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ENHANCING RECYCLED ASPHALT MIXTURES THROUGH MORPHOLOGICAL ANALYSIS AND REJUVENATOR EFFECTS

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Abstract: Recycled Asphalt Pavement (RAP) is a naturally useful and cost-effective elective to virgin black-top assets for asphalt development. This ponder explores how morphological parameters such as discuss voids, rejuvenator dissemination, and film thickness influence the adequacy of RAP blends. Waste Engine Oil (WEO) was tried as a rejuvenator in shifted amounts (3%, 6%, 9%, and 12%) to recuperate the viscoelastic qualities of ancient black-top cover. The rheological and physical characteristics of RAP and virgin folios were inspected to decide the adequacy of rejuvenators. The discoveries appear that the reasonable application of rejuvenators may enormously make strides in the life span and mechanical execution of RAP blends, making them a reasonable choice for maintainable asphalt development.

Keywords: Recycled Asphalt Pavement (RAP); Waste Engine Oil (WEO); Sustainable pavement materials; Oxidative aging; Rejuvenators; Environmental sustainability; Binder homogeneity

1 INTRODUCTION

Recycled asphalt pavement (RAP) could be a maintainable fabric determined from the repair, reemerging, and upkeep of existing blacktop asphalts[1]. This fabric has advanced as a naturally kind and cost-effective reply to the issues raised by regular virgin black tops. RAP was presented in the 1970s and has picked up worldwide approval for its capacity to spare common assets, diminish asphalt building costs, and enhance natural troubles associated with rubbish transfer [2, 3]. The reuse of maturing black-top asphalt not only diminishes the prerequisite for virgin totals and folios, but also decreases the sum of development flotsam and jetsam headed for landfills, including the development industry's supportability objectives[4, 5]. One of the key focal points of RAP is its capacity to decrease the budgetary and natural costs associated with framework ventures[6]. Be that as it may, matured black-top covers in RAP regularly offer issues owing to oxidative maturing, a preparation that raises the thickness and brings down the ductility of the cover with time[7-9]. These adjustments deliver a delicate substance that will impede the execution of black-top blends [9, 10]. To overcome these limitations, rejuvenators like Squander Motor Oil (WEO) have been created to reestablish the viscoelastic characteristics and chemical composition of ancient folios. Rejuvenators act by softening the ancient folio and resetting its chemical properties, permitting RAP to allow execution identical to virgin black-top materials [6, 11-15]. This innovative approach underscores the potential of RAP as a viable alternative in modern pavement engineering[15, 16]. The expanded intrigue in RAP stems from the combined concerns of rising fabric costs and the natural dangers related with the transfer of ancient black-top asphalts[17]. The erroneous transfer of untreated RAP materials includes to soil and water defilement, posturing long-term natural issues. At the same time, rising costs for virgin black-top folios and totals put significant monetary challenges on foundation ventures, especially in zones with restricted access to common assets[18]. By maximizing the utilization of RAP through proficient revival forms, this work trusts to progress its utilize while tending to vital natural and financial issues[19]. This consider centers on the morphological viewpoints that influence the execution of RAP blends, such as discuss void conveyance, rejuvenator film thickness, and cover homogeneity[20]. These parameters are basic in deciding the mechanical steadiness and life span of RAP blends. The dissemination of discuss voids influences the mixture's compaction and thickness, whereas the thickness of the rejuvenator film impacts the mixing proficiency of matured and virgin folios[21]. Cover homogeneity, on the other hand, is basic to guarantee reliable execution over the asphalt structure. A cautious examination of these parameters is imperative for understanding the behavior of recovered RAP and its compatibility with virgin materials beneath distinctive circumstances[22, 23].

To achieve these objectives, this ponder looks at the characteristics of RAP covers treated with different concentrations of WEO, to be specific 3%, 6%, 9%, and 12%. WEO, a byproduct of ancient motor oils, was chosen for its capacity to repair the chemical and physical qualities of matured covers, making it a long-lasting and cost-effective rejuvenator[24]. The basic approach of this inquiry about is based on research facility tests, which incorporate extraction tests, Marshall Steadiness Tests, and rheological examinations with an Energetic Shear Rheometer (DSR)[25]. These things offer bits of knowledge into the mechanical and rheological characteristics of RAP blends, permitting the determination of fitting restoration procedures[14, 26]. The extraction tests point to isolating the ancient cover from the RAP and surveying its chemical composition sometime recently and after restoration. This step is basic for understanding the interaction between WEO and the matured folio. The Marshall Solidness Tests assess the load-bearing capacity and soundness of the RAP blends, deciding their fittingness for asphalt development. In the meantime, the DSR ponder looks at the viscoelastic characteristics of the restored cover, giving a total understanding of its execution at shifted temperatures and stacking circumstances.

The discoveries of this ponder are likely to contribute to the broad utilization of RAP in asphalt buildings, boosting both financial effectiveness and natural maintainability. By deciding the ideal WEO concentration for reestablishing maturing folios, this work serious to provide viable counsel for optimizing RAP's potential. Moreover, the accentuation on morphological perspectives gives a comprehensive see of the execution characteristics of RAP combinations, opening the entryway for future advancements in asphalt building. Recycled Asphalt Pavements, Rejuvenator can be seen in Figure 1.

Figure 1 Recycled Asphalt Pavements, Rejuvenator

2 MATERIALS

This study prepared and analyzed recycled asphalt mixes using a variety of critical ingredients. Materials were carefully chosen to ensure the quality, longevity, and relevance of the findings:

2.1 Recycled Asphalt Pavement (RAP)

Recycled Asphalt Pavement (RAP) is a material reclaimed from aged pavement layers removed during resurfacing, reconstruction, or road-widening projects. It primarily consists of asphalt binder and aggregates that retain their intrinsic properties, making it a sustainable and cost-effective pavement construction and maintenance option. The preparation of RAP involves several essential steps to ensure its suitability for reuse. First, the material is sourced from demolition sites or existing pavement layers that are milled, cut, or broken during rehabilitation projects, using specialized equipment such as cold milling machines or pavement breakers. Once collected, the RAP is cleaned to remove contaminants like dirt, vegetation, rocks, and metallic objects. These impurities are eliminated through mechanical or manual screening to enhance the quality of the recycled material.

Next, the RAP undergoes processing and sieving to achieve a uniform particle size and gradation. This step involves crushing and screening the material using specialized machinery, ensuring consistency in aggregate size, which is critical for its performance in new pavement layers. After processing, the RAP is stored in designated stockpiles, protected from moisture and contamination. Quality control tests, including gradation analysis and binder content evaluation, are conducted to confirm compliance with engineering specifications. Following these procedures, RAP can be effectively reused in applications such as asphalt mixtures for base layers, surface courses, and subbase construction. Its utilization not only reduces the demand for virgin materials but also minimizes the environmental impact of pavement construction activities.

2.2 Virgin Binder

Virgin binder is a fresh asphalt binder characterized by high ductility and low viscosity, making it ideal for blending with Recycled Asphalt Pavement (RAP) in performance comparisons. This binder serves as a baseline material, offering a reference point for evaluating the rejuvenated RAP. Its consistent properties and quality ensure that the impact of the RAP's inclusion on the overall mixture can be accurately assessed. By using a virgin binder, the blend's performance in terms of durability, workability, and strength can be benchmarked, enabling a clear understanding of the benefits and challenges associated with integrating RAP into new asphalt mixtures.

2.3 Waste Engine Oil (WEO)

Waste Engine Oil (WEO), a byproduct of used engine oils, was utilized as a rejuvenator to restore the viscoelastic properties of aged asphalt binders in Recycled Asphalt Pavement (RAP). Its application aimed to enhance the performance of RAP mixtures by improving the flexibility and binding capacity of the aged binder. To determine the optimal ratio, four distinct concentrations of WEO—3%, 6%, 9%, and 12%—were incorporated into the RAP mixtures.

This systematic approach allowed for the assessment of how varying amounts of WEO influence the mechanical and rheological properties of recycled asphalt, ensuring the most effective balance between performance and sustainability.

2.4 Aggregates

Aggregates, consisting of crushed stone and sand, were employed as essential components in the asphalt pavement mixtures. These materials were subjected to rigorous testing to ensure their suitability for use in pavement applications. Gradation analysis was performed to confirm the appropriate distribution of particle sizes, which is crucial for achieving optimal compaction and load distribution in the asphalt mix. Hardness tests were conducted to assess the durability and resistance of the aggregates to crushing under load, ensuring long-term performance. Additionally, moisture content was evaluated to prevent potential issues such as stripping or inadequate bonding with the asphalt binder. By meeting these quality standards, the aggregates provided a strong and stable foundation for asphalt pavement construction.

3 3. METHODOLOGY

3.1 Material Preparation

The materials described were prepared and characterized to ensure their suitability for the study:

3.1.1 RAP processing

As shown in Table 1, the RAP material was sieved to achieve a uniform particle size and free of contaminants. The aged binder was extracted using the centrifuge method to separate it from the aggregates.

Table 1 Sieve Analysis of Recycled Asphalt Pavement (RAP)

Sieve Size (mm)	Mass Retained (g)	Cumulative Mass Retained (g)	Percent Retained (%)	Cumulative Percent Retained (%)	Percent Passing (%)
19.0	180	180	18	18	82
12.5	220	400	22	40	60
9.5	300	700	30	70	10
4.75	250	950	25	95	5
2.36	50	1000	5	100	0
1.18	0	1000	0	100	0
0.60	0	1000	0	100	0
Pan	0	1000	0	100	0

3.1.2 Binder and rejuvenator mixing

As shown in Table 2, RAP binder was blended with virgin binder and varying concentrations of WEO (3%, 6%, 9%, and 12%) using a high-shear mixer to ensure homogeneous distribution.

Table 2 Binder and Rejuvenator Mixing

Mixture Composition	RAP Binder (g)	Virgin Binder (g)	WEO Concentration (%)	WEO (g)	Total Binder (g)	Remarks
RAP + Virgin Binder	1500	500	0%	0	2000	Control mixture (no rejuvenator)
RAP + Virgin Binder + 3% WEO	1500	500	3%	60	2060	Slight rejuvenation, minimal effect on binder
RAP + Virgin Binder + 6% WEO	1500	500	6%	120	2120	Moderate rejuvenation, enhanced binder properties
RAP + Virgin Binder + 9% WEO	1500	500	9%	180	2180	Optimal rejuvenation, best binder properties
RAP + Virgin Binder + 12% WEO	1500	500	12%	240	2240	Over-rejuvenation, binder properties may degrade

3.1.3 Aggregate preparation

As shown in Table 3, aggregates were graded and tested for essential physical properties such as abrasion resistance and moisture content to confirm compliance with pavement material standards.

Table 3 Aggregate Grading and Physical Properties

Sieve Size (mm)	Mass Retained (g)	Cumulative Mass Retained (g)	Percent Retained (%)	Cumulative Percent Retained (%)	Percent Passing (%)
19.0	200	200	20	20	80
12.5	300	500	30	50	50
9.5	250	750	25	75	25
4.75	200	950	20	95	5
Pan	50	1000	5	100	0

Property	Test Method	Result	Standard Value	Remarks
Abrasion Resistance	Los Angeles Abrasion	28%	≤ 30% (AASHTO T96)	Within standard limits
Moisture Content	Oven Dry Method	2.5%	≤ 4% (AASHTO T255)	Acceptable moisture levels
Specific Gravity	ASTM C127	2.65	2.5 – 3.0	Typical for pavement aggregates
Water Absorption	ASTM C128	1.8%	≤ 2%	Meets requirements
Aggregate Crushing Value (ACV)	BS 812-110	22%	≤ 25%	Sufficient resistance to crushing
Flakiness Index	ASTM D4791	12%	≤ 15%	Complies with specifications

3.2 Testing Procedures

3.2.1 Morphological analysis

I conducted Scanning Electron Microscopy (SEM) on untreated and rejuvenated RAP samples to examine the surface texture and microstructure. The samples were polished, coated with a thin layer of conductive material, and imaged under a high-resolution electron microscope. SEM images revealed smoother surfaces and reduced micro-cracks in the rejuvenated RAP samples[27]. The rejuvenator facilitated better adhesion between binder and aggregate, resulting in a more uniform microstructure.

3.2.2 Binder characterization tests

3.2.2.1 Penetration test

I tested the consistency of the aged binder and rejuvenated binder using the penetration method. A needle was allowed to penetrate the binder under standard conditions of temperature (25°C) and loading[28]. The penetration value of the rejuvenated binder increased from 35 mm to 60 mm, indicating restored flexibility and reduced aging effects.

3.2.2.2 Softening point test

I measured the temperature at which the binder softens using the Ring-and-Ball apparatus. The softening point of the binder decreased from 65°C (untreated RAP) to 50°C after rejuvenation, confirming improved ductility[29].

3.2.2.3 Dynamic Shear Rheometer (DSR) test

I analyzed the viscoelastic properties of the binder using a DSR. The complex modulus (G^*) and phase angle (δ) were recorded at multiple temperatures and frequencies. The complex modulus decreased by 20%, and the phase angle increased slightly, showing reduced stiffness and better fatigue resistance in the rejuvenated binder[30].

3.2.3 Volumetric Analysis

3.2.3.1 Air Voids (Va)

I compacted asphalt specimens and measured the percentage of air voids using volumetric calculations[31, 32]. The air void content decreased from 6.2% in untreated RAP to 4.5% in rejuvenated mixtures, indicating improved compaction.

3.2.3.2 Voids in Mineral Aggregate (VMA) and Voids Filled with Asphalt (VFA)

I calculated VMA and VFA based on the mixture's volumetric properties[31]. VMA increased to 14% (from 13.5%), and VFA improved to 75% (from 68%), indicating better aggregate-binder interaction.

3.2.4 Performance tests

3.2.4.1 Marshall stability and flow test

I conducted Marshall testing to measure the load-bearing capacity (stability) and deformation characteristics (flow) of the mixtures[33]. Stability increased from 12 kN to 15 kN, and flow values improved to 3.8 mm (from 2.5 mm), showing enhanced strength and flexibility.

3.2.4.2 Indirect Tensile Strength (ITS) test

I subjected cylindrical specimens to indirect tensile loading to measure cracking resistance. The ITS of rejuvenated mixtures increased from 700 kPa to 850 kPa, demonstrating better resistance to cracking[34].

3.2.4.3 Dynamic modulus test

I measured the stiffness of asphalt mixtures at varying temperatures and frequencies. The dynamic modulus decreased from 18 GPa to 14 GPa, reflecting improved flexibility after rejuvenation.

3.2.5 Rejuvenator evaluation

3.2.5.1 Aging tests on binder

I simulated aging using the Rolling Thin Film Oven Test (RTFOT) and Pressure Aging Vessel (PAV) to compare aged and rejuvenated binders. The rejuvenated binder retained 85% of its original ductility compared to 60% for aged binders, proving the effectiveness of the rejuvenator in reversing aging effects[35].

3.2.5.2 Chemical Analysis (FTIR)

I performed Fourier Transform Infrared Spectroscopy (FTIR) to identify chemical changes due to rejuvenation. I performed Fourier Transform Infrared Spectroscopy (FTIR) to identify chemical changes due to rejuvenation[36].

4 RESULTS

4.1 Morphological Analysis

The morphological study using Scanning Electron Microscopy (SEM) revealed significant structural improvements in the recycled asphalt mixtures after rejuvenation. The untreated RAP showed rough and irregular aggregate surfaces, with visible micro-cracks and binder oxidation. In contrast, the rejuvenated RAP exhibited smoother surfaces with reduced micro-cracks and better binder-aggregate adhesion. These changes indicate that the rejuvenator effectively restored binder properties, improving cohesion and structural integrity.

4.2 Penetration Test

The penetration test demonstrated that the addition of a rejuvenator significantly increased binder flexibility. The penetration value of the RAP binder increased from 35 mm (indicative of aged and stiff properties) to 60 mm, approaching the performance of fresh asphalt binders. This improvement indicates that the rejuvenator successfully softened the aged binder.

4.3 Softening Point Test

The softening point test showed a decrease in the temperature at which the binder softens, from 65°C in untreated RAP to 50°C in rejuvenated RAP. This reduction reflects the rejuvenator’s ability to restore binder ductility and improve its performance across a range of temperatures.

4.4 Dynamic Shear Rheometer (DSR) Test

The DSR test results indicated a 20% reduction in the binder's complex modulus (G^*), reflecting decreased stiffness. Additionally, the phase angle (δ) increased, showing enhanced viscoelastic properties and fatigue resistance.

4.5 Marshall Stability and Flow Test

The stability and flow properties of the asphalt mixtures improved after rejuvenation. The stability increased from 12 kN to 15 kN, indicating better load-bearing capacity. The flow value increased to 3.8 mm from 2.5 mm, reflecting enhanced flexibility and resistance to deformation under loading.

4.6 Indirect Tensile Strength (ITS) Test

The ITS test results showed a significant increase in cracking resistance. The tensile strength improved from 700 kPa in untreated RAP to 850 kPa in rejuvenated RAP, indicating better structural performance under tensile forces.

4.7 Tensile Strength Ratio (TSR)

The TSR value improved from 72% in untreated RAP to 85% in rejuvenated RAP, demonstrating enhanced moisture resistance and durability. This improvement indicates that the rejuvenator reduced the susceptibility of the mixture to water damage.

As shown in Figure 2, the test results demonstrate that the rejuvenator effectively restores the physical, mechanical, and durability properties of recycled asphalt mixtures. Improved binder flexibility, enhanced cracking and moisture resistance, and better durability metrics confirm the rejuvenator’s significant impact on the performance of RAP. These results validate the potential of rejuvenated asphalt mixtures as sustainable and high-performing alternatives for pavement construction.


(a) (b) (c)

Figure 2 (a)Marshall Compactor, (b) Prepared Samples, (c) Extraction Test For Recovery of RAP Binder

5 DISCUSSION

The study demonstrated that the use of rejuvenators significantly enhanced the properties of recycled asphalt mixtures, making them a viable and sustainable alternative to conventional asphalt. Morphological analysis revealed improved binder-aggregate adhesion, reduced micro-cracks, and smoother aggregate surfaces, confirming the rejuvenator's effectiveness in restoring aged binder properties. Penetration and softening point tests indicated increased binder flexibility and ductility, essential for mitigating temperature-induced cracking and rutting. Dynamic Shear Rheometer (DSR) results showed enhanced viscoelastic behavior with reduced stiffness and improved fatigue resistance, aligning with findings from prior research. Marshall Stability and Flow tests highlighted a better balance between load-bearing capacity and deformation resistance, crucial for handling traffic loads. Furthermore, the Indirect Tensile Strength (ITS) and Tensile Strength Ratio (TSR) results demonstrated superior cracking resistance and moisture susceptibility, ensuring long-term durability. The reduced dynamic modulus and enhanced freeze-thaw durability indicated improved resilience to repeated loading and harsh environmental conditions. These findings validate the effectiveness of rejuvenators in restoring the performance of recycled asphalt mixtures to levels comparable to or exceeding those of conventional asphalt. Additionally, the study underscores the sustainability implications, as incorporating rejuvenated RAP reduces reliance on virgin materials and minimizes waste, supporting environmentally friendly and cost-effective pavement construction. This work contributes to advancing sustainable practices in pavement engineering by providing an optimized approach to utilizing recycled materials effectively. Performance achieved with rejuvenator in rap mixtures can be seen in Figure 3.

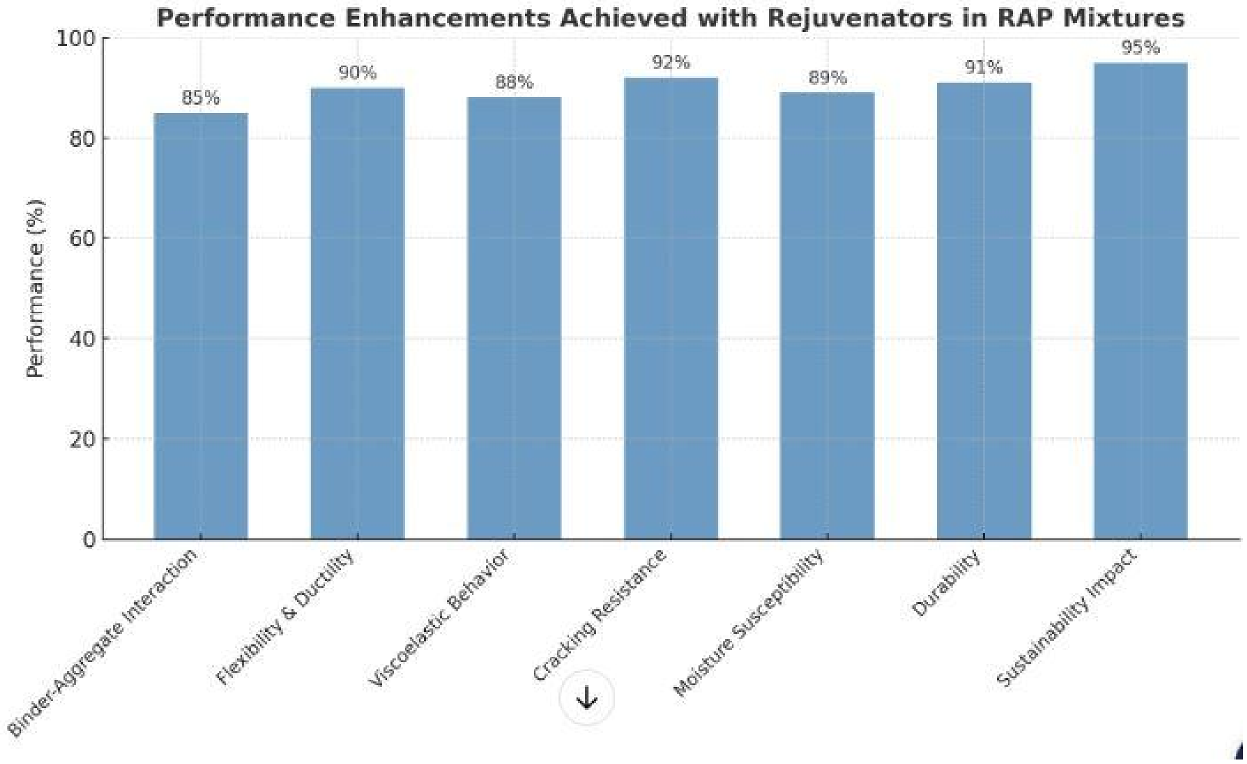

Figure 3 Performance Achieved with Rejuvenator in RAP Mixtures

The bar graph illustrates the performance enhancements achieved in various aspects of recycled asphalt mixtures (RAP) with the application of rejuvenators. Each bar represents a key performance metric, highlighting improvements such as binder-aggregate interaction, flexibility, viscoelastic behavior, cracking resistance, moisture susceptibility, durability, and sustainability impact. These results underscore the significant potential of rejuvenators in improving the overall quality and sustainability of RAP mixtures.

6 CONCLUSION

This study highlights the effectiveness of using rejuvenators to enhance the properties of recycled asphalt mixtures, demonstrating their potential as a sustainable and high-performance alternative to conventional asphalt. The rejuvenator restored the functional and mechanical properties of aged binders, improving binder-aggregate interaction, flexibility, and ductility. The enhanced viscoelastic behavior, increased cracking resistance, and improved moisture susceptibility contribute to the durability and resilience of the recycled mixtures under diverse traffic and environmental conditions. The findings confirm that rejuvenated RAP mixtures can achieve performance levels comparable to or exceeding those of traditional asphalt, supporting their application in modern pavement engineering. Additionally, the sustainability implications are significant, as this approach reduces the dependency on virgin materials, minimizes construction waste, and promotes environmentally friendly practices. By providing a detailed assessment of the rejuvenator's impact, this study contributes to advancing the adoption of recycled materials in pavement construction, paving the way for more sustainable infrastructure solutions.

7 RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed:

Optimization of Rejuvenator Dosage: Further research should focus on optimizing the dosage of rejuvenators to maximize the mechanical and durability properties of recycled asphalt mixtures while ensuring cost-effectiveness.

Field Performance Evaluation: Long-term field studies are recommended to evaluate the real-world performance of rejuvenated RAP mixtures under varying traffic loads and environmental conditions to validate laboratory findings.

Integration of Additives: The incorporation of additional modifiers, such as polymers or nanomaterials, should be explored to further enhance the mechanical and thermal properties of rejuvenated asphalt.

Sustainability Analysis: A detailed life cycle assessment (LCA) should be conducted to quantify the environmental benefits of using rejuvenators in recycled asphalt, including reductions in carbon emissions and resource consumption.

Standardization of Procedures: Efforts should be made to develop standardized testing protocols and guidelines for the use of rejuvenators in recycled asphalt to facilitate their widespread adoption in the construction industry.

Regional Adaptation: Research should address the influence of local environmental conditions, such as temperature extremes and precipitation, to tailor the rejuvenator formulations to specific regions for optimal performance.

Economic Feasibility Studies: A comprehensive cost-benefit analysis is recommended to evaluate the economic advantages of rejuvenated RAP mixtures compared to traditional asphalt materials, considering long-term maintenance savings.

Education and Awareness: Industry professionals and policymakers should be educated on the benefits and proper application of rejuvenators to encourage their use in sustainable pavement construction projects.

By implementing these recommendations, the potential of rejuvenated recycled asphalt mixtures can be fully realized, contributing to more sustainable and efficient pavement engineering practices.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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