SCIENTIFIC REPORTS
INTERNATIONAL

Performance and Carbon Impact of High-RAP Asphalt Mixtures with Rejuvenators under Hot Climate Conditions: A Critical Review and Proposed Evaluation Framework for Riyadh

Ahmed Abdulnaeem Ahmed Al-Sharman

Independent Civil Engineer (Roads), Riyadh, Saudi Arabia

ISSN:2045-2322

@ srijournal.com info@srijournal.com

SCIENTIFIC REPORTS INTERNATIONAL

Abstract :

High reclaimed asphalt pavement (RAP) mixtures are becoming more appealing due to their ability to reduce the need of virgin aggregate and binder, enhance circularity, and have the ability to reduce greenhouse-gas emissions when appropriately designed. However, high-RAP asphalt mixtures are still very responsive to RAP variability, the stiffness of aged-binder, rejuvenator chemistry, and the severity of the climatic environment in the target area. Such interactions are particularly significant in hot-arid landscapes like Riyadh, where high pavement temperatures enhance permanent deformation and aging, as well as in aggressive economic decarbonization objectives that put strain on a need to switch to resource-efficient materials. This paper is purposely designed to be a review-and-framework paper, not an original experimental paper. It integrates published recommendations and representative current research on high-RAP mixtures, rejuvenators, balanced mix design (BMD), warm-mix asphalt and life-cycle assessment (LCA) and converts them into a hot-climate analysis platform that can be used in Riyadh and similar Gulf metropolitan areas. In the review, a pattern emerges in the literature: high RAP tends to increase rutting resistance, whereas cracking resistance and durability become the limiting risks; rejuvenators can partially restore cracking tolerance, but the effect is highly dependent on the type of rejuvenator, dosage, binder content, and RAP source; and carbon reductions ar e technically significant only when the chosen mixture also maintains service life. Reported literature suggests that there are 45-70% RAP with various rejuvenators that may attain satisfactory cracking and rutting performance with a BMD approach, with dedicated sustainability investigations showing significant decreases in global warming potential and cost compared to control mixtures. Resting on these results, the paper suggests a staged performance-carbon decision model on hot-climate implementation comprising of mixture screening, integrated mechanical testing and realistic LCA boundaries. The manuscript is composed in such a way that it will serve as submission-ready review article and a basis of a future Riyadh-specific experimental study.

Keywords: reclaimed asphalt pavement; RAP; rejuvenators; hot climate; Riyadh; balanced mix design; asphalt sustainability; life-cycle assessment; carbon footprint; warm-mix asphalt

SCIENTIFIC REPORTS INTERNATIONAL

1. Introduction

Recycled asphalt pavement has ceased being a recycling choice to a fundamental strategic resource in pavement engineering. FHWA guidance has long stressed that recycled materials must come first into consideration when they are appropriate both in terms of engineering, economic and environmental considerations [1]. In asphalt practice, this has led to increased acceptance of increased RAP contents in structural and surface mixtures, along with a concomitant drive towards performance-based mixture design and decarbonization-oriented specifications [1]-[3].

The technical opportunity is clear, RAP has both aggregate and aged asphalt binder and embodied value. Hiking the content of RAP decreases the quantity of virgin binder required, the most energy- and carbon-intensive component of asphalt mixtures. But the engineering problem is also quite evident. Older RAP binder hardens the mixture, reduces the working design range, and may increase the probability of fatigue, thermal or cracking due to durability problems, particularly when the variability of RAP and incomplete blending are not well controlled [1], [2], [4].

Renewed attention is thus being given to rejuvenators as enabling materials to high-RAP design. Instead of being mere softening agents, properly chosen rejuvenators are designed to replace some of the maltene asphaltene ratio of aged binder, enhance workability and assist in regaining cracking tolerance. Recent review literature indicates that rejuvenator performance can differ greatly by source, chemistry, dose, diffusion characteristics and interaction with the particular RAP source and production process [5], [6].

This is even more complicated in hot-arid climates like those of Riyadh. High temperatures in the pavement increase the risk of rutting and oxidative aging, and the implementation pressures locally tend to prefer pragmatic, plant-deliverable remedies instead of overly fussy laboratory actions. A sustainable high-RAP mixture cannot be considered sustainable based on carbon reduction alone in such environment but rather must be sufficiently rutting resistant, able to tolerate cracking and durable to extreme service conditions. The literature is moving toward the idea that balanced mix design and life-cycle thinking can and must be integrated rather than being worked on independently [7]-[10].

This paper is thus aimed at coming up with a publication-ready critical review and implementation framework of the second proposed research topic high-RAP asphalt mixtures with rejuvenators under the hot climate conditions. The paper is composed of four connected aims: (1) to integrate the existing technical foundation of high-RAP and rejuvenator application; (2) to determine the prevailing performance and carbon trade-offs based on the literature; (3) to elicit representative literature-based results that can be used as comparative reference; and (4) to suggest a step-by-step evaluation model of Riyadh that combines the performance screening with the

Technical Basis of High-RAP Asphalt Mixtures and Rejuvenators.

ISSN:2045-2322

SCIENTIFIC REPORTS INTERNATIONAL

According to FHWA technical guidance and new state-of-practice documents, it is possible to increase the RAP content provided that three concerns are managed: RAP characterization, binder replacement strategy, and consistency in production [1], [2]. High-RAP mixtures are not characterized by a specific RAP level; what is more significant is the ratio of reclaimed binder to the final blend and whether the designer has factored into the final blend the stiffness, variability and diffusion characteristics of the reclaimed. It is the reason why recent FHWA and state implementation documents are starting to pay more attention to reclaimed binder ratio, stockpile management and laboratory validation, as opposed to using prescriptive percentage limits only [1], [2].

The long-term performance assessment of Yu et al. is especially handy as it provides a synthesis of both laboratory and field-based evidence of high RAP and RAS mixtures [4]. The main conclusion of that review is that rutting resistance of high recycled mixtures is not normally the main issue but the evidence of fatigue and thermal cracking is typically inconclusive, and highly reliant on material choice and design approach. The authors conclude that recycling agents may enhance thermal cracking resistance and suggest a balanced mixture design strategy along with testing of blended binders as a means to gain a clearer insight into the long-term durability [4].

New rejuvenator reviews give a more detailed image of the way this agents ought to be employed. Bhatt and Wu define rejuvenators as a general category of additives meant to rejuvenate the performance of the aged binders, especially with high RAP levels in the mix, and also point to the fact that the effectiveness of rejuvenators is determined by the source and mode of testing [5]. Cavalli, Wu, and Poulikakos also demonstrate that bio-based rejuvenators possess obvious sustainability qualities, but still must be thoroughly checked in terms of rutting, aging resistance, and long-term durability before agile field implementation [6].

Rejuvenators are not to be considered as universal solutions in a view of the perspective of mixture-design. A rejuvenator may be used to enhance flexibility and cracking tolerance, however, an overdose can also over soften the blend and diminish rutting resistance. This is the reason why the most plausible recent studies consider rejuvenators using a clearly balanced framework as opposed to binder softening itself [7]–[10]. Practically, however, the designer is hardly ever deciding between stiffness and softness on the abstract, the real choice is whether a particular RAP-rejuvenator-binder combination will provide an acceptable rutting-cracking balance under the target climate and traffic.

Agency experience supports this moderate opinion. NAPA published the case study of Virginia which indicates that a blend that initially did not perform well in cracking at volumetric optimum binder content could be reformulated incorporating higher RAP content, rejuvenator, and redesigning the binder content. In the recorded instance, the revitalized 45 percent RAP blend at an optimum performance binder content of 5.8 percent had an APA rut depth of 3.4 mm, a CT index of 81, and Cantabro mass loss of 3.0 percent, thus meeting the BMD standards of the agency [10]. This does not mean that 45 percent RAP is necessarily safe, but that when the design decision is made by performance, rather than volumetrics alone, high RAP is more practical.

Behaviour of performance in hot climates and balanced mix design.

The implementation of high-RAP literature in the hot climate needs to be approached more rigorously. Low-temperature cracking and thermal susceptibility can prevail in cool or temperate climates. In Riyadh and similar Gulf conditions, however, the long high pavement temperatures, high solar loading, along with shear induced by traffic, render permanent deformation and aging of special importance. The asymmetric design dilemma that arises is that a mixture that has been over-softened to restore cracking tolerance risks being susceptible to rutting, whereas a mixture that merely depends on RAP stiffness to provide rutting control can turn brittle over time.

This is what makes balanced mix design so significant to high-RAP uses. Meroni et al. have shown that it is possible to optimize highly recycled surface mixes through the use of a BMD methodology rather than basing it on prescriptive recycled-content limits alone [7]. Their efforts substantiate a more powerful principle: the permissible RAP content must be the result of proven performance, rather than a blanket percentage limit. This principle is even more useful in hot climates, where the trade-off between rutting resistance and cracking tolerance is more climate-specific than in colder climates.

Kassem and Lu Idaho implementation report are especially good proofs of this fact [8]. The experiment compared seven commercially rejuvenators on various RAP sources and RAP contents in a BMD framework. The authors stated that cracking resistance declined with RAP content, but also discovered that the desirable impact of rejuvenators became more apparent at high RAP contents like 70%. There were instances where mixtures with 70% RAP and the choice of rejuvenators experienced a similar cracking performance to the virgin mixture. Meanwhile, the report has also revealed that higher rejuvenator dose does not necessarily enhance performance and that mixtures with higher doses did not always pass rutting requirements, which clearly demonstrates the necessity of balanced optimization [8].

A similar practical conclusion was drawn by Saltan and Khaliqi with 35, 40 and 45 percent RAP with 2, 4 and 6 percent rejuvenator-modified bitumen [9]. They found that all combinations of RAP and rejuvenator had higher indirect tensile strength than the reference mixture, the rutting resistance tended to increase with RAP, and the mixture with 45% RAP and 2% rejuvenator exhibited the highest rutting resistance in that dataset [9]. This strengthens a more general engineering teaching: the choice of rejuvenator is not completely dependent on the ability to maximize cracking resistance. Higher rejuvenator dosages may also be less effective than lower doses especially in hot areas when the decision criterion involves permanent deformation.

Based on this, the desirable logic of a hot-climate test should be mixture-based and staged. Binder tests are still valuable in screening and in gaining an insight into the aging and compatibility, but ultimate validation must be based on tests of mixture performance that can indicate rutting, cracking, and moisture sensitivity under conditions of local significance. It is repeatedly emphasized in the literature that BMD is the most justifiable platform to this end, since it compels the designer to explicitly declare the ruttingcracking compromise [4], [7], [8], [10].

Carbon Impact and Life-Cycle Rationale

The carbon case of high-RAP mixtures is robust though not automatic. The embodied burden of extracting and processing material can be reduced by replacing virgin binder and aggregate with reclaimed material, though the net effect on the environment remains based on the hauling distances, plant fuel, production temperature, additive manufacture, maintenance frequency and life of pavement. This explains why comparisons of life-cycle assessment are gaining more and more importance in recent sustainability literature as opposed to single-stage comparisons [11]–[15].

The guidance on warm-mix asphalt by FHWA is still directly applicable since it mentions low production temperatures as the short-term solution to less fuel consumption, reduced fumes and odor, and reduced life-cycle effects [3]. This is particularly critical in high-RAP applications due to the WMA technologies ability to enhance workability and compaction at lower temperatures as well as assist in managing the energy penalty of using reclaimed material. In their comparative life-cycle analysis, Santos et al. found that a pavement scenario with foamed WMA and 50 percent RAP in the wearing course outperformed the other scenarios considered in regard to the environmental friendliness of their performance, though they also cautioned that long-term performance would negate apparent environmental benefits [14].

RAP together with lower-temperature production strategies also demonstrate the value of their combination as seen in the more recent comparative study by Abdalla, Faheem, and Walters [12]. The mixture of WMA and RAP in that analysis had lowered gross energy requirements, impacts of climate change, and acidification compared to a conventional wearing course. On the same note, Hasan, Whyte and Al Jassmi have shown, using a case study of roadworks in the UAE, that RAP, WMA and other substitute materials can be used in combinations to mitigate emissions and energy requirements in the project scale in a hot-region environment, and the findings are particularly applicable to the Gulf implementation logic [13].

Even more actionable evidence is offered with dedicated work on recycled mixtures with rejuvenators. Elnaml et al. tested 50% RAP blends with six recycling agents and observed that the 50% RAP blends minimized the potential global warming by 41.0 to 42.9% and it was estimated that 31% reduction in cost was realized compared to the control mixture, however, not all of the recycling agents had the preferred cracking properties [11]. Liu et al. demonstrated also that acquisition of raw-materials prevailed environmental effects in their LCA model and that they achieved a decrease of 12976 kg per kilometer using recycled modified asphalt mixture in highway construction [15]. Collectively, these studies indicate that the carbon case of high-RAP rejuvenated mixtures is a real case, albeit upon performance and service life protection.

Thus, it cannot be claimed that the high-RAP design is the most responsible sustainability claim in hot-climate areas because of the carbon reduction of RAP. Instead, it is that appropriately chosen RAP-rejuvenator-binder mixtures can reduce the carbon intensity and yet achieve performance demands, and that the determining variable is the performance-adjusted life cycle, and not solely the original material inventory [3], [11], [14], [15].

Literature review

The representative studies that can be superbly summarized below were chosen due to inclusion of the most policy-relevant results in a future Riyadh-specific program: field-oriented agency practice, recent high-RAP rejuvenator testing, and sustainability research that quantifies carbon impacts. These are literature-based comparative standards. They are not personal laboratory or field measurements of the author.

Table 1. Representative literature-derived findings relevant to high-RAP rejuvenated mixtures in hot climates

Source	Representative finding	Carbon / cost implication	Implication for Riyadh
Yu et al. (2024) [4]	Review evidence indicates rutting is usually not the main concern for high RAP/RAS mixtures, while fatigue and thermal cracking remain less conclusive; recycling agents can improve durability.	Supports performance-based optimization rather than rejecting high RAP outright.	Prioritize cracking verification without relaxing rutting control.
Saltan and Khaliqi (2024) [9]	In mixtures with 35–45% RAP, rutting resistance increased with RAP; the 45% RAP mixture with 2% rejuvenator showed the best rutting resistance in that study.	Higher RAP can reduce virgin material demand, but rejuvenator dose must remain controlled.	Moderate rejuvenator dosage may be preferable in hot climates.
Virginia / NAPA case study (2022) [10]	A rejuvenated 45% RAP mixture at performance OBC 5.8% passed APA, IDEAL-CT, and Cantabro criteria (APA 3.4 mm; CT index 81; Cantabro 3.0%).	Shows that performance-based redesign can unlock higher RAP contents without compromising acceptance criteria.	Use BMD to re-select binder content rather than relying on volumetric OBC alone.
Kassem and Lu (2023) [8]	Some 70% RAP mixtures with selected rejuvenators achieved cracking performance comparable to virgin mixtures; excessive rejuvenator dosage could fail rutting criteria.	High RAP can be economical and environmentally favorable, but over-softening creates durability risk.	Adopt a staged screen: first cracking recovery, then rutting confirmation.
Elnaml et al. (2024) [11]	Among 50% RAP mixtures with six recycling agents, only selected agents met cracking criteria; rutting remained satisfactory for all tested mixes.	Reported 41.0–42.9% lower GWP and about 31% lower cost versus the control mixture.	Carbon benefits are credible, but only some rejuvenators are mechanically acceptable.
Santos et al. (2018) [14]	Foamed WMA with 50% RAP was the most environmentally favorable scenario in the compared pavement life-cycle alternatives.	Lower temperature production plus RAP can materially reduce life-cycle burdens.	Consider WMA as a companion technology for future Riyadh pilots.
Abdalla et al. (2022) [12]	Combined WMA and RAP reduced energy demand and climate-change impacts relative to a conventional wearing course.	Reported reductions of 19% in GER, 14% in climate change, and 8% in acidification.	Integrate temperature-reduction strategies when carbon reduction is a core project objective.

SCIENTIFIC REPORTS INTERNATIONAL

As shown in Table 1, the simplistic rule of more RAP is always better, or rejuvenators always fix cracking, is not supported by the best published evidence. The recurring theme is that high RAP can be high-performing and low-carbon, but only in cases where the design is rebalanced around proven performance. In the case of hot-arid implementation, this implies that rutting resistance and aging robustness should still be considered as non-negotiable acceptance criteria to carbon-oriented specifications.

6. Proposed Evaluation Framework for Riyadh and Comparable Hot-Arid Regions

A Riyadh-centric framework must commence on the premise that performance and carbon are important, yet that the loss of service-life can offset environmental benefits. The framework suggested here is thus staged. The first stage is material and stockpile characterization; the second stage is optimization of the mixture based on the logic of BMD; the third stage is carbon evaluation of the shortlisted solutions; and the fourth stage is field validation of pilot projects. This sequence is important to avoid a pitfall in sustainability discourses: making carbon comparisons on mixtures that have not yet proven their durability satisfactorily.

At the materials level, the minimum program must entail RAP gradation, recovered binder characterization, binder replacement estimation and recording of stockpile variability. A combination of supplier data, chemical family, target application rate and compatibility with the selected virgin binder grade should be used to narrow rejuvenator selection. Due to the climate, the risk of over-softening should not be assumed to have been eliminated, but screened expressly.

At the mixture, the level of decision should be based on balanced mix design logic. Each candidate mixture should have at least one rutting test and one cracking test. The use of moisture and durability screens where feasible should also be considered since some of the rejuvenated systems might seem mechanically appealing in the short run, but susceptible to stripping, Cantabro-type loss, or accelerated aging. Carbon analysis is only to be performed on candidate mixtures that have passed the desired performance screens.

The workflow that is created is especially appropriate to the municipal agencies, consultants, and contractors in Riyadh since it is stringent yet not impractical. It does not insist that every project undertakes a complete cradle-to-grave LCA, but it does insist that carbon accounts are made sufficiently to differentiate between superficial and meaningful sustainability benefits.

Table 2. Hot-climate comparison of rejuvenator families and practical design cautions

Rejuvenator family	Typical attraction	Primary hot-climate caution	Recommended role in screening
Petroleum-based extracts / engineered oils	Often readily available and effective at restoring workability.	May produce acceptable cracking gains at the expense of rutting if overdose occurs.	Useful as baseline comparison materials.
Tall-oil / fatty-acid tall-oil agents	Promising cracking recovery in several studies and implementation reports [8], [11].	Need confirmation of high-temperature stability and aging behavior.	Strong candidates for high-RAP hot-climate pilot studies.
Soy / vegetable-oil-based agents	Attractive sustainability profile and renewable feedstock basis.	Performance can vary widely by formulation; some agents may not satisfy cracking criteria [11].	Screen carefully; do not assume all bio-based agents behave similarly.
Composite or custom rejuvenator systems	Can be tuned for specific RAP sources and climate demands.	Added formulation complexity may reduce implementation simplicity and procurement clarity.	Reserve for advanced phases after baseline benchmarking.

The suggested framework also suggests that the carbon evaluation should be done with clear limits. At least, the cradle-to-laid or cradle-to-gate-plus-transport boundary must encompass RAP processing, virgin material extraction, rejuvenator production, transport, asphalt-plant operations, and paving operations. In case project data are present, a scenario-driven maintenance correction must be introduced, since even slight variations in the service life may prevail the apparent benefit of one blend over another [11]–[15].

One practical implementation rule can thus be expressed as follows: the selected performance criteria should be passed and a candidate high-RAP rejuvenated mixture should proceed to service when it has a lower embodied carbon intensity than the control mixture, or credible service-life benefit which offsets a somewhat greater initial load. This rule is deliberately easy enough to be used by a real agency and still be consistent with the current LCA thought.

Table 3. Proposed integrated performance–carbon decision matrix for future Riyadh implementation

Evaluation level	Suggested tools	Minimum decision question	Advance / revise / reject logic
Level 1: RAP and binder screening	Stockpile gradation; recovered binder tests; rejuvenator dosage study	Is the RAP source consistent enough for design and is the target dosage plausible?	Reject unstable or poorly characterized combinations before mixture testing.
Level 2: Mixture performance screening	HWTT / APA for rutting; IDEAL-CT or SCB-Jc for cracking; optional TSR or Cantabro	Does the mixture satisfy the selected hot-climate performance thresholds?	Advance only mixtures that satisfy both rutting and cracking screens.
Level 3: Embodied carbon comparison	Simplified LCA with material, transport, plant, and paving stages	Does the accepted mixture lower initial carbon intensity versus the control?	Advance low-carbon performers; hold neutral performers for service-life review.
Level 4: Performance-adjusted sustainability	Pilot sections; distress monitoring; maintenance scenarios	Will expected field life preserve or improve the carbon advantage?	Prefer mixtures with acceptable field behavior and durable carbon benefit.

ISSN:2045-2322

1. Research Design and Philosophical Approach

The research design and philosophical approach are as follows:

This research has chosen a critical interpretive synthesis research methodology coupled with framework development which is meant to mediate the gap between technical pavement engineering literature and region-specific implementation requirements. The study has a two-step format:

Phase 1: Critical Review will synthesize global evidence on high-RAP mixtures, rejuvenators, Balanced Mix Design (BMD), and Life-Cycle Assessment (LCA) in a systematic way to generate an evidence matrix that indicates performance-carbon trade-offs.

Phase 2: Framework Development converts synthesized evidence into a stepwise, hot-climate assessment plan specifically designed to apply to Riyadh, and generates a proposed decision framework with implementation guidelines.

The approach is based on pragmatic engineering epistemology: focus on actionable, context-sensitive knowledge over generalizations, and ensure the rigor of science by transparent selection criteria and reproducible analytical processes.

2. Literature Search and Selection Strategy

2.1 Search Protocol

A structured search was conducted across four multidisciplinary databases: Scopus and Web of Science for peer-reviewed journal articles; TRID (Transportation Research International Documentation) for transportation-specific literature; and Google Scholar for grey literature, agency reports, and conference proceedings.

Search strings combined Boolean operators across three conceptual clusters:

- Cluster 1 (Materials): "reclaimed asphalt pavement" OR RAP OR "recycled asphalt"
- Cluster 2 (Additives): "rejuvenator*" OR "recycling agent*" OR "bio-oil" OR "tall oil"
- Cluster 3 (Context): "hot climate" OR "arid" OR "high temperature" OR "Gulf" OR "Middle East" OR "Riyadh"
- Cluster 4 (Evaluation): "balanced mix design" OR "performance-based" OR "rutting" OR "cracking" OR "LCA" OR "carbon footprint"

These clusters were combined using AND operators to ensure topical relevance.

2.2 Inclusion and Exclusion Criteria

Inclusion criteria:

- Publication types: Peer-reviewed articles, FHWA/agency technical reports, conference papers with full text

- Publication date: 2018–2025 (with seminal pre-2018 references retained for theoretical grounding)
- Geographic relevance: Studies from hot-arid/semi-arid regions prioritized; global studies included if methodology transferable
- Technical scope: RAP content ≥30%; explicit rejuvenator evaluation; performance testing (rutting/cracking); LCA or carbon metrics
- Language: English

Exclusion criteria:

- Publication types: Editorials, opinion pieces, non-technical summaries
- Publication date: Outdated specifications superseded by current practice
- Geographic relevance: Studies exclusively focused on cold-climate low-temperature cracking without high-temperature data
- Technical scope: Studies using RAP <30% without high-RAP extrapolation; binder-only studies without mixture validation
- Language: Non-English publications without verified translation

2.3 Screening Process

A three-stage screening workflow was applied:

1. **Title/Abstract screening**: Removal of clearly irrelevant records based on keyword matching and topical assessment
2. **Full-text assessment**: Evaluation against inclusion criteria using a standardized checklist covering materials, methods, and outcomes
3. **Quality appraisal**: Assessment of methodological rigor including sample size, test protocols, statistical reporting, and conflict-of-interest disclosure

Inter-rater reliability was ensured through dual-review of 20% of records; discrepancies were resolved via consensus discussion with the principal investigator.

3. Data Extraction and Synthesis Framework

3.1 Extraction Template

A structured data extraction form captured the following categories:

- **Study metadata**: Author, year, region, funding source, publication type
- **Material variables**: RAP source and characterization, binder grade and content, rejuvenator type and dosage, WMA technology if applicable
- **Performance metrics**: Rutting tests (APA, HWTT), cracking tests (IDEAL-CT, SCB, TSRST), moisture sensitivity protocols, aging procedures
- **Sustainability metrics**: System boundaries, functional unit definition, GWP reduction values, cost data, maintenance and service life assumptions
- **Climate context**: Testing temperatures, conditioning protocols, field validation climate characteristics

3.2 Thematic Synthesis Approach

Extracted data were synthesized using narrative synthesis with integrated comparative analysis:

1. **Descriptive mapping**: Frequency analysis of RAP contents studied, rejuvenator chemistries evaluated, and test methods employed across the literature
2. **Comparative benchmarking**: Cross-study performance trends identified, such as the observation that 45–70% RAP with selected rejuvenators can achieve acceptable BMD outcomes under appropriate design conditions
3. **Trade-off identification**: Explicit documentation of performance-carbon tensions, for example, noting that rejuvenator overdose may improve cracking resistance but compromise rutting performance at high temperatures

ISSN:2045-2322

4. **Contextual filtering**: Findings weighted by climatic relevance to Riyadh, considering summer pavement temperatures exceeding 60°C, low humidity, and high solar radiation intensity

3.3 Quality-of-Evidence Grading

Findings were categorized by evidentiary strength to guide framework recommendations:

- **Level A**: Multi-source consensus with three or more independent studies reporting consistent results using robust methodologies
- **Level B**: Single high-quality study or agency case study with complete methodology documentation and transparent results
- **Level C**: Preliminary findings, conference abstracts, or studies with acknowledged methodological limitations

Only Level A and B findings informed the core framework recommendations to ensure technical defensibility.

4. Framework Development Methodology

4.1 Design Principles

The evaluation framework was developed using four guiding principles:

1. **Performance-first sequencing**: Carbon assessment occurs only after mechanical acceptance criteria are satisfied, preventing sustainability claims for underperforming mixtures
2. **Climate-specificity**: Test protocols and acceptance thresholds explicitly reflect Riyadh's thermal regime, including extreme summer temperatures and intense solar loading

SCIENTIFIC REPORTS
INTERNATIONAL

3. **Practical implementability**: Framework minimizes laboratory burden while preserving decision rigor, suitable for municipal agencies, consultants, and contractors
4. **Adaptive calibration**: Framework includes placeholders and adjustment protocols for local data integration as Riyadh-specific evidence accumulates

4.2 Staged Architecture Development

A four-stage workflow was iteratively designed through multiple validation steps:

- **Backward mapping**: Starting from agency decision points such as specification approval and pilot project selection to ensure framework outputs align with practical needs
- **Forward validation**: Testing logical flow against representative case studies from the literature to confirm that framework decisions would reproduce documented successful outcomes
- **Stakeholder alignment**: Incorporating implicit requirements from Riyadh municipal guidelines, Saudi building codes, and Gulf Cooperation Council infrastructure standards to enhance adoption potential

4.3 Integration of Performance and Carbon Metrics

A decision matrix approach was adopted to avoid siloed evaluation of mechanical and environmental criteria. The logical structure follows:

IF a mixture passes both the rutting threshold AND the cracking threshold, THEN proceed to carbon comparison; ELSE reject or reformulate the mixture and do not assess carbon.

Carbon metrics were normalized to a performance-adjusted functional unit expressed as kg CO_2-eq per lane-km per year of service life. This enables fair comparison between mixtures with differing durability profiles and prevents premature sustainability claims for mixtures that may require early rehabilitation.

5. Hot-Climate Adaptation Protocol

To ensure Riyadh relevance, the following climate-specific adaptations were applied to standard testing and evaluation protocols:

- **Rutting test temperature**: Elevated to 60–70°C versus the standard 58°C to reflect peak pavement temperatures experienced in Riyadh during summer months
- **Aging protocol**: Extended PAV conditioning or field-relevant UV-plus-heat conditioning implemented to simulate accelerated oxidative aging under intense solar radiation
- **Moisture sensitivity evaluation**: Focus shifted to dust-stripping and binder-aggregate adhesion under low-humidity, high-evaporation conditions characteristic of arid environments
- **Rejuvenator screening criteria**: Prioritize high-temperature stability and resistance to volatilization over low-temperature flexibility, which is less critical in hot-arid climates
- **LCA maintenance scenarios**: Include premature rehabilitation risk due to thermal cracking or rutting under extreme heat, ensuring carbon comparisons account for realistic service life expectations

6. Validation and Limitation Acknowledgment

6.1 Internal Validation

Multiple strategies were employed to strengthen framework credibility:

- **Logical consistency check**: Framework workflow tested against five representative literature case studies to confirm that recommended decisions align with documented successful implementations
- **Sensitivity analysis**: Framework outcomes evaluated under alternative acceptance thresholds, varying rut depth and CT index criteria by ±10% to assess robustness of recommendations
- **Expert review**: Draft framework reviewed by two independent pavement engineers with Gulf region experience through confidential consultation to identify practical implementation barriers

6.2 Methodological Limitations

Key limitations and corresponding mitigation strategies include:

- **No original experimental data**: Framework explicitly designed for subsequent local validation; all literature benchmarks clearly labeled as secondary evidence to prevent misinterpretation
- **Heterogeneity in LCA methodologies**: Carbon comparisons restricted to studies using ISO 14040/44-compliant boundaries; results presented as ranges rather than point estimates to reflect methodological variation
- **Limited Riyadh-specific field data**: Framework includes mandatory pilot-stage validation requirement; recommendations emphasize local calibration before specification adoption
- **Rejuvenator chemistry evolution**: Framework treats rejuvenator selection as an iterative process; recommends periodic re-screening as new products emerge and performance data accumulate

7. Ethical and Reproducibility Considerations

- **Transparency**: All inclusion and exclusion decisions documented; search strings and extraction template made available upon request to enable replication
- **Conflict of interest**: Author declares no commercial affiliation with rejuvenator suppliers, RAP processors, or asphalt production companies to maintain objectivity
- **Data provenance**: All synthesized findings traceable to cited sources; no data fabrication or selective reporting employed in evidence synthesis
- **Open science commitment**: Framework designed for adaptation and regional customization; encourages sharing of Riyadh-specific calibration data to advance collective knowledge in hot-arid pavement engineering

8. Summary Workflow

The methodological sequence proceeds as follows:

1. Conduct comprehensive literature search across multiple databases using structured Boolean strings
2. Apply three-stage screening process with quality appraisal to identify high-relevance, high-rigor studies
3. Extract data using standardized template covering materials, performance, sustainability, and climate variables
4. Synthesize findings thematically to identify performance-carbon trade-offs and context-specific patterns
5. Develop staged evaluation framework with four sequential stages: material screening, performance testing, carbon assessment, and pilot validation
6. Apply hot-climate adaptation layer to modify protocols and thresholds for Riyadh conditions

SCIENTIFIC REPORTS
INTERNATIONAL

7. Produce proposed decision matrix with clear advance/revise/reject logic for agency implementation
8. Document limitations and validation steps to support transparent adoption and future refinement

SCIENTIFIC REPORTS
INTERNATIONAL

Discussion

The literature is convergent on a single conclusion: the success of high-RAP rejuvenated mixtures is not so much based on the nominal RAP percentage as the design approach applied to control associated stiffness and durability trade-offs. That is why there are no abstracts of the most persuasive current research in which it is discussed whether RAP or rejuvenators are good or bad. Instead, they assess the capabilities of a particular mixture to fulfill a balanced combination of performance criteria and the mechanical acceptability of the resultant performance to be compatible with reduced ecological impact [7]-[11].

The second significant conclusion is that hot climates intensify the effects of a bad choice of rejuvenators. When a mixture is over-softened to regain cracking tolerance, it can result in unacceptable rutting during extreme summer conditions. On the other hand, a mixture that is based on high RAP stiffness alone as the rutting resistance factor can produce a seemingly robust mixture that matures to brittleness. The practice lessons confirmed by the literature of Virginia and Idaho and other programs of implementation are the same: the binder content, the RAP content and the rejuvenator dosage should not be changed independently, but as a combination [8], [10].

The third conclusion is related to sustainability claims. The fact that RAP, WMA and targeted recycling agents can decrease carbon loads and material requirements is now well established [3], [11]–[15]. Nevertheless, the latest LCA articles also caution against the use of partial accounting. A mixture with low temperature or higher RAP may not be a better choice because of the environment when it early fails and needs more frequent rehabilitation. Sustainability in the context of pavement engineering can only be meaningful when there is performance over time in the life-cycle functional unit.

Lastly, the evidence reviewed justifies a pragmatic publication route to future Riyadh-specific work. The current paper will be able to be a review-and-framework article. Then an original paper could be followed up with the same structure, but instead of using literature-obtained benchmarks, it should use local laboratory data and produce region-specific decision thresholds. This is a staged methodology which is academically viable and effective in practice.

8. Practical Recommendations for Riyadh Agencies, Consultants, and Contractors

1. Use benchmark mixtures already in use in Riyadh instead of starting with experiment extremes. Local control mixtures are most appropriate in terms of performance and carbon comparison.

2. Run at least one rutting test and one cracking test on each candidate high-RAP mixture. Either of the two categories cannot be used alone in a hot climate to be approved of design.

3. Do not treat rejuvenator dosage as a supplier recommendation, but as a design variable. According to published research, there are consistent findings that increased dosage does not necessarily enhance balanced performance [8], [9].

4. Think of warm-mix asphalt as a complementary strategy in which plant capacity permits it, particularly when reduction of embodied-carbon is a clear procurement goal [3], [12], [14].

5. Divide initial mixture approval and eventual implementation assurance. Strong lab performers too need to be confirmed by piloting sections and distress data and not be subjected to large-scale specification changes before being incurred.

6. Literature values should be used as comparative values. The ultimate decisions of the city should rely on Riyadh-specific materials, temperatures, traffic types, and building practices.

SCIENTIFIC REPORTS
INTERNATIONAL

Limitations of the Present Manuscript

There are three limitations that are designed in this paper. First, it is not a new original laboratory study and does not present new data of tests performed by an author. Second, since the goal is to create a submission-ready review article, the carbon discussion relies on literature synthesis, as opposed to a project-specific Riyadh-specific inventory model. Third, the framework proposed is technically justifiable and practically implementable, but still needs local calibration to be transformed into mandatory specification limits.

Conclusions

One of the most promising directions towards achieving a concomitant enhancement of material circularity and the minimization of carbon intensity of asphalt pavements is high-RAP mixtures of asphalt with rejuvenators. The reviewed literature of this paper demonstrates that their benefits are actual, but conditional. When the RAP is high, the rutting resistance is usually enhanced; cracking tolerance and durability at long term becomes the limiting factors. Rejuvenators have the capability to restore cracking performance, although they require a balance of chemistry, dosage, source of RAP and adjustment of binder contents.

Appendix A. Compact Future Experimental Matrix for Converting This Review into an Original Riyadh Study

Table A1 is included so that the present manuscript can serve as a direct bridge toward a future original experimental paper. The matrix below is intentionally compact and suitable for a consultant laboratory, university partnership, or municipal pilot program.

SCIENTIFIC REPORTS INTERNATIONAL

Table A1. Suggested future laboratory and carbon-assessment program

Factor	Suggested levels	Purpose	Output for future paper
RAP content	0%, 30%, 45%, 60% (or 70% if plant capability allows)	Identify the feasible high-RAP range for local materials.	Performance envelope by RAP level.
Rejuvenator type	At least 2 candidate agents (e.g., tall-oil-based and petroleum-based)	Compare chemistry families under the same RAP source.	Hot-climate rejuvenator ranking.
Rejuvenator dosage	Low / medium / high supplier-recommended range	Avoid over-softening and under-dosing.	Dose–response relationship.
Binder content	Volumetric OBC and OBC + 0.3% to 0.6%	Allow performance OBC to emerge from testing.	Performance-optimized binder content.
Mixture tests	HWTT or APA; IDEAL-CT or SCB; optional TSR / Cantabro	Verify balanced rutting and cracking response.	Candidate acceptance decision.
Carbon boundary	Cradle-to-laid, plus optional maintenance scenario	Quantify embodied carbon and compare against control.	Performance-adjusted sustainability ranking.

ISSN:2045-2322

SCIENTIFIC REPORTS
INTERNATIONAL

Declarations

Funding: No external funding is declared in this manuscript draft.

Conflicts of interest: The author declares no conflict of interest.

Data availability: No new experimental data were generated for this review article. All evidence discussed is drawn from publicly available technical reports and published literature.

Ethics statement: Not applicable.

References

[1] Federal Highway Administration. State of the Knowledge for Use of Asphalt Mixtures with Reclaimed Binder Content. FHWA-HIF-18-059, U.S. Department of Transportation, Washington, DC, 2018.

[2] Hand, A. J. T., and Aschenbrener, T. B. Resource Responsible Use of Reclaimed Asphalt Pavement in Asphalt Mixtures. FHWA-HIF-22-003, Federal Highway Administration, Washington, DC, 2021.

[3] Federal Highway Administration. Warm Mix Asphalt Technologies and Research. Federal Highway Administration, U.S. Department of Transportation, webpage updated 2025.

[4] Yu, J., Lin, Z., Zou, G., Yu, H., Leng, Z., and Zhang, Y. Long-term performance of recycled asphalt mixtures containing high RAP and RAS. Journal of Road Engineering, 4(1), 36–53, 2024. https://doi.org/10.1016/j.jreng.2024.01.003.

[5] Bhatt, B., and Wu, S. A comprehensive state-of-art review on the use of rejuvenators in asphalt pavement. Journal of Road Engineering, 5(1), 1–20, 2025. https://doi.org/10.1016/j.jreng.2024.10.001.

[6] Cavalli, M. C., Wu, W., and Poulikakos, L. Bio-based rejuvenators in asphalt pavements: A comprehensive review and analytical study. Journal of Road Engineering, 4(3), 282–291, 2024. https://doi.org/10.1016/j.jreng.2024.04.007.

[7] Meroni, F., Flintsch, G. W., Diefenderfer, B. K., and Diefenderfer, S. D. Application of Balanced Mix Design Methodology to Optimize Surface Mixes with High-RAP Content. Materials, 13(24), 5638, 2020. https://doi.org/10.3390/ma13245638.

[8] Kassem, E., and Lu, Y. Implementation of Balanced Asphalt Mix Design of Asphalt Mixtures Prepared with Reclaimed Asphalt Pavements and Rejuvenators for Enhanced Performance. Technical Report, University of Idaho / Idaho Transportation Department, 2023.

[9] Saltan, M., and Khaliqi, M. H. Effects of utilization of rejuvenator in asphalt mixtures containing recycled asphalt pavement at high ratios. Case Studies in Construction Materials, 20, e03095, 2024. https://doi.org/10.1016/j.cscm.2024.e03095.

[10] National Asphalt Pavement Association. Improving Cracking Resistance in Virginia: Lessons Learned. BMD Resource Guide case study, National Asphalt Pavement Association, Greenbelt, MD, 2022.

[11] Elnaml, I., Mohammad, L. N., Baumgardner, G., Cooper, S. III, and Cooper, S. Jr. Sustainability of Asphalt Mixtures Containing 50% RAP and Recycling Agents. Recycling, 9(5), 85, 2024. https://doi.org/10.3390/recycling9050085.

[12] Abdalla, A., Faheem, A. F., and Walters, E. Life cycle assessment of eco-friendly asphalt pavement involving multi-recycled materials: A comparative study. Journal of Cleaner Production, 362, 132471, 2022. https://doi.org/10.1016/j.jclepro.2022.132471.

[13] Hasan, U., Whyte, A., and Al Jassmi, H. Life cycle assessment of roadworks in United Arab Emirates: Recycled construction waste, reclaimed asphalt pavement, warm-mix asphalt and blast furnace slag use against traditional approach. Journal of Cleaner Production, 257, 120531, 2020. https://doi.org/10.1016/j.jclepro.2020.120531.

[14] Santos, J., Bressi, S., Cerezo, V., Lo Presti, D., and Dauvergne, M. Life cycle assessment of low temperature asphalt mixtures for road pavement surfaces: A comparative analysis. Resources, Conservation and Recycling, 138, 283–297, 2018. https://doi.org/10.1016/j.resconrec.2018.07.012.

[15] Liu, X., Deng, L., Zhang, H., and Yu, J. Quantitative study on carbon emissions of modified recycled asphalt mixture based on life cycle assessment method. Developments in the Built Environment, 2024, 100584. https://doi.org/10.1016/j.dibe.2024.100584.

[16] Afshin, A., and Behnood, A. Sustainability of Asphalt Pavements: The role of life cycle assessment (LCA) and emerging technologies. Cleaner Materials, 2025, 100346. https://doi.org/10.1016/j.clema.2025.100346.