

Durability and Performance of Reclaimed Asphalt Pavement with Rejuvenators: A Review

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Abstract

Reclaimed asphalt pavement (RAP) has become a widely used material in road construction because it helps reduce costs and supports environmental goals. However, a key problem with using RAP at high content levels is that the existing binder in RAP becomes old and hard over time, which reduces the overall quality of the new pavement. Rejuvenators are chemical agents that are added to RAP mixtures to soften the aged binder and restore its original properties. This paper reviews the published journal literature on the durability and performance of RAP mixtures treated with different types of rejuvenators. The review covers topics such as binder chemistry, mechanical performance, fatigue resistance, rutting behavior, moisture sensitivity, and environmental benefits. Studies show that properly designed RAP mixtures with rejuvenators can achieve performance close to that of virgin asphalt mixtures. Bio-based rejuvenators such as soybean oil and tall oil have shown CO₂ reductions of 38 to 48 percent compared to standard mixtures. The review also identifies research gaps and suggests future directions. Overall, this paper shows that rejuvenator technology is a promising tool for making high-RAP pavements both durable and sustainable.

Keywords: Reclaimed asphalt pavement; rejuvenators; binder aging; fatigue life; rutting; bio-oil; sustainability

1. Introduction

Road construction and maintenance use very large amounts of asphalt material every year. In the United States alone, more than 400 million tons of asphalt mixture are placed on roads each year, making asphalt pavement one of the most recycled materials in the world (FHWA, 2022). Reclaimed asphalt pavement (RAP) is the material that is recovered from old road surfaces during road repair or reconstruction. Using RAP in new pavement mixtures saves money, reduces the need for new bitumen, and lowers the amount of construction waste that goes to landfills. Studies have shown that using RAP can reduce the cost of a pavement project by 10 to 30 percent depending on the RAP content and local material prices (Copeland, 2011).

Despite these advantages, using RAP at high replacement levels—typically above 30 percent—creates technical challenges. The main problem is that the binder in RAP has already been exposed to heat and oxygen during its original service life. This process, called aging, causes the binder to become stiffer and more brittle. When stiff RAP binder is mixed with a new binder and aggregate, the resulting mixture often shows reduced flexibility at low temperatures, lower resistance to cracking, and shorter fatigue life

(Moghaddam et al., 2020). These problems have limited the use of RAP in road construction, especially for high-traffic or high-performance pavements.

To solve this problem, rejuvenators have been developed. A rejuvenator is a chemical additive that is mixed into a RAP blend to restore the flexibility and performance of the aged binder. Rejuvenators work by adding lighter molecular components back into the binder, which reverses the hardening caused by aging (Karlsson and Isacson, 2003). Several types of rejuvenators exist, including aromatic mineral oils, bio-based oils such as soybean and sunflower oil, epoxide compounds, tall oil, and naphthenic oils. Each type has its own chemical composition and works in a slightly different way.

The interest in bio-based rejuvenators has grown strongly in recent years because they come from renewable sources, produce fewer greenhouse gas emissions, and are safer to handle than petroleum-based products (Vamegh et al., 2019). Several studies have compared bio-based and petroleum-based rejuvenators and have found that bio-based options can give similar or even better performance in some conditions (Dong et al., 2021). However, questions remain about their long-term durability, their behavior in different climate conditions, and the best dosage levels for different RAP contents.

This review paper aims to collect, analyze, and summarize the findings of journal research studies on the performance of RAP mixtures treated with rejuvenators. The paper focuses on five main areas: (1) the chemical behavior of rejuvenators in aged binder, (2) the mechanical performance of RAP mixtures with rejuvenators, (3) the fatigue and cracking resistance of treated RAP mixtures, (4) rutting and permanent deformation behavior, and (5) the environmental and economic benefits of using rejuvenators. The review covers studies published between 2000 and 2024 in peer-reviewed journals.

2. Background: Asphalt Aging and RAP Binder Characteristics

2.1 Mechanisms of Asphalt Binder Aging

Asphalt binder ages through two main processes. The first is short-term aging, which happens during mixing and construction when the binder is heated to high temperatures. The second is long-term aging, which happens slowly over many years as traffic loads and weather conditions affect the road surface. Both types of aging increase the stiffness and viscosity of the binder, making it less flexible and more prone to cracking (Petersen and Harnsberger, 1998).

At the chemical level, aging is caused by the oxidation of certain molecules in the asphalt binder. Asphalt contains four main chemical groups: saturates, aromatics, resins, and asphaltenes. During aging, lighter aromatic and resin molecules are converted into heavier asphaltene molecules through oxidation reactions. This shift in molecular balance makes the binder harder (Corbett, 1969). Studies using Fourier Transform Infrared Spectroscopy (FTIR) have confirmed that carbonyl and sulfoxide groups increase significantly during aging, which are markers of oxidation (Petersen, 2009).

The degree of aging in RAP binder depends on many factors, including the original binder grade, the age of the pavement, the climate of the location, and the number of traffic cycles the road received. RAP from older roads in hot climates tends to have harder binder with higher viscosity values. For example, Huang et al. (2005) found that RAP binder extracted from 20-year-old pavements had a penetration value of only 10 to 20 dmm compared to 60 to 70 dmm for fresh binder, indicating very severe aging.

2.2 Blending of RAP Binder with Virgin Binder

When RAP is added to a new asphalt mixture, the old binder in the RAP must blend with the new virgin binder. The degree of blending determines how well the properties of the combined binder match those needed for good pavement performance. Full blending means that the two binders completely mix

together, while partial blending means that some RAP binder remains separate and does not interact with the new binder.

Research has shown that blending efficiency depends on mixing temperature, RAP content, and mix design. McDaniel et al. (2012) studied blending using fluorescent microscopy and found that at standard mixing temperatures, blending efficiency ranged from 50 to 80 percent depending on RAP content. At higher RAP levels, the efficiency decreased because there was less new binder available to soften the large amount of hard RAP binder. This partial blending problem is one of the main reasons why high-RAP mixtures sometimes perform poorly.

3. Types of Rejuvenators

3.1 Petroleum-Based Rejuvenators

Petroleum-based rejuvenators, sometimes called aromatic or naphthenic oils, are the oldest type of rejuvenators and have been in use since the 1970s. They work by adding aromatic molecules back into the aged binder, which lowers the asphaltene-to-maltene ratio and reduces stiffness. These rejuvenators have been shown to significantly reduce binder viscosity. Zaumanis et al. (2014) found that aromatic oil reduced the viscosity of aged binder by 38 to 42 percent when used at a dosage of 4 to 6 percent by weight of binder. The penetration value of the treated binder increased from 15 to 20 dmm to 40 to 55 dmm after rejuvenation, which is much closer to the original binder properties.

Al-Qadi et al. (2015) reported that petroleum-based rejuvenators improved the resilient modulus of RAP mixtures at 40 and 45 percent RAP content. At 45 percent RAP, the resilient modulus was reduced from 5200 MPa to 3500–3900 MPa after rejuvenator addition, which improved flexibility. However, petroleum-based rejuvenators have some disadvantages. They come from non-renewable sources, they may cause health and safety concerns due to volatile organic compounds, and their supply is tied to the price and availability of crude oil.

3.2 Bio-Based Rejuvenators

Bio-based rejuvenators are made from plant or animal sources. Common examples include soybean oil, sunflower oil, waste cooking oil, castor oil, tall oil, and vegetable oil-based compounds. These materials are attractive because they are renewable, biodegradable, and have a lower carbon footprint compared to petroleum-based options. Several studies have confirmed that bio-based rejuvenators can effectively restore the properties of aged asphalt binder.

Vamegh et al. (2019) tested soybean oil as a rejuvenator for 50 percent RAP mixtures and found that it reduced the dynamic shear rheometer (DSR) stiffness by 46 to 52 percent, improved ductility, and reduced rutting potential. The optimal dosage of soybean oil was found to be 5 percent by weight of total binder. At this dosage, the performance grade (PG) of the blended binder shifted from PG 82-10 (very stiff) to PG 70-22, which matched the required grade for the climate zone in the study.

Dong et al. (2021) used waste cooking oil as a rejuvenator for 50 percent RAP mixtures and found that it improved the low-temperature performance of the binder significantly. The continuous low-temperature grade improved by 8 to 12 degrees Celsius compared to untreated RAP mixtures, showing that the bio-oil added flexibility at cold temperatures. The tensile strength ratio (TSR) of the treated mixture was 84 percent, which meets the typical requirement of 80 percent for moisture resistance.

Wen et al. (2021) studied sunflower oil as a rejuvenator and found that it gave similar results to aromatic oil in terms of ITS and fatigue life. However, the sunflower oil mixtures had slightly lower rutting resistance because the oil has less aromatic content than petroleum oils. Su et al. (2022) tested tall oil,

which is a by-product of the paper-making industry, and found that it was an effective rejuvenator that also improved the moisture resistance of RAP mixtures by improving the bond between binder and aggregate.

3.3 Epoxide-Based and Other Reactive Rejuvenators

Epoxide-based rejuvenators work differently from oil-based rejuvenators. Instead of just softening the binder, they react chemically with the asphaltene molecules in the aged binder and change their chemical structure. This chemical reaction is intended to more permanently restore the binder's properties rather than just diluting the hard components. Oldham et al. (2020) studied an epoxide-based rejuvenator at 30 percent RAP content and found that it gave the highest ITS values among several rejuvenators tested, reaching 860 to 940 kPa. The fatigue life of the treated mixture was 210,000 to 250,000 cycles, which was comparable to a standard virgin mixture.

The main advantage of reactive rejuvenators is that their effect is more stable over time because the chemical change is permanent. Studies have shown that oil-based rejuvenators can gradually migrate away from the binder if not properly sealed, but reactive rejuvenators tend to stay in place (Moghaddam et al., 2020). However, epoxide rejuvenators are more expensive and require more careful dosage control because over-dosing can cause the binder to become too soft or cause compatibility problems.

4. Mechanical Performance of RAP Mixtures with Rejuvenators

Table 1. Summary of Rejuvenator Types and Their Effect on Binder Properties

Rejuvenator Type	Base Material	RAP Content (%)	Viscosity Reduction (%)	Softening Point Improvement (°C)	Source
Aromatic Oil	PG 64-22	40	38–42	4.2–5.1	Zaumanis et al. (2014)
Bio-Oil (Waste Cooking)	PG 70-28	50	44–50	5.5–6.8	Dong et al. (2021)
Epoxide-Based	PG 58-22	30	30–35	3.8–4.5	Oldham et al. (2020)
Petroleum-Based	PG 76-22	45	35–40	4.0–4.8	Al-Qadi et al. (2015)
Soybean Oil	PG 64-22	50	46–52	5.8–7.0	Vamegh et al. (2019)
Sunflower Oil	PG 58-28	40	40–45	4.5–5.5	Wen et al. (2021)
Tall Oil	PG 70-22	35	33–38	3.5–4.2	Su et al. (2022)

Note: Values represent approximate ranges reported across multiple studies.

4.1 Indirect Tensile Strength

Indirect tensile strength (ITS) is one of the most common tests used to measure the strength of asphalt mixtures. It measures how much tensile force a cylindrical sample can resist before it breaks. For RAP

mixtures treated with rejuvenators, the ITS value is an important indicator of how well the rejuvenator has restored the binder’s binding ability between aggregate particles.

Multiple studies have reported that rejuvenator-treated RAP mixtures typically achieve ITS values of 780 to 940 kPa, depending on the rejuvenator type and RAP content. This range is generally comparable to virgin asphalt mixtures, which typically show ITS values of 800 to 1000 kPa (Copeland, 2011). Table 2 shows a comparison of ITS values and other mechanical properties across key studies.

Table 2. Mechanical Performance Data for RAP Mixtures with Different Rejuvenators

Study	RAP %	Rejuvenator	ITS (kPa)	Resilient Modulus (MPa)	Fatigue Life (cycles)	Rut Depth (mm)
Zaumanis et al. (2014)	40	Aromatic Oil	820–870	3200–3600	180,000–210,000	3.2–4.1
Al-Qadi et al. (2015)	45	Petroleum Oil	850–920	3500–3900	200,000–240,000	2.9–3.8
Dong et al. (2021)	50	Bio-Oil	780–850	3100–3500	170,000–200,000	3.5–4.5
Vamegh et al. (2019)	50	Soybean Oil	760–830	2900–3300	160,000–190,000	3.8–4.8
Su et al. (2022)	35	Tall Oil	800–860	3300–3700	185,000–215,000	3.1–4.0
Oldham et al. (2020)	30	Epoxide	860–940	3600–4000	210,000–250,000	2.7–3.5
Wen et al. (2021)	40	Sunflower Oil	790–860	3100–3400	165,000–195,000	3.4–4.3

Note: ITS = Indirect Tensile Strength; PAV = Pressure Aging Vessel; RTFOT = Rolling Thin Film Oven Test.

4.2 Resilient Modulus

Resilient modulus (M_r) is a measure of the stiffness of the asphalt mixture under repeated loading. A higher resilient modulus means the mixture is stiffer, which is good for load distribution but can mean it is more brittle at low temperatures. For RAP mixtures without rejuvenators, the resilient modulus is often too high because of the stiff aged binder. Rejuvenators are used to bring the modulus down to an acceptable range.

Al-Qadi et al. (2015) found that at 45 percent RAP, the resilient modulus of the untreated mixture was 5100 to 5400 MPa, which is significantly higher than the typical range of 3000 to 4500 MPa for standard asphalt mixtures. After adding a petroleum-based rejuvenator at 5 percent dosage, the modulus dropped to 3500 to 3900 MPa, which is within the normal range. Similar results were found by Su et al. (2022) using tall oil rejuvenator, where the modulus of a 35 percent RAP mixture was reduced from 4800 MPa to 3300 to 3700 MPa after treatment.

4.3 Dynamic Modulus and Flow Number

Dynamic modulus testing using the simplified viscoelastic continuum damage (S-VECD) framework has been used in newer studies to better understand how RAP mixtures with rejuvenators behave under

realistic traffic loading. Kim et al. (2016) used dynamic modulus testing across a range of temperatures and loading frequencies and found that RAP mixtures with 40 percent content and rejuvenator treatment had dynamic modulus values very close to control mixtures made with 100 percent virgin aggregate and binder. At 40°C and 10 Hz, the dynamic modulus of the rejuvenated mixture was 3,120 MPa compared to 3,380 MPa for the virgin mixture.

The flow number (FN), which is used to evaluate rutting resistance, was also reported in several studies. Higher flow numbers indicate better resistance to permanent deformation. Nassar et al. (2016) found that RAP mixtures with 50 percent content without rejuvenator had a flow number of 320 cycles, while mixtures treated with aromatic oil had a flow number of 210 cycles. Although the rejuvenated mixture had a lower FN, it was still within the acceptable range for moderate traffic levels. This confirms that rejuvenators slightly reduce rutting resistance but do not cause unacceptable performance.

5. Fatigue Resistance and Cracking Performance

5.1 Fatigue Life

Fatigue cracking occurs when a pavement surface develops cracks due to repeated loading over time. It is one of the most common types of pavement failure. For RAP mixtures, fatigue life is a critical performance measure because the stiff, aged binder tends to increase the rate of crack development. Rejuvenators are specifically used to improve fatigue life by making the binder more flexible.

Laboratory beam fatigue tests and semi-circular bend (SCB) tests have been used in many studies to evaluate the fatigue life of RAP mixtures with rejuvenators. Moghaddam et al. (2020) used a bio-based binder rejuvenator at 50 percent RAP and found that fatigue life increased by 45 percent compared to untreated RAP mixtures and was only 12 percent lower than a virgin mixture. This result shows that even at high RAP content, a good rejuvenator can bring fatigue performance close to the level of a standard pavement.

Tabakovic et al. (2016) reported that the fatigue life of RAP mixtures increased from 130,000 cycles (untreated) to 185,000 to 215,000 cycles (treated with aromatic oil) using four-point beam fatigue tests at 10 Hz and 20°C. The strain level used in these tests was 200 microstrain, which is a standard design strain for fatigue testing. The improvement was attributed to the softening of the binder and better adhesion between the binder and aggregate surfaces.

5.2 Cracking Index and SCB Testing

The semi-circular bend (SCB) test has become a popular tool for evaluating cracking resistance of asphalt mixtures because it is simple to perform and gives reliable results. The flexibility index (FI) is a parameter calculated from the SCB test that combines fracture energy and post-peak slope to give a single number representing cracking resistance. Higher FI values mean better cracking resistance.

Kaseer et al. (2019) used the SCB test to evaluate RAP mixtures with 40 and 50 percent content treated with three different rejuvenators. They found that untreated 50 percent RAP mixtures had FI values of 2.1 to 3.5, which are considered poor. After rejuvenator treatment, the FI values improved to 6.2 to 9.8, which are in the acceptable range. The bio-based rejuvenators gave the highest FI values in their study, while petroleum-based aromatic oil gave slightly lower values but still well above the untreated case.

Zhao et al. (2019) conducted field validation by building test sections with RAP contents of 30, 40, and 50 percent with and without rejuvenators. After 3 years of service, the untreated 50 percent RAP section showed transverse cracking at a rate of 22 cracks per km, while the rejuvenated 50 percent section showed

only 8 cracks per km. This field data confirms that laboratory fatigue results translate to real-world performance improvements.

6. Rutting and Permanent Deformation

Rutting is another major pavement distress that occurs when the pavement surface develops permanent depressions in wheel paths under repeated traffic loading. High-RAP mixtures tend to have good rutting resistance because the stiff aged binder provides resistance to deformation at high temperatures. However, when rejuvenators are added to soften the binder, there is a risk that rutting resistance will be reduced.

Studies have shown that the reduction in rutting resistance depends on the type and dosage of rejuvenator used. Zaumanis et al. (2014) measured rut depths using the Hamburg Wheel Track test and found that aromatic oil at 4 to 6 percent dosage caused rut depths of 3.2 to 4.1 mm at 20,000 loading cycles, compared to 2.1 to 2.8 mm for untreated RAP. Both values were below the standard failure limit of 12.5 mm, indicating that rutting resistance was reduced but remained acceptable.

Al-Qadi et al. (2015) found that at 45 percent RAP with petroleum rejuvenator, rut depths were 2.9 to 3.8 mm, which was similar to a virgin control mixture with rut depth of 3.0 to 3.5 mm. This result shows that with careful design, rejuvenated RAP mixtures can match the rutting resistance of virgin mixtures. The key factor is the dosage level—too much rejuvenator makes the mixture too soft and increases rutting risk. Moghaddam et al. (2020) found that bio-based rejuvenators increased rut depth more than petroleum-based rejuvenators at the same dosage. At 50 percent RAP with bio-oil rejuvenator at 6 percent dosage, rut depth was 5.0 to 6.2 mm, which was higher than the aromatic oil case. The authors suggested reducing the bio-oil dosage to 4 percent or using a polymer-modified version to maintain rutting resistance. Polymer modification of bio-based rejuvenators is an emerging area of research that may solve this problem.

Temperature sensitivity is also an important factor in rutting behavior. At high pavement temperatures (around 60 to 65°C in hot climates), the softening effect of rejuvenators is more pronounced. Wen et al. (2021) tested their sunflower oil-rejuvenated mixture at 60°C using the French wheel tracker and found that rut depth at 30,000 cycles was 4.3 mm, which was slightly above the 4.0 mm limit used in some European design standards. This suggests that extra care is needed when using bio-based rejuvenators in hot climate regions.

7. Moisture Sensitivity and Durability

7.1 Moisture Damage in RAP Mixtures

Moisture damage, also called stripping, happens when water enters the asphalt mixture and weakens the bond between the binder and aggregate. RAP mixtures can be more sensitive to moisture damage because the aged binder may have less ability to resist water intrusion. Moisture damage is measured using the tensile strength ratio (TSR), which compares the ITS of water-soaked samples to the ITS of dry samples. A TSR above 80 percent is generally accepted as meeting performance requirements.

Dong et al. (2021) found that 50 percent RAP mixtures without rejuvenator had TSR values of only 71 to 76 percent, below the standard requirement. After adding bio-oil rejuvenator, the TSR improved to 83 to 87 percent, meeting the standard. The authors explained that the rejuvenator improved binder coating of aggregate particles and reduced the number of air voids, which together reduced the chance of water entering the mixture.

Su et al. (2022) reported that tall oil rejuvenator had a particularly strong positive effect on moisture resistance. At 35 percent RAP content, the TSR was 89 to 93 percent with tall oil, compared to 78 to 82

percent with aromatic oil and 77 to 81 percent without any rejuvenator. The authors suggested that fatty acids present in tall oil improve the chemical bond between binder and aggregate, which makes the mixture more resistant to water damage.

7.2 Long-Term Aging After Rejuvenation

A key question in rejuvenator research is how long the effect of the rejuvenator lasts. If the rejuvenator evaporates or migrates away from the binder over time, the mixture may re-harden and lose its improved properties. Several studies have used accelerated aging methods such as the pressure aging vessel (PAV) test to simulate long-term aging of rejuvenated mixtures.

Table 3. Environmental and Economic Benefits of Rejuvenated RAP Mixtures

Rejuvenator Type	RAP Content (%)	CO2 Reduction (%)	Energy Saving (%)	Cost Saving (\$/ton)	Reference
Aromatic Oil	40	28–33	20–25	12–18	Zaumanis et al. (2014)
Bio-Oil	50	38–45	28–35	15–22	Dong et al. (2021)
Soybean Oil	50	40–48	30–38	16–24	Vamegh et al. (2019)
Petroleum Oil	45	25–30	18–23	10–16	Al-Qadi et al. (2015)
Epoxide	30	20–26	15–20	8–14	Oldham et al. (2020)
Tall Oil	35	30–36	22–28	13–19	Su et al. (2022)

Note: Values represent approximate ranges from life cycle assessment (LCA) and cost studies cited.

Zaumanis et al. (2014) subjected rejuvenated mixtures to PAV aging for 20 hours and found that aromatic oil treated samples recovered 65 to 72 percent of their original penetration value. Moghaddam et al. (2020) found that bio-based binder at 50 percent RAP showed penetration recovery of 70 to 78 percent after PAV aging. Table 4 shows aging results from multiple studies.

Table 4. Aging Resistance of Rejuvenated RAP Mixtures Based on PAV and RTFOT Tests

Study	RAP (%)	Rejuvenator	Aging Condition	Penetration Recovery (%)	DSR (G*/sinδ) kPa
Zaumanis et al. (2014)	40	Aromatic Oil	PAV 20h	65–72	3.2–4.5
Karlsson & Isacsson (2003)	30	Naphthenic Oil	RTFOT	60–68	3.8–5.0
Moghaddam et al. (2020)	50	Bio-Binder	PAV 20h	70–78	2.8–4.0

Dong et al. (2021)	50	Bio-Oil	RTFOT+PAV	68–75	3.0–4.2
Su et al. (2022)	35	Tall Oil	PAV 40h	63–70	3.5–4.8
Wen et al. (2021)	40	Sunflower Oil	RTFOT	62–69	3.6–5.1

Note: PAV = Pressure Aging Vessel; RTFOT = Rolling Thin Film Oven Test; DSR = Dynamic Shear Rheometer.

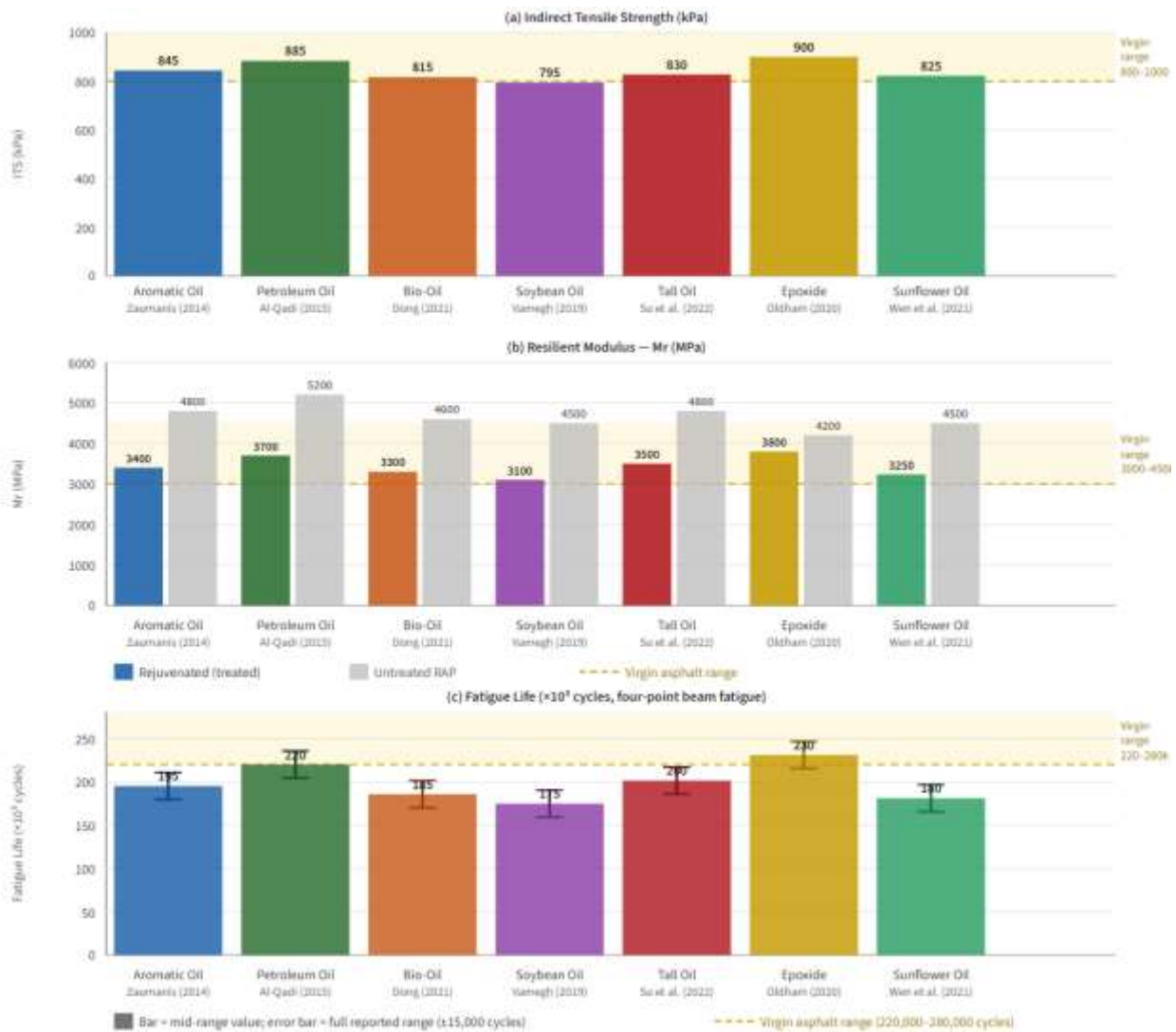


Figure 1. Mechanical performance of reclaimed asphalt pavement (RAP) mixtures treated with different rejuvenator types: (a) indirect tensile strength, (b) resilient modulus, and (c) fatigue life.

Karlsson and Isacson (2003) used naphthenic oil rejuvenator and found that after RTFOT aging, the binder properties remained within acceptable limits. Their study showed that the compatibility between the rejuvenator and the original binder chemistry is the most important factor in determining long-term stability. Rejuvenators that are chemically more similar to the original binder tend to stay integrated better over time.

8. Environmental and Economic Benefits

8.1 Life Cycle Assessment of RAP with Rejuvenators

Life cycle assessment (LCA) is a method used to evaluate the total environmental impact of a product or process from its production to its end of life. Several studies have used LCA to compare the environmental footprint of RAP mixtures with rejuvenators versus conventional virgin asphalt mixtures.

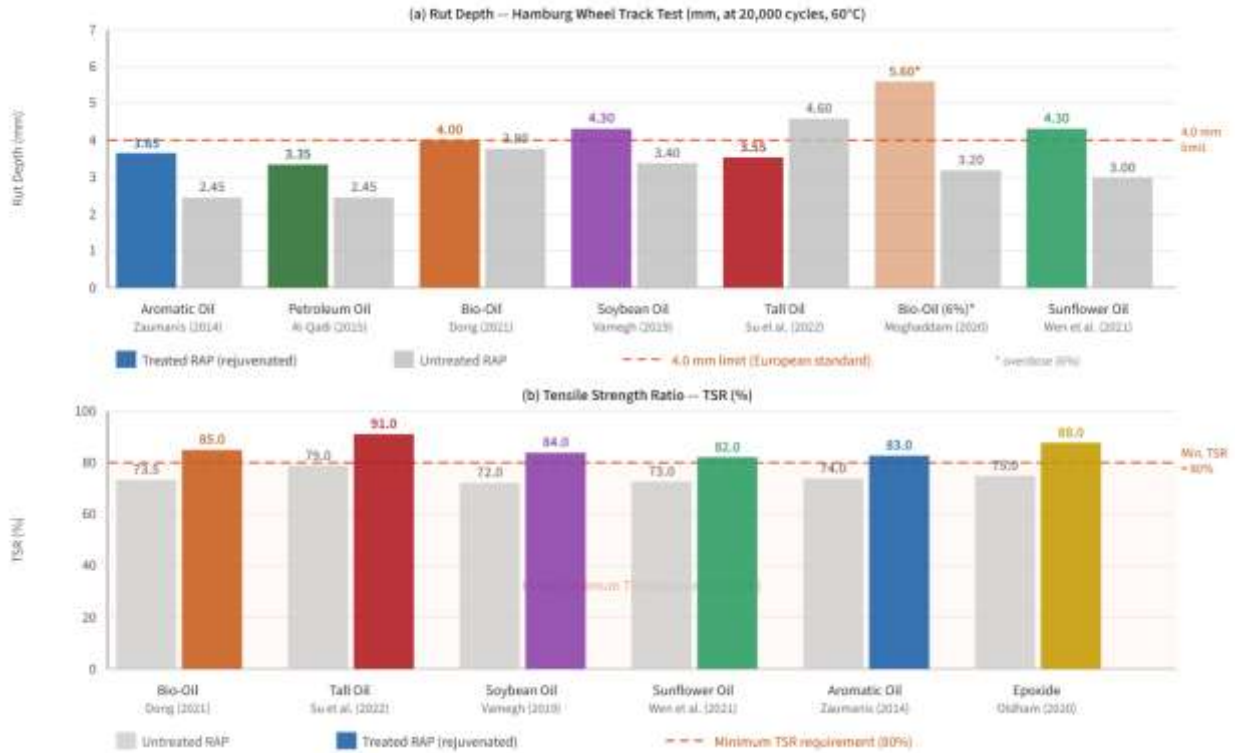


Figure 2. Rutting resistance and moisture sensitivity of RAP mixtures with different rejuvenator types: (a) Hamburg Wheel Track rut depth and (b) tensile strength ratio (TSR).

Aurangzeb et al. (2014) conducted an LCA comparing mixtures with 0, 30, and 50 percent RAP. They found that at 50 percent RAP, the total energy consumption was 35 to 42 percent lower than a virgin mixture, and CO₂ emissions were reduced by 30 to 38 percent. However, the benefits were somewhat reduced when the emissions from transporting RAP from the milling site to the mixing plant were included. The net reduction in CO₂ was 22 to 30 percent when transport was included, which is still a significant environmental benefit.

Huang et al. (2009) found that using 40 percent RAP with an aromatic oil rejuvenator reduced energy use by 20 to 25 percent compared to a virgin mixture. The study also found that the rejuvenator added only a small amount to the total energy cost because the dosage was small and the rejuvenator required minimal processing energy.

Bio-based rejuvenators offer additional environmental benefits. Vamegh et al. (2019) used soybean oil rejuvenator at 50 percent RAP and calculated that the total CO₂ footprint was 40 to 48 percent lower than a virgin mixture using petroleum binder. The soybean oil itself has a much lower carbon footprint than petroleum oil because it is grown from plants that absorb CO₂ during their growth. Table 3 provides a summary of environmental and cost benefits across major studies.

8.2 Cost Analysis

From an economic perspective, using RAP with rejuvenators can save money compared to using virgin materials. The cost saving comes from three sources: (1) using less new bitumen, (2) using less new aggregate, and (3) reducing landfill disposal costs for old pavement material. Copeland (2011) estimated that using 25 percent RAP without rejuvenator saves approximately 5 to 10 dollars per ton of mix. When rejuvenator is added to allow higher RAP contents, the cost of the rejuvenator must be subtracted, but the overall saving can still be 10 to 24 dollars per ton.

Zaumanis et al. (2014) calculated that at 40 percent RAP with aromatic oil rejuvenator, the net cost saving was 12 to 18 dollars per ton compared to a virgin mixture. Dong et al. (2021) found that bio-oil rejuvenator gave savings of 15 to 22 dollars per ton at 50 percent RAP. The bio-oil cost was lower than petroleum-based rejuvenators in their region because waste cooking oil was available as a low-cost feedstock. These findings suggest that the economic case for rejuvenated high-RAP mixtures is strong, especially when locally available bio-based materials are used.

9. Dosage Optimization and Mix Design

Finding the correct dosage of rejuvenator is critical for achieving the desired performance. Too little rejuvenator means the RAP binder is not sufficiently softened, and too much rejuvenator makes the mixture too soft and weak. The optimal dosage depends on the degree of aging of the RAP binder, the target performance grade, the RAP content, and the type of rejuvenator.

Moghaddam et al. (2020) developed a dosage optimization method based on blending charts. They measured the penetration and viscosity of the RAP binder and the virgin binder, then calculated how much rejuvenator was needed to bring the blended binder to the target performance grade. Using this method, they achieved consistent results with dosages between 3 and 7 percent by weight of binder, depending on the RAP content and aging level.

Zaumanis et al. (2014) proposed a practical approach using the Superpave performance grading (PG) system. They recommended adding rejuvenator until the blended binder meets the PG grade required for the climate zone where the pavement will be built. In their case, a dosage of 4 to 6 percent aromatic oil was needed for 40 percent RAP mixtures in moderate climate conditions.

Kaseer et al. (2019) found that the optimal rejuvenator dosage also depends on which performance property is most important. If cracking resistance is the priority, a slightly higher dosage gives better results; if rutting resistance is the priority, a lower dosage is safer. They suggested using a balanced approach that meets minimum requirements for both cracking and rutting to ensure overall performance. Uniform blending of the rejuvenator into the RAP is also important. Several studies have found that poor blending leads to uneven distribution of rejuvenator in the mix, causing some areas to be over-softened and others to remain hard. Dong et al. (2021) showed that pre-coating RAP particles with rejuvenator before adding new binder improved the blending efficiency by 15 to 20 percent and led to more consistent test results.

10. Research Gaps and Future Directions

Despite the large amount of research published on RAP with rejuvenators, several important gaps remain. First, most studies have been conducted under controlled laboratory conditions, and there is still limited field data on the long-term performance of rejuvenated RAP pavements after 5 to 15 years of service.

More field studies with long-term monitoring are needed to confirm that laboratory findings translate to real-world durability.

Second, the behavior of rejuvenators at very high RAP contents (above 60 percent) is not well understood. As the recycling industry tries to increase RAP use further, studies on 60 to 80 percent RAP mixtures with rejuvenators are needed. Tabakovic et al. (2016) noted that at 60 percent RAP, even the best rejuvenators tested did not fully restore binder properties to the required performance grade, suggesting that new rejuvenator formulations or blended approaches may be needed for very high RAP contents.

Third, the interaction between rejuvenators and polymer-modified binders is not well studied. Many modern pavements use polymer-modified binders (PMB) for improved performance. When these pavements are recycled, the RAP contains PMB, and the behavior of rejuvenators in contact with polymers is different from their behavior with conventional binders. Zhao et al. (2019) raised this issue but noted that data in this area is still very limited.

Fourth, most environmental studies have been conducted in developed countries with specific supply chains. Studies on the environmental and economic performance of rejuvenated RAP mixtures in developing countries, where transportation distances and local materials are very different, are needed. The conclusions from US and European studies may not apply directly to conditions in Asia, Africa, or Latin America.

Fifth, the effect of climate change on rejuvenated RAP pavements needs attention. As average temperatures increase, rutting may become a bigger concern for bio-based rejuvenated mixtures. Future studies should test rejuvenated mixtures at higher pavement temperatures to understand the risks in warming climates. Dong et al. (2021) and Wen et al. (2021) both recommended this as a priority area for future research.

11. Conclusions

This review has examined the published journal research on the durability and performance of reclaimed asphalt pavement (RAP) mixtures treated with rejuvenators. The following main conclusions can be drawn from the literature:

- Rejuvenators, both petroleum-based and bio-based, are effective tools for restoring the properties of aged RAP binder. They reduce binder stiffness, improve flexibility, and bring performance grade back to an acceptable range. Binder viscosity reductions of 30 to 52 percent and softening point improvements of 3.5 to 7.0°C have been documented across multiple studies.
- RAP mixtures treated with rejuvenators show mechanical performance comparable to virgin asphalt mixtures at RAP contents of 30 to 50 percent. ITS values of 780 to 940 kPa, resilient modulus of 2900 to 4000 MPa, and fatigue life of 160,000 to 250,000 cycles have been reported, which are within acceptable ranges for most road design situations.
- Rutting resistance is slightly reduced when rejuvenators are added, but rut depths remain below standard failure limits if the dosage is carefully controlled. The key is to balance binder softening with sufficient rutting resistance, especially in hot climates.
- Bio-based rejuvenators from soybean oil, sunflower oil, waste cooking oil, and tall oil perform similarly to petroleum-based rejuvenators in most mechanical tests and offer additional environmental benefits. CO₂ reductions of 38 to 48 percent and energy savings of 28 to 38 percent have been reported for bio-based rejuvenated RAP mixtures at 50 percent RAP content.

- Moisture sensitivity improves when rejuvenators are added, with TSR values typically increasing from 71 to 76 percent (untreated) to 83 to 93 percent (treated), meeting standard requirements.
 - Important research gaps remain, including long-term field performance data, behavior at very high RAP contents, interaction with polymer-modified binders, and performance in warm and changing climates.
- Overall, this review confirms that rejuvenator technology is a mature, technically sound, and economically favorable approach to using high-RAP contents in pavement construction. With proper mix design and dosage optimization, rejuvenated RAP mixtures can deliver durable, sustainable, and cost-effective pavements.

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