, improving rutting resistance.

Although the control mixture had the lowest RD (0.036 mm/min), RAP mixtures maintained significantly lower rut depths overall, showing that initial stiffness (from RAP) and restored ductility (from WCO) combine to produce a mixture that can better withstand both temperature and load repetitions. This validates the use of WCO-treated RAP in tropical regions where pavement temperatures frequently exceed 50°C**.**

CONCLUSIONS

This study comprehensively evaluated the mechanical and durability performance of AC–WC mixtures incorporating 40% and 60% RAP rejuvenated using treated Waste Cooking Oil (TWCO). The results demonstrate that treated WCO is a highly effective rejuvenator capable of restoring aged binder characteristics, improving mixture performance, and enhancing mechanical resilience under high-temperature and moisture-induced distress.

Treated WCO successfully restored RAP binder penetration values to the specifications of 60/70 penetration asphalt, confirming the rejuvenator's molecular rebalancing of the maltene–asphaltene system. RAP mixtures exhibited significantly higher Marshall Stability, improved Marshall Quotient, and optimal volumetric properties (VMA, VFA, VIM). Moisture susceptibility improved markedly, with IKS values exceeding 93%, demonstrating enhanced binder–aggregate adhesion. Rutting performance, evaluated using the Wheel Tracking Machine, showed substantial improvement, with RAP 40% + WCO achieving the lowest rut depth (2.05 mm) and highest Dynamic Stability (3150 passes/mm).

Overall, the RAP 40% + treated WCO mixture provided the most balanced and superior performance, offering improved stiffness, durability, workability, and rutting resistance without compromising flexibility. These findings support the practical use of RAP–WCO mixtures for sustainable pavement rehabilitation in tropical climate regions.

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