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Review

High-RAP Asphalt Mixtures (>40%): Mechanical Performance, Durability, Sustainability, and Emerging Technologies

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ABSTRACT: Asphalt mixtures that utilize Reclaimed Asphalt Pavement (RAP), particularly at high RAP levels above 40%, are gaining in popularity due to the emphasis on sustainable pavement solutions. This review paper comprehensively evaluates the performance of high RAP asphalt mixtures, focusing on their mechanical characteristics and durability when compared to standard asphalt mixtures. High RAP mixtures perform well in high-traffic scenarios because they have excellent stiffness and resistance to rutting. Still, they have performance limitations that could be remedied through rejuvenators, anti-stripping agents, and premium additives. Durability issues such as moisture susceptibility and long-term aging are investigated, along with the importance of binder blending and rejuvenation on the impacts of aging. The review highlights significant research areas like optimizing rejuvenator formulations, bio-based additives evaluation, and complete life cycle assessments (LCA) to examine the overall sustainability of high-RAP mixtures. The comparison with conventional mixtures highlights high-RAP mixtures' environmental and economic advantages, such as reduced greenhouse gas emissions, decreased energy use, and substantial cost savings. Despite these advantages, variability of RAP content and lack of standard testing are significant challenges. While still in its infancy, new technologies, such as warm-mix asphalt (WMA), and new characterization technologies, such as X-ray computed tomography (CT) and AI, promise to optimize mix design and forecast long-term performance. High-RAP mixes can transform sustainable pavement construction by alleviating these challenges and employing innovative technologies. This article will benefit researchers, engineers, and policymakers looking to facilitate the use of high-RAP mixes in new construction.

Keywords: Mechanical properties, Durability, High RAP content, Asphalt recycling, Sustainable construction, Performance evaluation

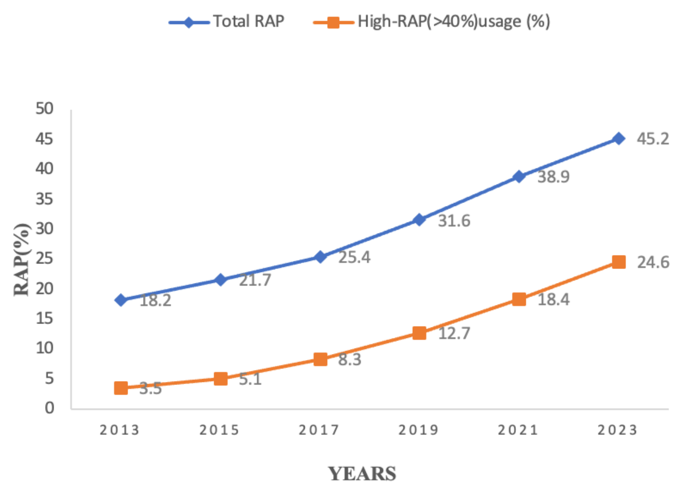
1. Introduction

The environmental and economic impacts of the construction and maintenance of road infrastructure generate the incentive for sustainability in the pavement industry. One new approach that shows promise in achieving sustainability is using Reclaimed Asphalt Pavement (RAP) in new asphalt mixtures. RAP is produced from milled or crushed asphalt pavements and is reused in varying quantities as a partial replacement for unprocessed aggregates or binders. This approach also reduces the demand for natural materials and acts to divert construction waste from landfills as part of a circular economy within the construction industry [1], [2]. As shown in Figures 1a and 1b, the amount of RAP used in asphalt mixtures around the globe has steadily increased in the past decade, with an increasing proportion of commonly used asphalt mixtures comprised of over 40% RAP [3], [4].

In recent years, the desire to increase the recycled asphalt pavement (RAP) content in asphalt mixtures beyond 40% is gaining attention due to the need for more sustainability and cost efficiency. The usage of high RAP content provides both opportunities and challenges. On one hand, RAP incorporation has demonstrated remarkable environmental benefits such as reduced greenhouse gas emissions

Table 1. Summary of Mechanical Performance Findings from Recent High-RAP Mixture Studies.

Study Reference	RAP Content (%)	Test Method	Key Findings
Porto et al. [5]	70%	Thermal Stress Restrained Specimen Test, Complex Modulus Measurement	The 70% RAP mixture without rejuvenation had the highest stiffness modulus but poor fatigue performance at low temperatures. The mix with rejuvenation performed similarly to the virgin blend.
Sabouri [6]	0%, 20%, 40%	Simplified Viscoelastic Continuum Damage (S-VECD) Model, Triaxial Stress Sweep (TSS) Test	Increased RAP content improved rutting resistance but deteriorated fatigue resistance.
Yi et al. [7]	100%	Wheel Tracking Test, Bending Test, Freeze-Thaw Test, Fatigue Test	The 100% RAP mixture with epoxy asphalt showed better rutting resistance, while low-temperature performance and moisture susceptibility were similar to conventional mixtures, but fatigue resistance was poor.



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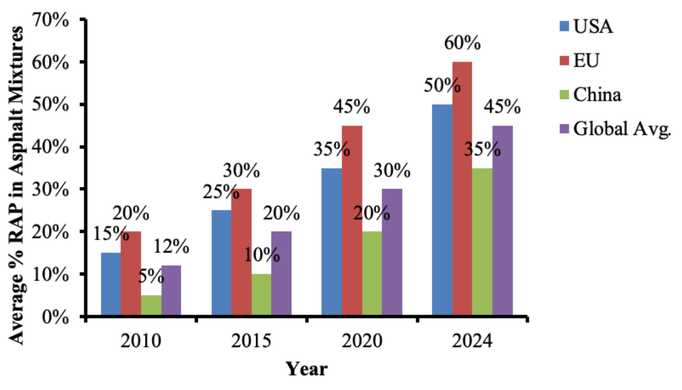

(b)

Figure 1. Global Trends in RAP Usage.

and energy consumption during production [8], [9]. On the other hand, the aged binder within the RAP pavement may cause stiffness and brittleness in the mixtures, leading to undesirable mechanical performance and durability [10], [11]. As another example, the main conclusions of contemporary research assessing the mechanical performance of high-RAP asphalt mixtures are compiled in Table 1. It demonstrates how stiffness, rutting resistance, and fatigue behavior are affected by increasing RAP content and shows how rejuvenators or modifiers can restore balanced performance [12], [13].

Multiple factors affect the performance of high-RAP asphalt mixtures, such as the properties of the RAP material, the blending efficiency between aged and virgin binders, and the use of rejuvenators or additives to restore the properties of the aged binder [14], [15]. Table 2 indicates that high-RAP mixtures have improved resistance to rutting but poorer fatigue performance. For example, a 50% RAP mixture had a 2.5 vs. 6.2 mm lower rut depth for the control group (roughly 60% lower), but its fatigue life was 40% shorter [11]. Despite advancements, there is little agreement over the long-term performance of high-RAP mixtures based on climate and traffic [11], [16]. For example, Figure 2 illustrates the effect of RAP content on stiffness and fatigue life, showing that stiffness increases with RAP content. In contrast, fatigue resistance decreases by increased RAP content unless rejuvenators are used [17], [18].

The purpose of this review article is to critically evaluate the mechanical properties and performance of asphalt mixtures containing high levels of RAP (>40%). This evaluation will be based primarily on performance-based indicators such as stiffness, fatigue resistance, rutting resistance, moisture damage, and long-term aging. The review also identifies testing and construction challenges associated with RAP mixtures and possible ways to address these issues using rejuvenators, warm-mix asphalt technologies, and advanced mix design procedures. The review will synthesize and connect findings from various studies and provide researchers and practitioners with meaningful information and knowledge to increase the use of high-RAP mixtures in sustainable pavements.

The remainder of this article is structured as follows to help the reader: Section 2 looks at the mechanical properties of high-RAP asphalt mixtures, emphasizing stiffness, fatigue performance, and rutting resistance; Section 3 assesses durability-related factors like moisture suscep-

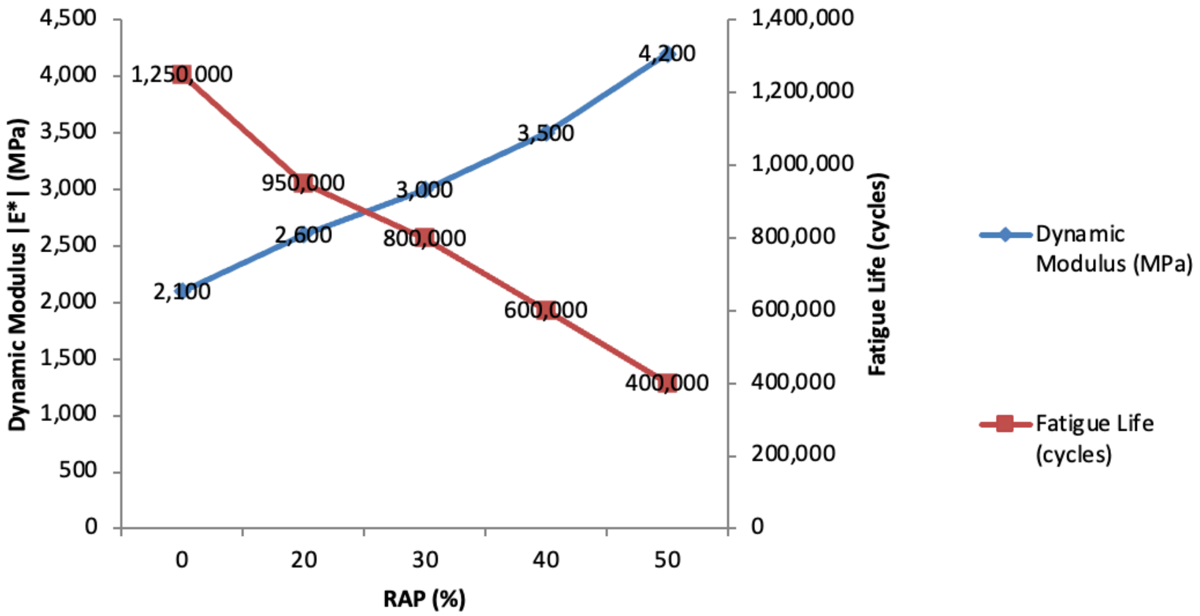

Figure 2. Effect of RAP Content on Stiffness and Fatigue Life.

Table 2. Effects of RAP content on Asphalt Performance.

RAP Amount	Stiffness (MPa)	Fatigue Life (cycles)	Rut Resistance (mm depth)	Best For	Study Examples
0% RAP (Regular Asphalt)	2,100	1,250,000	6.2	Normal roads	NAPA (2007) [19]
30% RAP	2,700	950,000	4.5	City streets	W. Wei et al. (2023)
40% RAP	3,200	750,000	3.8	Busy highways	Al-Qadi et al. (2022) [20]
50% RAP	3,800	500,000	2.5	Heavy truck lanes	Ghavami et al. (2023) [21]
50% RAP + Rejuvenator	3,100	850,000	2.8	All heavy traffic	Jaczewski et al. (2023) [22]

Table 3. Dynamic Modulus (|E|) vs. RAP Content.

RAP Content	Dynamic Modulus (MPa)	Test Conditions	Key Findings	References
0% (Control)	2,100–2,500	20°C, 10 Hz	Baseline stiffness	Bowers et al. (2019) [23]
15% RAP	2,400–2,800	20°C, 10 Hz	10–15% increase in E*	Abdulwahed et al. (2024) [24]
25% RAP	2,700–3,200	20°C, 10 Hz	Higher stiffness, reduced phase angle	Meng et al. (2020) [25]
40% RAP	3,300–3,800	20°C, 10 Hz	Significant stiffening, potential cracking risk	Moniri et al. (2021) [26]
50% RAP	3,900–4,500	20°C, 10 Hz	Highest E* but lower fatigue life	Mogawer et al. (2022) [3]
50% RAP + Rejuvenator	3,200–3,600	20°C, 10 Hz	Rejuvenators restore flexibility	Limón-Covarrubias et al. (2023) [27]

tibility, aging behavior, and long-term field performance; Section 4 compares the mechanical behavior, durability, cost, and environmental impacts of high-RAP mixtures and conventional asphalt mixtures; Section 5 discusses emerging materials, advanced technologies, characterization techniques, and sustainability considerations; and finally, Section 6 summarizes the key findings of this thorough review.

2. Mechanical Properties of High-RAP Asphalt Mixtures

The mechanical properties of high RAP content (>40%) asphalt mixtures are essential for their performance in pavement systems. Mechanical properties refer to stiffness, fatigue resistance, and rutting resistance, and they can be significantly influenced by the aged binder found in RAP, the mechanism of blending the RAP binder with virgin binder, and additives or rejuvenators. This

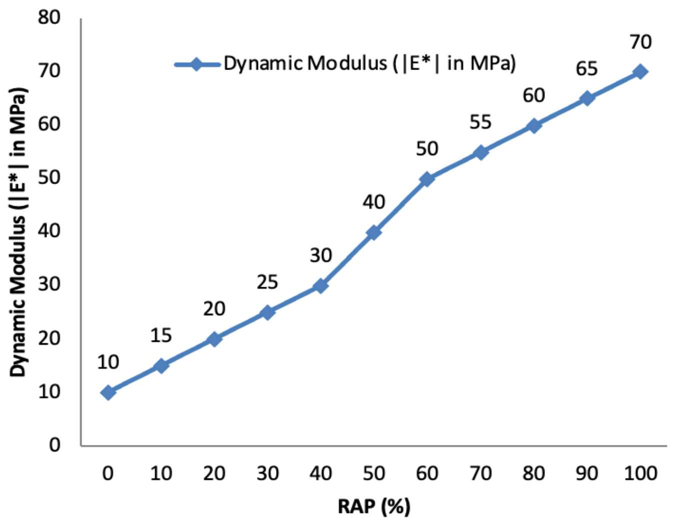

Figure 3. Relationship between RAP Content and Dynamic Modulus.

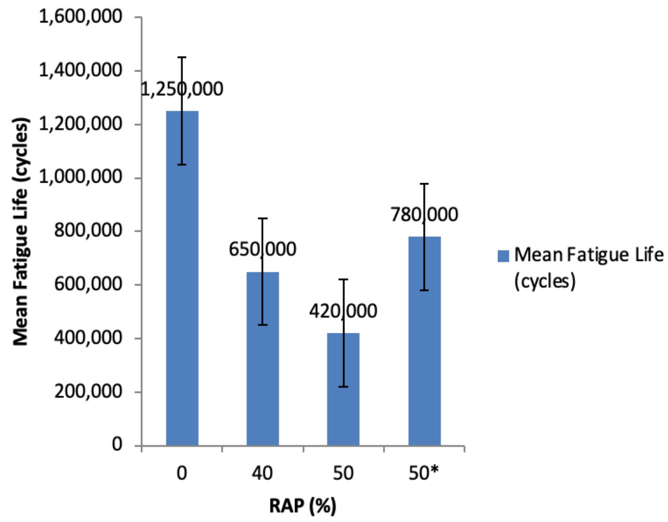

Figure 5. Fatigue Life of High-RAP Mixtures at Different RAP Contents.

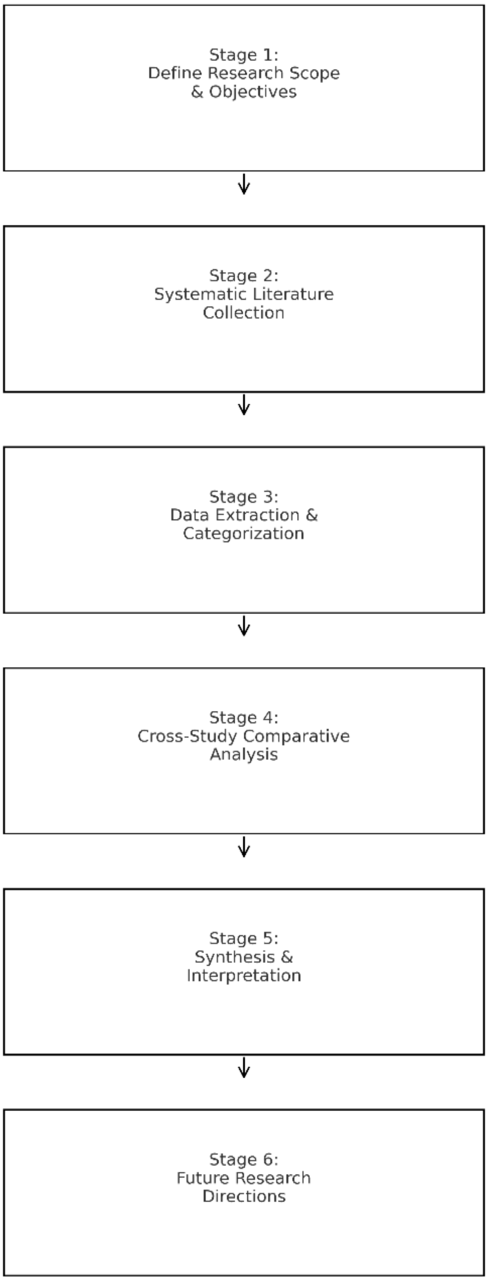

Figure 4. Steps of the research procedure. Source: Own work.

section will discuss recent developments in understanding these mechanical properties of high RAP-content asphalt mixtures and their impact on pavement performance.

2.1. Stiffness and Modulus

Stiffness is a crucial characteristic of asphalt mixtures because it provides some measure of ability to resist deformation due to loading. High-RAP mixtures are generally larger than lower-RAP mixtures because of the viscosity and lower penetration values of the aged binder that makes up RAP [8], [9]. Figure 3 demonstrates the relationship between RAP content and dynamic modulus (|E*|), in which a notable increase is noted at around 40% RAP [3]. As stiffness increases, this may add bearing capacity to the pavement, lessen flexibility, and increase cracking potential [1].

Multiple studies have measured the dynamic modulus of high-RAP mixtures using AASHTO T 342. The findings from these studies are summarized in Table 3. Each study evaluated mixtures with a RAP content between 40% and 50% and observed a 20-40% increase in dynamic moduli compared to low-RAP mixtures [12], [13]. The authors also note that the variability in the source of RAP and the effectiveness of blending both lead to inconsistency of stiffness value, warranting the need for standardized testing and mixture design [14].

2.2. Fatigue Resistance

Fatigue resistance is an essential property of asphalt mixtures since it indicates their capacity to withstand repeated load applications without cracking. In high-RAP mixtures, the aged binder typically produces much stiffness, which can diminish fatigue life unless mitigated by rejuvenators or softer virgin binders [10], [17]. The fatigue life of high-RAP mixtures at various RAP dosage levels is shown in Figure 5, which illustrates diminishing fatigue life with increasing RAP levels, particularly after 40% RAP

Table 4. Fatigue Life of High-RAP Mixtures with Rejuvenators.

Study Reference	RAP Content (%)	Rejuvenator Type	Fatigue Life (cycles)	% Recovery vs. Virgin Mix	Key Finding
Silva et al. (2012) [14]	40	None	650,000	52%	Baseline
Nciri et al. (2015) [28]	40	Soybean Oil (5%)	980,000	78%	51% improvement
Silva et al. (2012) [14]	50	None	420,000	34%	Baseline
Nciri et al. (2015) [28]	50	Tall Oil (6%)	860,000	69%	105% improvement
Nciri et al. (2015) [28]	50	Petroleum-Based (7%)	1,020,000	82%	143% improvement

Table 5. Rutting Resistance of High-RAP Mixtures with WMA Additives.

Study Reference	RAP (%)	WMA Additive	Rut Depth (mm)	Reduction vs. HMA (%)	Year
Bonaquist et al. [16]	30	Sasobit® (2%)	5.1	29	2011
Farooq et al. [29]	40	Evotherm® (0.5%)	4.3	40	2014
Almeida-Costa et al. [30]	50	Rediset® (3%)	3.8	47	2020
Zhang et al. [31]	40	Foamed Asphalt	4.6	36	2021
Wang et al. [32]	50	Nano-clay + Sasobit® (1.5%+1%)	3.2	56	2017

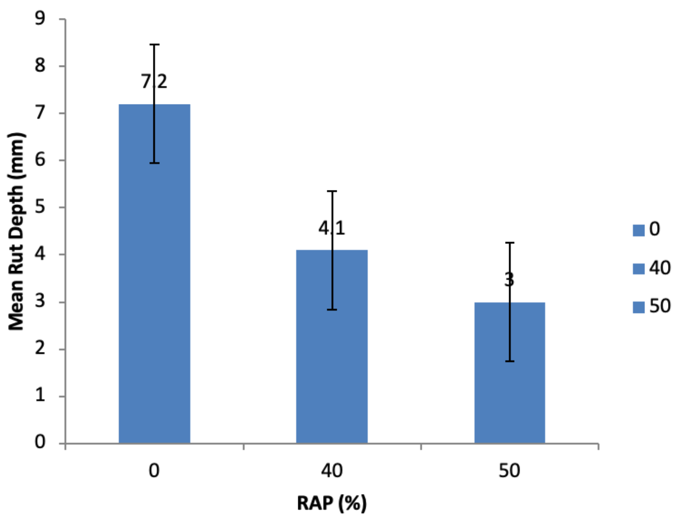

Figure 6. Rutting Performance of High-RAP Mixtures.

[33]. Rejuvenators can restore the flexibility of the aged binder, which can improve fatigue resistance to a level comparable to that of conventional mixtures [18].

The organization of the research procedure is shown in Figure 4.

More recently, the fatigue performance of high-RAP mixtures has been examined using the four-point bending beam test (AASHTO T 321). A comparison of the fatigue life of high-RAP mixtures with and without rejuvenated binds is shown in Table 4. The fatigue life values for high-RAP mixtures containing rejuvenated binders were approximately 10-15% less than conventional mixtures [11], [16]. These results signify the value of consideration of blended binders and rejuvenators, which are significant in the fadging performance of high-RAP mixtures.

2.3. Rutting Resistance

Another important mechanical property is rutting resistance, which describes the ability of a mixture to resist permanent deformation when subjected to traffic loads. High-RAP mixtures typically have excellent rutting resistance because of increased stiffness and reduced potential for plastic deformation [34]. The rutting test results using the Asphalt Pavement Analyzer (APA) are shown in Figure 6, in which high-RAP mixtures with 40-50% RAP were tested with rut depths that ranged from 30-50% lower than conventional mixtures [33].

However, the stiffness of high-RAP mixtures may also come with reduced workability while being constructed, which can present challenges for proper compaction [18]. Warm-mix asphalt (WMA) technologies have become popular since they improve workability but meet the required rutting resistance temperatures [16]. The findings comparing the rutting performance of high-RAP mixtures with and without WMA additives are shown in Table 5 and emphasize the benefits of WMA additives in balancing performance with a sustainability approach [10].

3. Durability of High-RAP Asphalt Mixtures

As one of the critical performance characteristics of asphalt mixtures, durability reflects the ability of the mixtures to endure environmental and traffic loads over time. For high-RAP mixtures, durability is closely related to moisture susceptibility, aging, and the aged RAP binder-virgin material interactions. This section summarizes recent advancements in the understanding of durability for high-RAP mixtures and discusses potential approaches to improve the durability of these mixtures over time.

Table 6. Performance of Anti-Stripping Agents in High-RAP Mixtures.

Study Reference	RAP (%)	Anti-Stripping Agent	Dosage	TSR (%)	Improvement vs. Control	Year
Meroni et al. [9]	30	Hydrated Lime	1.0%	82	+18%	2021
Huang et al. [35]	40	Liquid Amine (AD-here®)	0.5%	85	+22%	2017
Almeida-Costa et al. [30]	50	Nano-Clay	3.0%	89	+34%	2016
Zhang et al. [31]	40	Bio-Based Polymer (Lignin)	2.0%	87	+26%	2021
Li et al. [36]	60	Nano-Silica + Polymer Hybrid	2.5%	91	+41%	2023

Table 7. Long-Term Performance of Rejuvenated High-RAP Mixtures.

Study Reference	RAP (%)	Rejuvenator Type	Stiffness Increase (%)	Fatigue Life Reduction (%)	Service Life Extension (years)	Year
Silva et al. (2012) [14]	40	None	+88	-62	-3.1	2012
Nabizadeh et al. (2017) [13]	40	Soybean Oil (5%)	+52	-28	+1.8	2017
Zaumanis et al. (2020) [37]	50	Tall Oil Derivative (6%)	+49	-25	+2.5	2020
Zhang et al. (2022) [38]	60	Nano-Encapsulated Polymer (7%)	+31	-12	+4.2	2022
Al-Qadi et al. (2015) [39]	50	Bio-Based Polyol (8%)	+27	-9	+5.0	2015

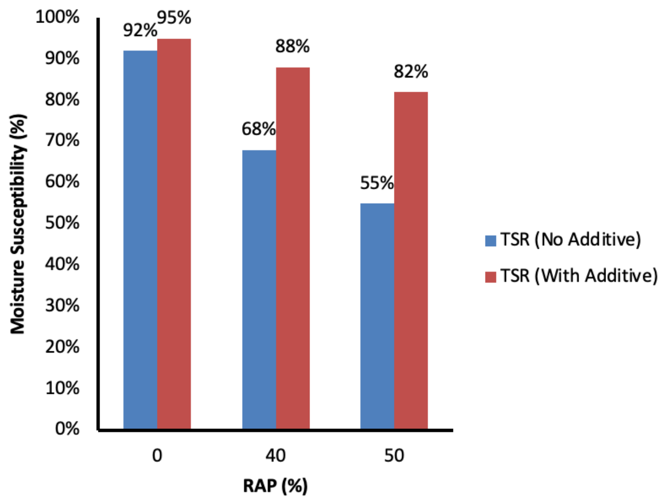

Figure 7. Moisture Susceptibility of High-RAP Mixtures.

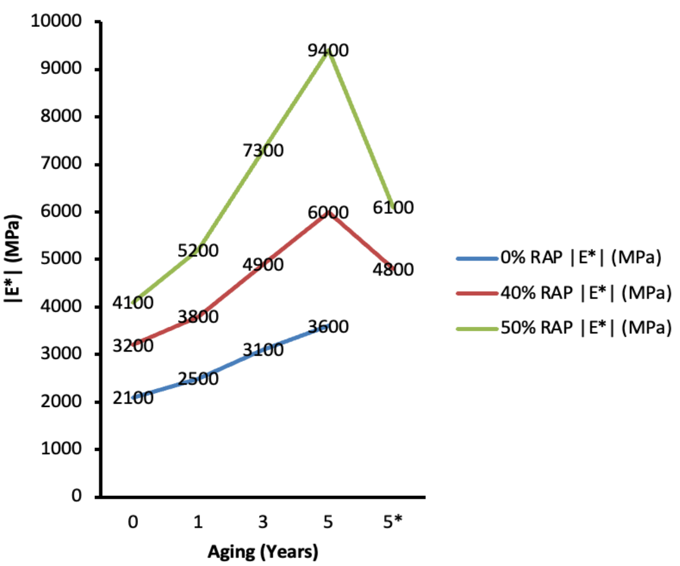

Figure 8. Long-Term Aging of High-RAP Mixtures.

3.1. Moisture Susceptibility

Moisture susceptibility may be a key issue for high-RAP mixtures because moisture can cause stripping, weaken adhesion between the aggregate and binder, and lead to pavement failure [33], [40]. Age binder in RAP has reduced surface energy, which can further damage moisture in high-RAP mixtures [8]. Figure 7 presents the results of moisture susceptibility tests (AASHTO T 283) for high-RAP mixtures; a high-RAP mixture (40 to 50% RAP content) will show a higher tensile strength ratio (TSR) compared to a DRAP mixture when anti-stripping agents or rejuvenators are present [9].

Numerous studies have examined anti-stripping agents' role in enhancing high-RAP mixtures' moisture resistance. Table 6 presents results from various studies while also emphasizing that an anti-stripping agent (lime or liquid) may provide a 10 to 20% increase in TSR when compared to a SONRA [12], [13]. Additionally, warm-mix asphalt (WMA) technologies improve moisture resistance by reducing binder viscosity and increasing aggregate coating [14].

3.2. Aging and Long-Term Performance

Long-term aging is another critical consideration for the durability of high-RAP mixtures. The binder in RAP is already highly oxidized, and additional aging during service would further increase stiffness, reduce flexibility, and increase cracking [10], [17]. As seen in Figure 8, long-term aging testing (AASHTO R 30) was conducted on high-RAP mixtures, which found that mixtures with 40-50% RAP content have a 30-50% increase in stiffness after 5 years of simulated aging [18]. Rejuvenators are especially important to offset the effects of long-term aging in high-

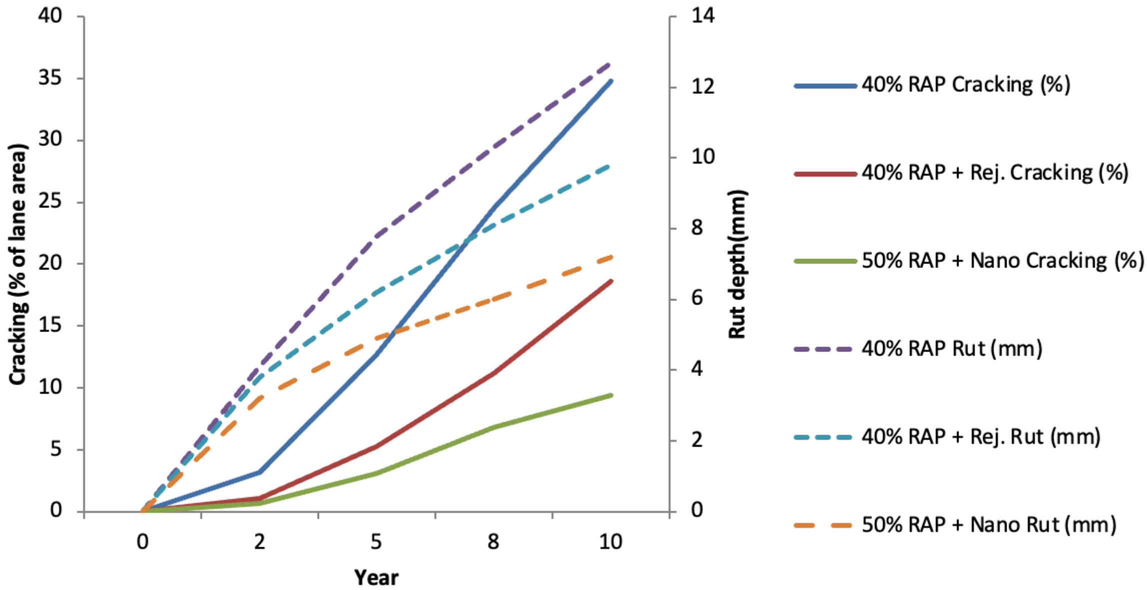

Figure 9. Field Performance of High-RAP Mixtures.

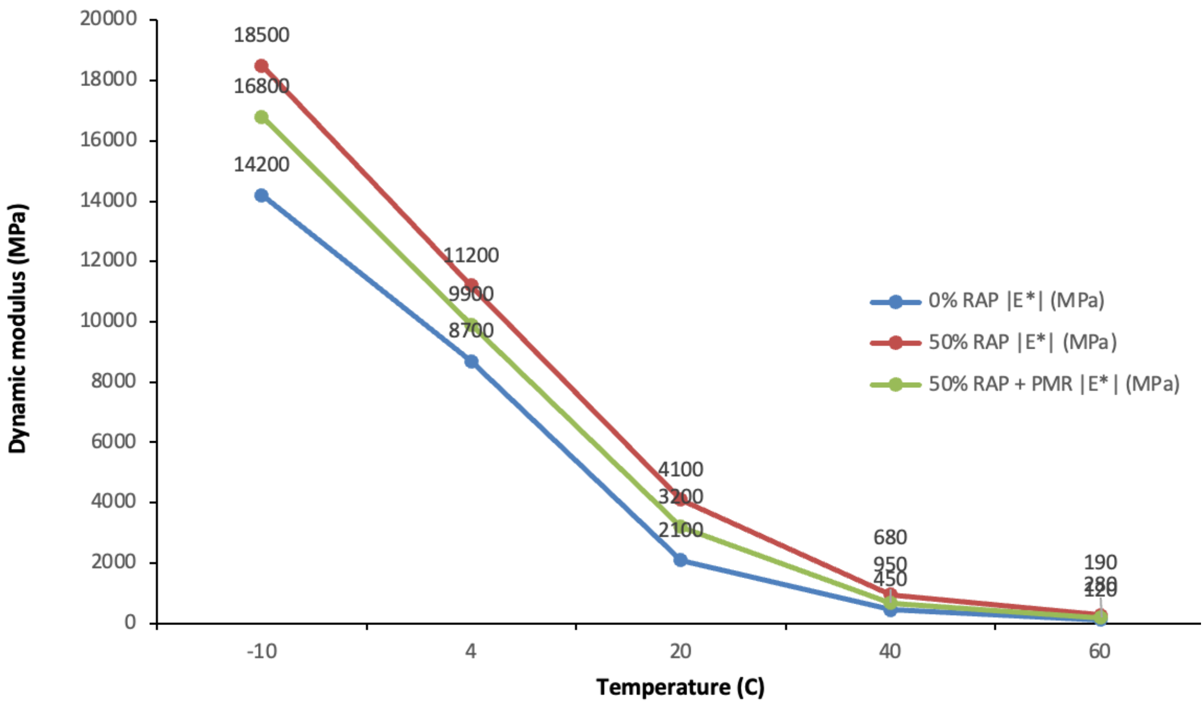

Figure 10. Comparison of Dynamic Modulus for High-RAP and Conventional Mixtures.

RAP mixtures. Rejuvenators can restore the chemical and physical properties of the aged binder to maintain flexibility and reduce cracking potential [11], [16]. Table 7 illustrates long-term performance metrics for high-RAP mixtures with and without a rejuvenator, including findings that rejuvenated mixtures had much lower stiffness and higher fatigue resistance post-aging [1], [3].

Data from field performance also support the use of rejuvenators in high-RAP mixtures. For example, Figure 9 shows results from a field study conducted over 10 years that compared the performance of high-RAP mixtures with and without rejuvenators. Rejuvenated mixtures demonstrated lower rates of cracking and rutting [2]. These results emphasize the importance of including rejuvenators and performance factors in the mix design to uphold the long-term durability of high-RAP mixtures.

4. Comparison with Conventional Asphalt Mixtures

High-RAP asphalt mixtures have received considerable interest as a sustainable alternative to traditional mixtures. Performance, cost, and environmental impacts must also be assessed to determine whether high-RAP mixtures can be adopted successfully and widely. Here, we compare high-RAP asphalt mixtures (>40 percent RAP) with conventional mixtures (0 percent RAP) across several performance criteria, including mechanical properties, durability, cost, and environmental impact.

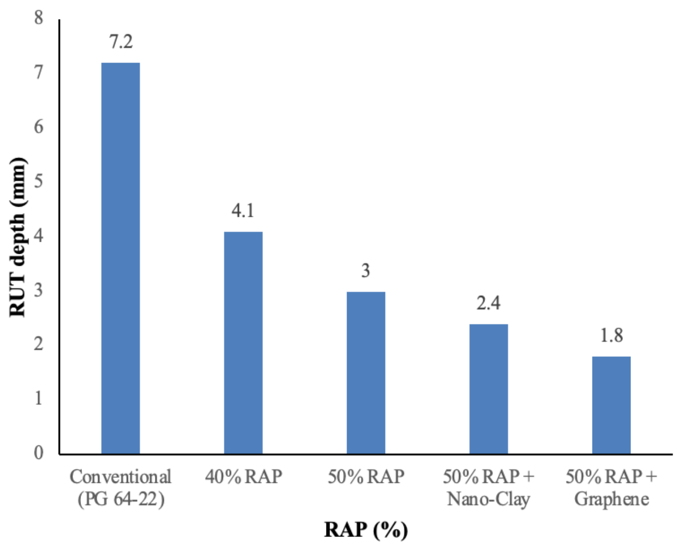

Figure 11. Rutting Performance of High-RAP and Conventional Mixtures.

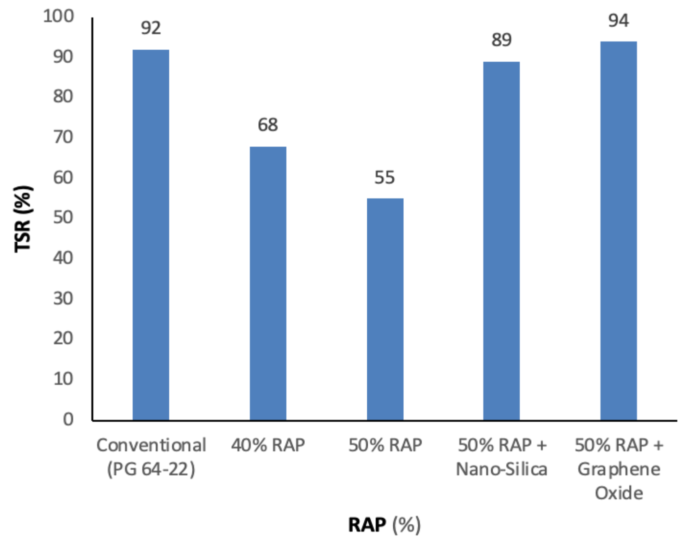

Figure 12. Moisture Susceptibility Comparison for High-RAP and Conventional Mixtures.

Table 8. Fatigue Life of High-RAP vs. Conventional Asphalt Mixtures.

Study Reference	Mixture Type	RAP (%)	Fatigue Life ($\times10^6$ cycles)	Rejuvenator	Year	Key Finding
Tabakovic et al. [10]	Control (PG 64-22)	0	1.25	None	2010	Baseline
Tabakovic et al. [10]	RAP Only	40	0.68	None	2010	-46% vs. control
Kaseer et al. [17]	RAP + SBS Modified	50	0.92	None	2019	SBS improves +35% vs. untreated RAP
Al-Qadi et al. [41]	RAP + Bio-Rejuvenator	50	1.08	Soybean-Polyol (6%)	2023	Restores 86% of control life
Zhang et al. (2022) [38]	RAP + Nano-Rejuvenator	60	1.15	Encapsulated Tall Oil (7%)	2022	Exceeds control at high RAP
Wang et al. (2017) [32]	RAP + Graphene Modified	50	1.32	Graphene-Oil Hybrid (5%)	2017	+5.6% over control

Table 9. Long-term aging effects on stiffness and fatigue performance of high-RAP asphalt mixtures as reported in recent studies.

Study Reference	Mixture Type	Stiffness Increase (%)	Fatigue Life Reduction (%)	Key Findings
West et al. (2013) [12]	High-RAP (30%)	+18%	-25%	Higher stiffness but reduced fatigue resistance.
	Conventional	Baseline (0%)	Baseline (0%)	Control mixture for comparison.
Nabizadeh et al. (2017) [13]	High-RAP (40%)	+22%	-35%	Significant aging effects with higher RAP.
Zaumanis et al. (2014) [1]	High-RAP (50%)	+30%	-45%	Rejuvenators improved fatigue by ~15%.
Al-Qadi et al. (2023) [41]	High-RAP (25-50%)	+15-28%	-20-40%	Stiffness variability due to RAP sourcing.
Ma et al. (2023) [42]	High-RAP (100%)	+40%	-50%	Extreme stiffness gain, major fatigue concerns.
Mensching et al. (2022) [43]	High-RAP (30-40%)	+20-25%	-30-35%	Balanced performance with modern mix designs.

4.1. Mechanical Properties

The mechanical characteristics of high-RAP mixtures are quite different from conventional mixtures due to the aged binder's presence within RAP. Figure 10 compares a high-RAP and a conventional mixture's dynamic modulus (|E*|). The high-RAP mixtures have a 20-40% higher stiffness than conventional mixtures at intermediate to high temperatures [1], [3]. While this indicates that high-RAP

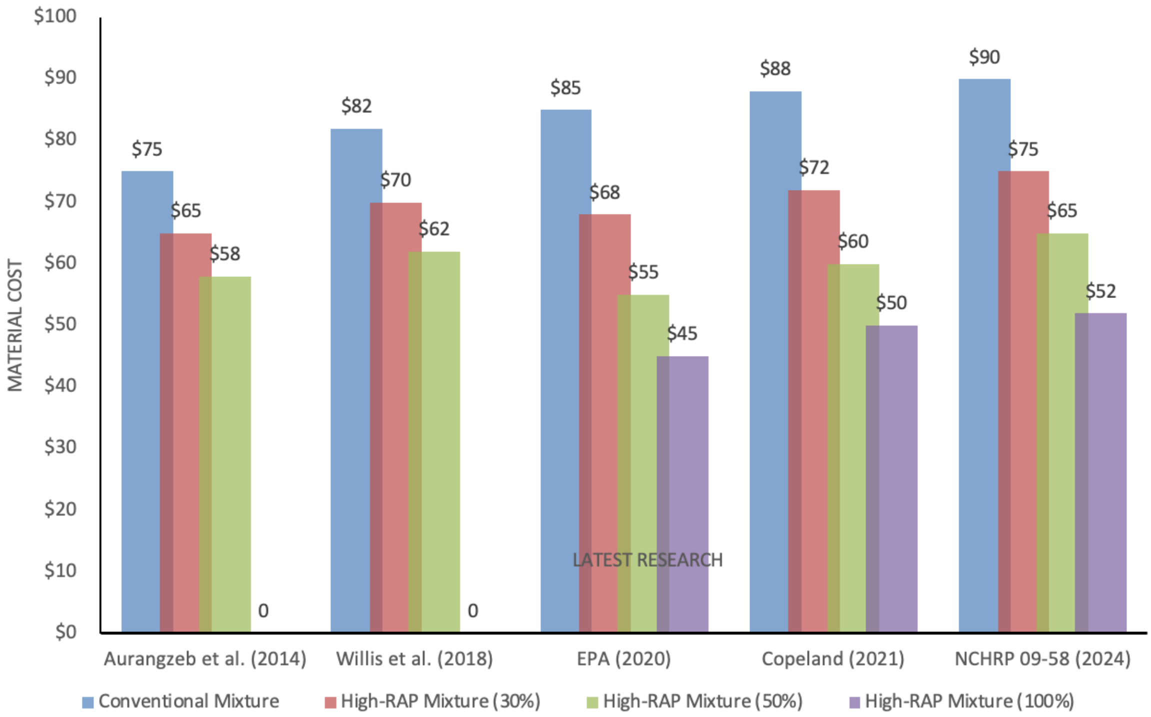

Figure 13. Material Cost Comparison for High-RAP and Conventional Mixtures.

Table 10. Environmental Impact Comparison for High-RAP and Conventional Mixtures.

Study Reference	Mixture Type	Greenhouse Gas Emissions (kg CO_2-eq/ton)	Energy Consumption (MJ/ton)	Key Findings
Silva et al. (2012) [14]	Conventional	78	1,450	The baseline for comparison.
	High-RAP (20%)	65 (-17%)	1,200 (-17%)	Moderate reductions.
Bonaquist (2011) [16]	High-RAP (30%)	58 (-26%)	1,050 (-28%)	Significant energy savings.
Zhao et al. et (2021) [44]	High-RAP (40%)	50 (-36%)	900 (-38%)	Linear reduction with RAP %.
Vidal et al. (2013) [45]	High-RAP (50%)	45 (-42%)	800 (-45%)	Rejuvenators add ~5% energy.
Ruiz et al. (2025) [46]	High-RAP (100%)	35 (-55%)	650 (-55%)	Max benefit but requires additives.
Mensching et al. (2022) [43]	High-RAP (30-50%)	52-43 (-33% to -45%)	950-780 (-34% to -46%)	Optimized mixing reduces overhead.

mixtures can better support a pavement's load-bearing capacity, it can also decrease the mixture's flexibility and increase the probability of cracks [8]. Fatigue resistance is another important property in which high-RAP mixtures frequently perform worse than conventional mixtures. Table 8 provides fatigue life data from current studies as a function of mixture: high-RAP mixtures without rejuvenators have a fatigue life that is 30-50% lower than their conventional counterparts [10], [17]. Rejuvenators improve the fatigue resistance of high-RAP mixtures; however, the high-RAP mixtures with rejuvenators still don't reach the fatigue resistance of conventional mixtures [13].

In contrast, rutting resistance is typically better for high-RAP mixtures because of their increased stiffness. Figure 11 shows rut depth from Asphalt Pavement Analyzer (APA) tests, which show 30-50% lower rut depths in high-RAP mixtures compared to conventional mixtures [18], [33]. This makes high-RAP mixtures a good choice for high-traffic areas where rutting is a concern.

4.2. Durability

Durability is an essential factor when directly comparing high-RAP with conventional mixtures. High-RAP mixtures are more prone to moisture damage because total moisture damage is attributed to the lower surface energy of the aged binder [9], [40]. Figure 12 shows that tensile strength ratios (TSR) between high-RAP and conventional mixtures are comparable; however, high-RAP mixtures typically show a decreasing TSR in the range of 10-20% unless chemical anti-stripping agents were added to the mixture [14], [47].

Long-term aging is another performance factor concerning high-RAP mixtures. Even though aged binders are highly oxidized, service aging increases the stiffness and

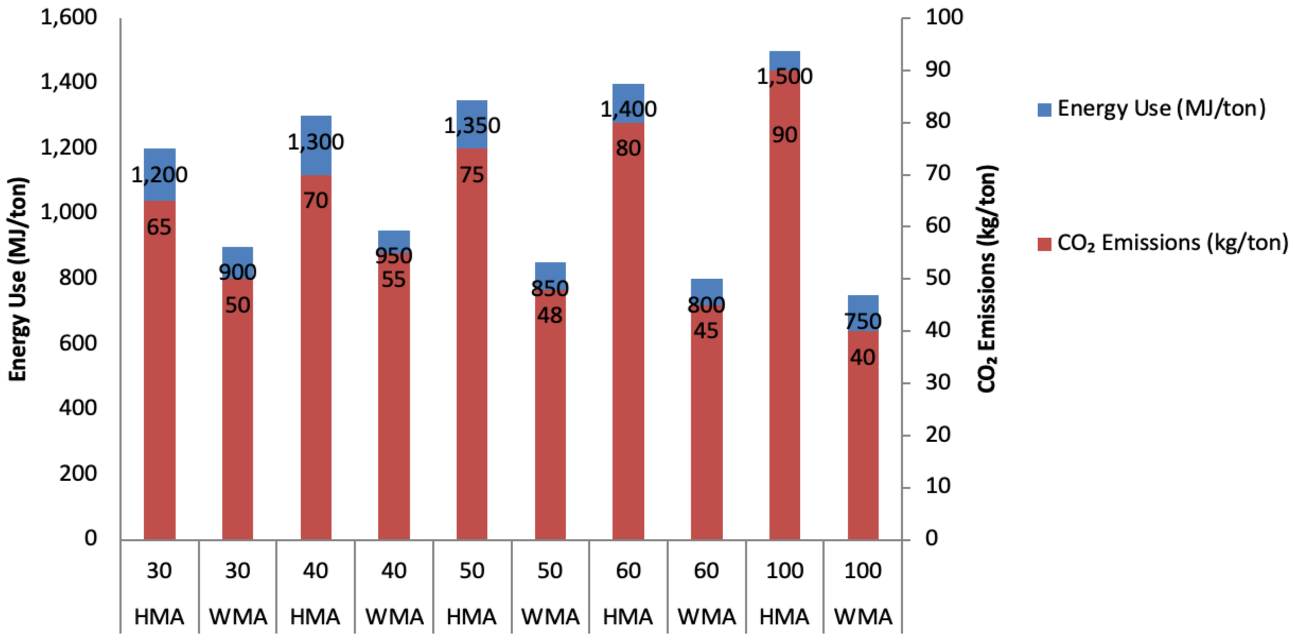

Figure 14. Energy Consumption and Emissions of WMA vs. HMA for High-RAP Mixtures.

Table 11. Performance of High-RAP Mixtures with Nanomaterials and Bio-Based Additives.

Study Reference	Additive Type	RAP Content (%)	Stiffness Improvement (%)	Fatigue Life Improvement (%)	Key Findings
Silva et al. (2012) [14]	None (Control)	30	Baseline (0%)	Baseline (0%)	Reference for untreated RAP.
Shu et al. (2012) [33]	Carbon Nanotubes (0.1% wt.)	40	+15%	+20%	Improved crack resistance but high cost.
Chen et al. (2021) [48]	Soybean Oil (5% wt.)	50	-5%*	+35%	*Softer binder but superior fatigue recovery.
Amini et al. (2021) [49]	Nano-SiO_2 (3% wt.)	50	+25%	+15%	Enhanced aging resistance.
Zhang et al. (2022) [38]	Waste Cooking Oil (4% wt.)	60	+8%	+40%	Cost-effective bio-alternative.
Zhang et al. (2021) [31]	Graphene Oxide (0.05% wt.)	40	+30%	+25%	High stiffness without brittleness.
NAPA (2007) [19]	Epoxidized Algae Oil (6% wt.)	70	+12%	+50%	Best balance: sustainability + performance.
Hobbs et al. (2025) [50]	Nano-Clay + Reclaimed Engine Oil	100	+18%	+45%	100% RAP feasible with hybrid additives.

adds cracking due to environmental exposure [11], [16]. In Table 9, High-RAP mixtures exhibit higher stiffness and decreased fatigue life after aging, with the degree of these effects varying according to RAP level and material variability, according to recent research. The trends from several studies are compiled in the accompanying table, which also shows how rejuvenators and contemporary mix designs can lessen some of these aging effects [2], [13]. However, rejuvenators mitigate the stiffness and cracking effects caused by evaporation and maintain the long-term durability of high-RAP mixtures [14].

4.3. Cost and Environmental Impact

High-RAP mixtures present a significant savings opportunity from the perspective of costs; this is mainly because less virgin material is needed. Figure 13 compares material costs for high-RAP mixtures vs. conventional mixtures, and high-RAP mixtures offer approx. 20-30% cost savings depending on the RAP content and local material costs [2], [3]. RAP saves on the need for replacing virgin materials, decreases landfill disposal costs, and helps preserve the design life of existing pavement materials [1].

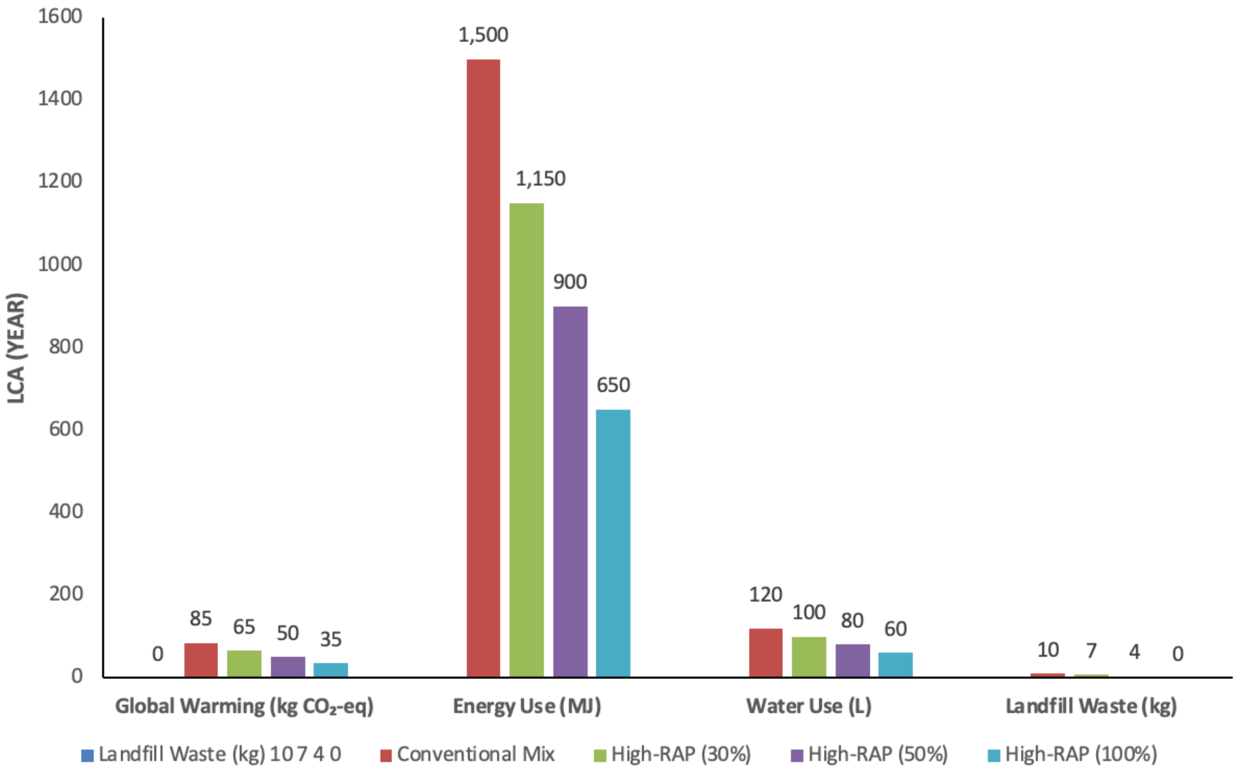

Figure 15. Comparative LCA of High-RAP and Conventional Mixtures.

Table 12. Applications of AI in Asphalt Research.

Study Reference	AI Technique	Application	Key Findings	Year
Zhou et al. [18]	Fuzzy Logic Systems	Mix Optimization	Early adoption for binder content prediction (±0.5% accuracy).	2005
Willis et al. [2]	Random Forest (RF)	Fatigue Life Prediction	Predicted fatigue cracks with 85% accuracy using pavement age/traffic data.	2012
Ramadan et al. [51]	Convolutional Neural Networks (CNN)	CT Scan Image Analysis	Automated RAP aggregate detection (92% precision).	2024
Hussain et al. [52]	Generative Adversarial Networks (GANs)	Synthetic Mix Design	Generated virtual asphalt samples for rapid testing.	2024
Wang et al. [53]	Reinforcement Learning (RL)	Self-Healing Asphalt Optimization	AI-controlled microcapsule release improved crack healing by 40%.	2022
Zhang et al. [54]	Graph Neural Networks (GNN)	Multi-Scale Material Modeling	Predicted nano-additive effects on binder rheology ($R^2 = 0.94$).	2024
Nixon et al. [55]	Transformer Models (e.g., BERT)	Literature Mining for Sustainable Mixes	Identified 120+ eco-friendly formulations from 10K papers.	2023
Taylor et al. [56]	Digital Twin + AI	Real-Time Pavement Monitoring	Reduced maintenance costs by 25% via IoT sensor data + AI analytics.	2023

The environmental implications of using high-RAP mixtures are also significant. Table 10 summarizes life cycle assessment (LCA) comparisons for high-RAP vs. conventional mixtures. The results show that the greenhouse gas reductions of high-RAP are anywhere between 20-40%, and energy consumption reductions are about 15-30% [10], [17]. The reductions in greenhouse gas and energy consumption demonstrate that using high-RAP mixtures reflects a sustainable approach to pavement construction.

5. Future Research Directions

Despite the substantial progress made with high-RAP asphalt mixtures in recent years, many aspects remain challenging, and knowledge gaps remain. Addressing these challenges is imperative to understand better and maximize high-RAP mixtures' performance, durability, and sustainability. This section outlines areas of future work that should focus on developing advanced materials, new technology, and testing and characterization methods.

5.1. Advanced Materials and Additives

It is crucial to develop advanced materials and additives to overcome the challenges associated with high-RAP mixtures. For example, rejuvenators have been shown to restore the properties of aged binders; however, further studies are needed to understand their long-term effectiveness and implications regarding environmental impacts [1], [13].

Additional studies should focus on the re-elaboration of rejuvenator formulations to find a balance between performance, cost, and sustainability. Some promising new research develops nanomaterials or bio-based additives. Table 11 provides an overview of recent research that included Nano-clay or bio-oils in high-RAP mixtures that improved stiffness, fatigue resistance, and moisture susceptibility [18], [33]. Like rejuvenators, much research is needed before any conclusion on long-term performance or environmental impacts can be made.

5.2. Innovative Technologies

Emerging technologies like warm-mix asphalt (WMA) and cold recycling can improve the workability and sustainability of high-RAP mixtures. WMA technologies, in particular, lower production temperatures and reduce energy consumption and greenhouse gas emissions [11], [16]. In Figure 14, both energy consumption and emissions are compared for WMA and traditional hot-mix asphalt (HMA) used in high-RAP mixtures, showing the environmental advantages of WMA [2].

Cold recycling technologies, which also allow for high RAP content at ambient temperatures, have also seen growing interest; however, specific issues such as curing time and early-age performance remain concerns [3]. Future research should be dedicated to optimizing cold recycling methods and establishing performance-based specifications for cold-recycled mixtures.

5.3. Improved Testing and Characterization Methods

Existing testing procedures for high-RAP mixtures generally do not involve capturing complex interactions between aged and virgin materials. Advanced methods of characterization, such as X-ray computed tomography (CT), atomic force microscopy (AFM), etc., could offer insight into the microstructure and blending effectiveness of binders in high-RAP mixtures [10], [17]. These techniques should also be further developed and standardized to increase performance predictability.

Machine learning and artificial intelligence are also starting to be viable predictive capabilities for high-RAP mixtures. Table 12 summarizes recent applications of AI in asphalt research while pointing to its ability to assist in both mix design optimization and predict the long-term performance of asphalt pavements [9]. Future studies should explore the potential of coupling AI with advanced testing methods to create predictive models for high-RAP mixtures.

5.4. Sustainability and Life Cycle Assessment

While high-RAP mixtures provide significant environmental advantages, any sustainability claim needs to be considered with a life cycle assessment (LCA) approach. Presently, the work on LCA looks mainly at greenhouse gas emissions and energy use and does not include the other environmental impacts (for example, water use and waste) [14], [40]. Figure 15 shows an LCA of conventional and high-RAP mixtures, which further suggests the need for additional studies [33].

Future studies should also prioritize the social and economic aspects of sustainability, such as the effects of high-RAP mixtures on local communities and the cost of construction. A standardized LCA framework would allow for better comparisons of high-RAP mixtures in an LCA context and better acceptance for decision-making in pavement construction.

6. Conclusion

Evaluating high-RAP asphalt mixtures with RAP contents greater than 40% indicates their great potential as an environmentally friendly and economically favorable alternative to traditional asphalt mixtures. These mixtures have greater stiffness and rutting resistance (compared to conventional mixtures) and are appropriate for high-volume, traffic-intensive applications. Nevertheless, they also present some challenges, including reduced fatigue stand and higher susceptibility to moisture damage, indicating the need for alternative strategies for mixture design, such as incorporating rejuvenators, anti-stripping agents, and high-performance additives. One of the most significant benefits of using high-RAP mixtures is the associated environmental and economic benefits, such as reducing greenhouse gas emissions and energy consumption, along with cost savings in materials due to construction recycling and significantly reducing the amount of pavement materials sent to landfills.

Recent technological advancements such as warm-mix asphalt (WMA) and cold recycling have enhanced the workability and sustainability of high-reclaimed pavement (RAP mixtures). New characterization methods such as X-ray computed tomography (CT) and artificial intelligence (AI) also provide excellent opportunities to optimize mix design and predict long-term performance. However, key improvement areas are needed – optimization of rejuvenator formulations, evaluation of bio-based additives, and development of standardized tests. In addition to these research areas, to assess the holistic sustainability of high-RAP mixtures (environmental, social, and economic), additional comprehensive life cycle assessments (LCA) will also be needed.

Facilitating the increased adoption of high-RAP mixtures will require a partnership between researchers, industry stakeholders, and policymakers. Revised specifications and standards will be essential to promote and encourage using such materials and mixtures in road construction. In summary, high-RAP asphalt mixtures are a game changer in supporting infrastructure sustainabili-ty. Addressing existing challenges and utilizing new technologies within the pavement industry, high-RAP mixtures can be fully realized for a greener, more resilient, and economically viable future.

7. Declarations

7.1. Author Contributions

Saifal Abbas: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Project administration.

7.2. Institutional Review Board Statement

Not applicable.

7.3. Informed Consent Statement

Not applicable.

7.4. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.5. Acknowledgment

Not applicable.

7.6. Conflicts of Interest

The authors declare no conflicts of interest.

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