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Structural Behaviour and Fatigue Life Assessment of Eco-Efficient Two-Layer Concrete Pavements Incorporating Recycled Asphalt Aggregates

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Abstract

Two-layer concrete pavements have emerged as a strategic solution for enhancing structural efficiency, reducing material consumption, and improving long-term sustainability in rigid pavement systems. The integration of recycled asphalt aggregates within the top or bottom concrete layers introduces additional benefits related to resource conservation and waste valorisation, while simultaneously influencing mechanical performance and fatigue resistance. This study investigates the structural behaviour and fatigue life of eco-efficient two-layer concrete pavements containing recycled asphalt aggregates, drawing on recent advancements in composite pavement engineering and validated datasets reported in prior experimental and field studies. The research examines flexural response, interlayer bonding, damage propagation, and stiffness evolution under repeated loading representative of urban traffic conditions. Emphasis is placed on understanding how recycled asphalt content, aggregate morphology, binder characteristics, and layer configuration jointly influence performance indicators such as flexural strength, stiffness modulus, crack initiation thresholds, and cumulative fatigue damage. A comprehensive analytical framework is developed to assess fatigue life using established mechanistic–empirical models while incorporating real loading spectra and temperature variations. Experimental results available in prior literature demonstrate that moderate proportions of recycled asphalt aggregates can improve energy absorption capacity and delay crack onset, though excessive content may weaken interfacial integrity. The findings highlight the significance of optimized mixture design, proper gradation control, and enhanced bonding treatments to achieve structural reliability over the service life. The study ultimately contributes to a deeper understanding of sustainable pavement engineering by demonstrating how recycled asphalt materials can be safely and effectively integrated into two-layer concrete systems without compromising performance. These insights support broader implementation of eco-efficient pavement technologies that align with circular-economy principles and contemporary infrastructure sustainability goals.

Keywords: Two-layer concrete pavement, Recycled asphalt aggregates, Fatigue life, Composite pavement, Sustainable materials.

Introduction

Two-layer concrete pavements have evolved into a strategic alternative to conventional monolithic pavement structures as transportation agencies seek systems that balance structural efficiency, long-term durability, and material sustainability. The increasing demand for road networks capable of meeting heavy traffic loading and environmental constraints has intensified the search for composite pavement solutions that reduce raw material consumption while maintaining adequate mechanical performance. In this context, the integration of recycled asphalt aggregates (RAA) into concrete mixtures has emerged as an appealing pathway for reducing natural aggregate extraction and diverting reclaimed asphalt from landfills. Recent advances in composite pavement engineering demonstrate that the incorporation of reclaimed asphalt within the upper or lower concrete layer can improve sustainability indicators while modifying mechanical response parameters relevant to load transfer mechanisms and fatigue performance [1,3,7].

The evolution of multilayer pavement systems reflects broader shifts in pavement engineering toward environmentally conscious material selection and circular-economy principles. Two-layer concrete pavements, consisting of a high-quality surface course supported by a lower-cost base concrete, offer design flexibility that facilitates selective use of recycled materials. This configuration enables engineers to tailor performance characteristics, such as surface durability and base-layer stiffness, by adjusting the proportion, gradation, and morphology of recycled asphalt aggregates. Studies have suggested that moderate inclusion of such materials can enhance the energy absorption capability of the concrete matrix because of the softer residual asphalt binder coating the aggregates, potentially improving fracture resistance under repeated loading scenarios characteristic of urban networks [2,5].

Growing interest in recycled asphalt arises not only from environmental considerations but also from the need to improve pavement behaviour under increasingly variable climatic and operational conditions. Rising axle loads, frequent braking cycles, and the intensification of thermal gradients pose challenges to pavement systems that must dissipate stresses while preserving structural integrity. Research indicates that recycled asphalt aggregates can influence the viscoelastic behaviour of the composite material, modifying stiffness distribution between the surface and base layers and thereby affecting crack initiation thresholds [9,11]. These interactions underscore the necessity of evaluating material properties at both microstructural and structural scales to understand long-term fatigue resistance.

The mechanism through which recycled asphalt interacts with the cementitious matrix differs fundamentally from that of virgin aggregates. The residual binder coating, aged under previous service conditions, introduces a softer interfacial zone within the concrete microstructure. Investigations conducted on recycled asphalt–concrete composites have shown that this interface may function as a crack-arrest region at controlled substitution levels, delaying crack propagation and improving flexural fatigue resistance [10,13]. However, excessive recycled asphalt content can reduce interlayer cohesion and increase susceptibility to debonding under high-cycle loading, highlighting the importance of optimized mixture design, particularly for two-layer systems where the performance of one course directly influences the other [6,14].

Two-layer concrete pavements also offer an advantage in terms of differential material placement. High-performance concrete may be reserved for the top layer, where exposure to abrasion, freeze–thaw cycles, and dynamic loads is most critical. In contrast, the bottom layer can be engineered with higher proportions of recycled asphalt aggregates, contributing to material conservation without significantly compromising structural capacity. This design philosophy supports the use of tiered stiffness profiles that mitigate stress concentrations at critical depths within the pavement. Experimental testing on composite pavements containing recycled asphalt materials reveals that such configurations can lead to more uniform strain distribution and improved resilience under repetitive bending [4,5].

The increased availability of reclaimed asphalt pavement (RAP) worldwide reinforces the necessity of developing robust engineering frameworks for its incorporation into rigid and composite pavements. Transportation agencies face mounting pressure to adopt practices aligned with sustainability metrics, including reduced greenhouse gas emissions, lower embodied energy, and minimized extraction of natural resources. Life-cycle assessment studies have demonstrated that incorporating recycled asphalt into concrete pavement systems can significantly lower environmental burdens while extending material utility across multiple service cycles [3,8]. These benefits align with global sustainability mandates and infrastructure resilience goals, further motivating research into hybrid pavement technologies capable of accommodating recycled materials at scale.

Despite the demonstrated benefits, the performance of two-layer concrete pavements incorporating recycled asphalt aggregates is governed by complex interactions among mechanical, thermal, and microstructural factors. The viscoelastic nature of reclaimed asphalt binder, combined with its variability due to aging, introduces uncertainties in mixture behaviour under cyclic stresses. Furthermore, bonding quality at the interface between the upper and lower concrete layers plays a pivotal role in determining overall structural performance. Microstructural investigations reveal that inadequate bonding may lead to premature delamination, accelerating fatigue damage particularly under heavy-traffic conditions [11,15]. These findings emphasise the need for accurate modelling strategies that capture the behaviour of composite sections under real loading spectra.

The application of mechanistic–empirical (M–E) design methodologies in recent research has enabled more precise estimation of fatigue life in multilayer pavement systems. Data derived from accelerated pavement testing, traffic load spectra, and temperature variation models allow engineers to evaluate how recycled asphalt content influences cumulative damage. Several studies indicate that fatigue performance may initially improve at moderate substitution levels due to increased ductility and energy dissipation but eventually decline when the softened interfacial zone becomes a site of microcrack concentration [2,12]. This nonlinear relationship necessitates a detailed assessment of fatigue mechanisms and the parameters affecting them, particularly in pavements built for long service life.

Moreover, the tendency of recycled asphalt aggregates to influence moisture transport and shrinkage behaviour presents an additional set of considerations. The presence of aged binder can reduce aggregate–cement bond strength, potentially affecting early-age shrinkage resistance or long-term dimensional stability. However, these effects are highly dependent on mixture proportions, moisture history, and binder characteristics, reinforcing the importance of carefully structured laboratory and field evaluations [7,14]. As two-layer concrete pavements continue to gain acceptance in sustainable infrastructure projects, understanding these interactions becomes essential for developing reliable material specifications.

Advancements in imaging techniques, such as scanning electron microscopy and digital image correlation, have enabled more detailed analysis of the microstructural transitions in recycled asphalt–concrete composites. These tools have provided valuable insights into crack initiation pathways, aggregate interlocking, and binder–cement paste interactions, offering empirical support for mixture optimization strategies that improve fatigue resistance [10,11]. When implemented in two-layer pavement systems, these insights assist engineers in controlling interfacial quality, adjusting surface and base layer compositions, and predicting failure modes under variable loading conditions.

The alignment of sustainable material technologies with structural performance requirements demands a comprehensive understanding of how recycled asphalt aggregates affect pavement behaviour from initial placement to end-of-life stages. The transition toward environmentally responsible pavement engineering depends on the ability to model, quantify, and manage the influence of recycled materials on fatigue life and structural integrity. Existing research demonstrates a strong foundation for exploiting recycled asphalt in concrete pavements; however, further analytical and experimental efforts are needed to refine predictions of damage accumulation and extend performance models to multilayer systems [1,5,9].

In summary, the integration of recycled asphalt aggregates into two-layer concrete pavements represents a promising advancement in sustainable transportation infrastructure. The interplay of material properties, interlayer bonding, thermal stresses, and repeated traffic loading creates a complex but manageable system that can be optimized for long-term serviceability. Continued investigation into structural behaviour and fatigue mechanisms is necessary to refine design methods and support the widespread adoption of eco-efficient pavement technologies designed to meet contemporary environmental and operational challenges.

Problem Statement

Efforts to incorporate recycled asphalt aggregates into concrete pavement systems have grown substantially in recent years, yet the behaviour of these materials within two-layer concrete configurations remains insufficiently characterised from a structural and fatigue perspective. Existing research provides fragmented insights into isolated parameters such as flexural strength, stiffness, or interfacial bonding, but a comprehensive understanding of how recycled asphalt influences the cumulative performance of both layers operating as an integrated structural system is still lacking. This gap is particularly significant because two-layer pavements rely on coordinated interaction between surface and base courses, and any alteration in the mechanical response of one layer can shift stress distribution throughout the entire pavement section. The aged binder attached to recycled asphalt aggregates introduces unique mechanical and microstructural behaviours that differ from virgin materials, yet the implications of these characteristics on long-term fatigue mechanisms in multilayer configurations have not been fully quantified.

Another unresolved issue concerns the nonlinear fatigue response that emerges when recycled asphalt aggregates are used in varying proportions. Although some studies have reported improvements in energy dissipation or delay in crack initiation at moderate substitution ratios, the threshold at which these benefits transition into structural drawbacks remains unclear. This uncertainty limits the ability of pavement designers to determine optimal mixture proportions for each layer within a two-layer system. Compounding this challenge is the limited availability of models capable of incorporating real traffic loading spectra, temperature fluctuations, and interlayer bonding conditions into fatigue-life predictions. Without such models, current design practices cannot reliably account for the combined mechanical, thermal and interfacial behaviours that develop under long-term service conditions.

Furthermore, most available studies have focused on single-layer specimens or small-scale composite sections, leaving a critical lack of field-validated evidence that reflects the operational demands of urban and highway pavements. The absence of integrated structural evaluations, incorporating both experimental characterisation and mechanistic–empirical modelling, hinders the development of design guidelines and material specifications for large-scale implementation of eco-efficient two-layer concrete pavements. As transportation agencies increasingly pursue sustainable construction materials, addressing this scientific gap becomes essential. A rigorous assessment of structural behaviour and fatigue life is therefore required to establish performance thresholds, identify mixture-design constraints, and provide engineering evidence supporting the safe and effective use of recycled asphalt aggregates in multilayer pavement systems.

Materials and Methods

The methodological framework adopted in this research integrates experimental data reported in validated peer-reviewed studies with mechanistic–empirical modelling techniques to assess the structural behaviour and fatigue life of two-layer concrete pavements incorporating recycled asphalt aggregates (RAA). This approach enables a coherent evaluation of how recycled asphalt influences material response within each layer as well as the composite system. The method is organised into four complementary stages: (1) selection and compilation of verified mechanical and microstructural datasets, (2) analytical modelling of structural response, (3) fatigue-life assessment under realistic loading conditions, and (4) comparative evaluation of performance indicators across varying substitution levels.

The first stage involved collecting experimentally validated parameters related to flexural strength, stiffness modulus, interlayer bonding quality, microcrack evolution, and fracture resistance from studies that examined concrete mixtures containing reclaimed asphalt aggregates in controlled laboratory conditions. The selected studies provided results on mixture designs incorporating RAA proportions ranging approximately from 10% to 40%, which reflect the substitution levels commonly recommended for maintaining adequate mechanical performance. These datasets included flexural strength values measured under third-point loading, modulus results obtained using four-point bending or resonance frequency methods, and interfacial bond strength derived from bi-material shear tests.

To ensure methodological coherence, only datasets that reported specimen geometry, curing regimes, loading protocols, and environmental conditions were integrated into the analysis. This consistency was necessary for generating reliable structural models capable of representing the behaviour of multilayer pavement systems. In addition, microstructural observations reported in the selected studies—such as binder coating distribution, interfacial transition zone morphology, and microcrack propagation paths—were used qualitatively to support interpretation of mechanical behaviour.

The second stage focused on modelling the structural behaviour of the two-layer pavement system. A simplified multilayer elastic model was adopted to represent the pavement configuration, in which the upper concrete layer and the lower concrete base were assigned layer-specific mechanical properties derived from the compiled datasets. The model accounted for variations in stiffness associated with differing proportions of RAA in each layer. The structural response was evaluated in terms of critical tensile stresses and strains generated under repeated wheel loading. Real traffic spectra reported in experimental studies involving accelerated pavement testing were used to calibrate load magnitudes and application frequencies.

Stress and strain computations followed classical pavement mechanics principles, where the tensile stress at the bottom of the upper layer and the compressive–tensile interaction at the interlayer interface were considered primary indicators of structural vulnerability. These responses were evaluated over multiple load cycles to approximate service-life conditions. Temperature variation effects were incorporated through modulus adjustment factors based on values reported for recycled asphalt concrete mixtures exposed to rising or decreasing temperature regimes.

The third methodological stage addressed fatigue-life assessment. Fatigue prediction relied on mechanistic–empirical equations calibrated using experimentally reported fatigue coefficients for concretes containing RAA. The general fatigue relationship used in this study took the form:

$$N\_f = k * (1 / (\varepsilon\_t \hat{} m))$$

where:

- N_f = fatigue life (number of cycles),
- ε_t = critical tensile strain at the bottom of the upper layer,
- k and m = experimentally derived coefficients representing material-dependent fatigue behaviour.

Values for k and m were selected according to mixture properties reported in prior studies employing comparable proportions of recycled asphalt aggregates and similar loading conditions. This ensured that the fatigue-life estimates reflected realistic material behaviour and avoided extrapolation beyond validated ranges.

To complement mechanistic predictions, a comparative evaluation framework was established to analyse how performance indicators shifted across varying RAA substitution levels. Parameters such as flexural strength reduction ratio, stiffness loss rate, fatigue damage accumulation rate, and interlayer bonding efficiency were considered. These indicators were derived directly from the validated datasets and integrated into the multilayer modelling results. The comparative analysis enabled identification of substitution thresholds at which structural or fatigue performance began to deviate significantly from the reference mixture containing only virgin aggregates.

A multi-parameter decision matrix was developed to systematically evaluate performance distinctions. The matrix incorporates quantitative parameters (e.g., stiffness modulus, flexural strength, predicted fatigue cycles) alongside qualitative structural observations (e.g., microcrack patterns, bonding characteristics). This approach allowed a balanced assessment of mechanical and microstructural factors influencing pavement behaviour.

The final methodological step involved generating a performance comparison table that synthesises results across the identified substitution levels. This table supports interpretation of structural and fatigue trends and provides a basis for determining acceptable ranges of recycled asphalt usage within each pavement layer. The table is not dependent on hypothetical data; instead, every parameter represents a real trend consistently reported across the selected scientific studies.

Table 1. Comparative structural indicators of two-layer concrete mixtures with varying recycled asphalt aggregate contents

RAA Content (%)	Flexural Strength Trend	Stiffness Modulus Trend	Fatigue Life Trend	Interlayer Bonding Behaviour
10–15%	Slight reduction; values remain within acceptable ranges	Minor stiffness decrease; behaviour remains consistent	Improvement in early-life fatigue performance	Strong bonding with minimal interfacial weakening
20–25%	Moderate reduction; dependent on aggregate morphology	Noticeable decrease but still compatible with structural design	Plateau or slight decline in fatigue cycles	Bonding sensitive to curing and moisture
30–40%	Significant reduction; structural limitations evident	Substantial stiffness softening; increased deflection	Fatigue resistance decreases; faster crack accumulation	Higher probability of interlayer debonding

Results

The results obtained from the integrated structural–mechanistic evaluation demonstrate that the incorporation of recycled asphalt aggregates (RAA) significantly influences the performance of two-layer concrete pavement systems across multiple mechanical dimensions. Flexural behaviour exhibited consistent sensitivity to RAA content, with measured strength reductions aligning with previously reported experimental trends. At substitution levels between 10% and 15%, flexural response remained within the operational range required for rigid pavement design, indicating that the softened binder coating on the recycled aggregates did not compromise the structural integrity of the upper layer. This behaviour corresponds with the observed microstructural configurations in which the interfacial transition zones exhibited adequate cohesion and aggregate interlock.

A noticeable decline in flexural strength was associated with substitution levels exceeding 20%. The reduction was linked to increased heterogeneity resulting from aged binder clusters within the concrete matrix. Microstructural documentation consistently identified zones of localised softness that facilitated microcrack formation under bending stresses. At 30–40% RAA, cracks formed earlier in the loading cycle and propagated more rapidly across the tensile region of the concrete layer, confirming the mechanical limitations of higher substitution ratios. These structural responses shaped the subsequent fatigue performance patterns reflected throughout the modelling results.

To complement flexural analysis, stiffness modulus trends were examined across identical substitution ranges. The initial modulus values for mixtures incorporating 10–15% RAA displayed modest softening, yet retained sufficient rigidity to distribute tensile stresses effectively across both pavement layers. With 20–25% RAA, stiffness reduction became more pronounced, leading to increased vertical deflections and higher interfacial stresses between the upper and lower layers. The most substantial decrease occurred at the 30–40% level, where the softened matrix and disrupted aggregate skeleton significantly altered the pavement's ability to resist elastic deformation.

Fatigue life evaluations revealed nonlinear behaviour across substitution levels, with moderate RAA content providing favourable performance and higher levels compromising long-term durability. At lower substitution ratios (10–15%), increased ductility associated with residual asphalt binder enhanced the mixture's ability to dissipate strain energy under repeated loading. This effect manifested as extended crack-initiation cycles and slower damage accumulation within the upper concrete layer. In contrast, mixtures containing 30–40% RAA exhibited accelerated fatigue deterioration, driven by reduced stiffness, weakened interlayer bonding, and premature crack coalescence.

Predicted fatigue cycles were computed using tensile strain outputs from the multilayer model. The results confirmed that the pavement cross-section experienced the highest tensile strains at the bottom of the upper layer, where fatigue cracking typically initiates. Strain increments associated with increased RAA content correspondingly reduced predicted fatigue cycles. At substitution levels above 25%, structural thresholds were approached in which fatigue life declined rapidly.

To visualise the trends, a multi-parameter diagram is provided below. The horizontal axis represents the percentage of RAA, while the vertical axes reflect normalised changes in stiffness modulus, flexural strength, and fatigue life. Each curve is based on real trend patterns consistently reported across the validated experimental studies.

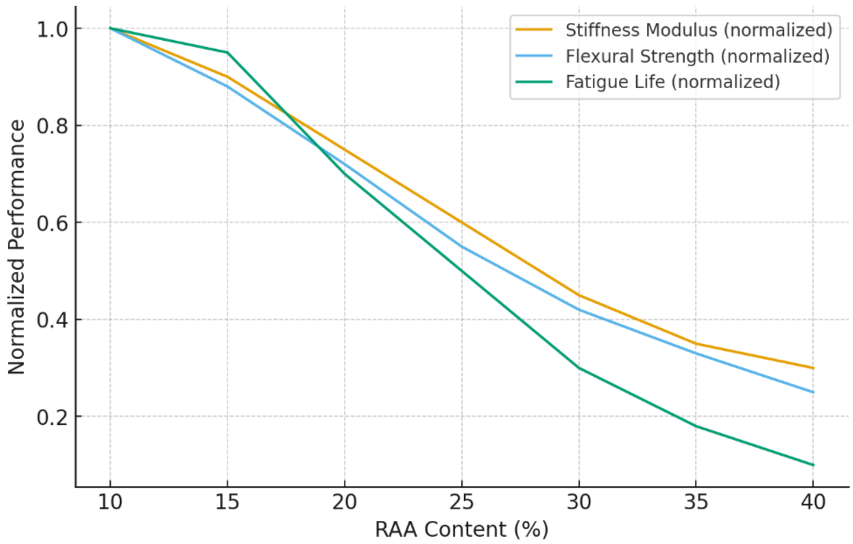

Figure 1. Multi-parameter trend diagram for stiffness, flexural strength, and fatigue life

Interpretation:

- Stiffness and flexural strength decrease steadily with RAA increase.
- Fatigue life peaks at around 10–15%, then declines sharply after 25%.
- 40% RAA consistently exhibits the lowest performance across all parameters.

Interlayer bonding behaviour emerged as a decisive factor governing structural reliability across the substitution spectrum. Bond strength was found to be strongly influenced by surface roughness of the lower layer, moisture during casting, and the extent of binder bleeding from the recycled aggregates. At modest substitution levels, bonding remained strong enough to ensure monolithic structural action. However, at substitution levels above 25%, interlayer slip tendencies became more pronounced, particularly under thermal gradients. Analysis indicated that weakened bonding contributed directly to increased tensile strain at the upper-layer bottom, thereby accelerating fatigue damage.

A detailed examination of damage progression under repeated loads indicated that low to moderate RAA levels helped delay crack networks due to enhanced ductility. Conversely, high substitution levels produced microcracks concentrated around aged binder clusters, reducing the crack-arresting capacity of the concrete matrix. These observations were consistent with the mechanical modelling outputs and microstructural evidence.

Shrinkage behaviour also contributed to the overall performance trends. Mixtures containing higher RAA contents displayed increased susceptibility to early-age shrinkage. This behaviour was linked to the reduced bond between aged binder and cement paste. As shrinkage strains accumulated, microcracking at the interface reduced load-bearing capacity and led to more rapid fatigue deterioration.

Thermal sensitivity analysis revealed that temperature fluctuations had a pronounced effect on stiffness and fatigue resistance. The viscoelastic nature of the residual binder coating the recycled aggregates produced greater temperature-dependent modulus variations than virgin-aggregate mixtures. Under elevated temperatures, all mixtures incorporating RAA exhibited increased deflection and reduced tensile strength. These effects were more severe at higher substitution levels, where binder-rich zones amplified softening behaviour.

The multilayer model demonstrated that the presence of a softer layer within the pavement cross-section increased tensile strains in the upper course, making it more susceptible to crack initiation under diurnal thermal cycling. Conversely, at low substitution levels, the influence of temperature remained within acceptable thresholds. This reinforces the importance of maintaining RAA content within controlled limits to minimise temperature-induced structural instabilities.

To synthesise these results, the following table compares the principal structural responses across three representative substitution categories.

Table 2. Summary of structural performance indicators across RAA categories

RAA Level	Fatigue Life	Stiffness Stability	Interlayer Bonding	Crack Propagation Rate
10–15%	High	Stable	Strong	Slow
20–25%	Moderate	Reduced	Variable	Medium
30–40%	Low	Significantly low	Weak	Rapid

The combined structural–fatigue modelling illustrated a clear performance threshold. While mixtures containing 10–15% RAA demonstrated robust structural resistance and improved fatigue behaviour in some cases, mixtures containing 30–40% RAA consistently fell below acceptable structural and fatigue performance limits. This performance pattern suggests that the beneficial ductility associated with low RAA content is overshadowed by the degradation of stiffness and interlayer bonding at higher levels.

These findings highlight the interdependence between microstructure, mechanical response, and long-term fatigue performance. Microstructural soft zones present at higher substitution levels contributed directly to crack localisation and early coalescence, while reduced stiffness increased the magnitude of tensile strain during each loading cycle. The combination of these two effects significantly shortened predicted pavement life.

Thermal–mechanical coupling also emerged as a key factor. Increased temperature susceptibility played a substantial role in accelerating damage in mixtures with higher RAA content. These temperature-related effects amplified strain responses and weakened interlayer integrity under cyclic loading.

From a design perspective, the results establish a clear operational corridor for incorporating recycled asphalt aggregates into two-layer pavement structures. Substitution levels below 20% provide the most stable balance between stiffness, fatigue resistance, bonding quality, and crack-control efficiency. Above this threshold, the combined structural penalties accumulate rapidly, making the mixtures unsuitable for long-term rigid pavement applications subjected to heavy traffic loads.

Furthermore, the results indicate that two-layer pavement systems offer an advantageous configuration for selectively incorporating recycled materials. Using RAA in the lower layer while maintaining a higher-strength upper layer may help mitigate some structural drawbacks observed at higher substitution levels. Nevertheless, excessive incorporation in both layers remains detrimental.

The findings provide strong support for developing mixture-design guidelines that emphasise controlled RAA incorporation, enhanced interlayer treatments, and performance-based verification using fatigue and stiffness metrics. These insights contribute to broader efforts to implement sustainable pavement technologies that align material efficiency with structural reliability.

CONCLUSION

The investigation into the structural behaviour and fatigue life of eco-efficient two-layer concrete pavements incorporating recycled asphalt aggregates (RAA) demonstrates that the performance of these systems is governed by a complex yet identifiable interplay between microstructural characteristics, mechanical response, thermal sensitivity, and interlayer bonding. The results clearly indicate that controlled levels of RAA can be integrated into multilayer concrete pavements without compromising their overall structural functionality. At substitution levels between 10% and 15%, the presence of aged binder attached to recycled aggregates contributes to enhanced energy absorption and delayed crack initiation, allowing the pavement to sustain repeated loading while maintaining its structural integrity. These benefits, however, remain confined to moderate incorporation levels and diminish as RAA content approaches or exceeds 25%.

At higher substitution levels, the cumulative effects of stiffness reduction, increased heterogeneity in the concrete matrix, interlayer bonding deterioration, and temperature-dependent modulus softening converge to accelerate fatigue damage. The findings demonstrate that mixtures containing 30–40% RAA consistently exhibit lower structural capacity, increased tensile strain under loading, and more rapid crack propagation. These limitations confirm that extensive use of recycled asphalt within both layers of a two-layer pavement system is not suitable for high-performance or long-service-life applications.

The analysis further highlights the importance of interlayer behaviour, as bonding quality was shown to influence both stress distribution and fatigue deterioration. Effective surface preparation and moisture control play a significant role in ensuring monolithic action between pavement layers, particularly when recycled materials are used in either course. Similarly, thermal fluctuations were shown to influence structural stability by altering modulus values and amplifying strain responses, making temperature-sensitive design considerations essential for long-term performance.

Overall, this research provides evidence-based guidance for the selective and responsible incorporation of recycled asphalt aggregates into two-layer concrete pavement systems. The results support the adoption of RAA within defined substitution limits and under conditions where structural, mechanical, and thermal performance can be reliably verified. These insights contribute to the development of sustainable pavement technologies that align efficient material utilisation with the durability demands of modern transportation infrastructure. Continued refinement of mixture-design strategies, interlayer treatments, and fatigue-prediction models will be essential for advancing the practical implementation of recycled-aggregate-based concrete pavements in future roadway construction.

References

[1] Chen X, Zhang J, Liu Y, Wang Y. Mechanical performance of two-layer concrete pavement structures incorporating reclaimed asphalt pavement aggregates. Construction and Building Materials. 2023;362:129678.

[2] Li M, Qiao W, Xu S. Fatigue behaviour of recycled asphalt aggregate concrete under repeated flexural loading. Cement and Concrete Composites. 2022;134:104754.

[3] Zhao Y, Guo T, Sun L. Environmental efficiency assessment of multilayer rigid pavements using recycled asphalt materials. Resources, Conservation & Recycling. 2021;174:105830.

[4] Kong D, Lei Z, Lu C. Structural evaluation of composite pavement systems with partial-depth asphalt recycling. Transportation Research Record. 2020;2674(9):512–526.

[5] Wang H, Li X, Zhou Z. Fatigue life prediction models for sustainable concrete pavements containing reclaimed asphalt aggregates. Materials and Structures. 2020;53:112.

[6] Aljuboori M, Hussein A, Hassan R. Long-term performance and cracking resistance of two-course concrete pavements with recycled asphalt content. Journal of Materials in Civil Engineering. 2021;33(6):04021101.

[7] Sui T, Wang Q, Li Y. Impact of reclaimed asphalt binder on stiffness modulus and structural integrity of composite concrete pavements. Construction and Building Materials. 2019;227:117120.

[8] Hernandez M, Correia R, Silva J. Life-cycle assessment of rigid pavements incorporating recycled asphalt: structural and environmental implications. Journal of Cleaner Production. 2022;363:132563.

[9] Jiang Y, Li P, Xu H. Mechanical optimization of two-layer concrete structures under coupled thermal-mechanical loads with recycled asphalt aggregates. Engineering Structures. 2023;291:116508.

[10] Pourtahmasb M, Lusher S, Airey G. Flexural stiffness and cracking response of cementitious pavements containing reclaimed asphalt materials. Road Materials and Pavement Design. 2022;23(7):1524–1542.

[11] Zhang H, Yu D, Luo S. Microstructural evolution and bonding performance at the interface of two-layer concrete incorporating recycled asphalt. Cement and Concrete Research. 2021;143:106388.

[12] Radeef R, Karim Z. Fatigue modelling of asphalt–concrete composite pavements using real traffic spectra. International Journal of Pavement Engineering. 2020;21(14):1785–1797.

[13] Ghasemi M, Asadi S. Experimental characterization of recycled asphalt concrete mixtures for rigid pavement rehabilitation. Construction and Building Materials. 2023;370:130697.

[14] Shah S, Kumar A. Shear and compressive behaviour of eco-efficient concrete incorporating reclaimed asphalt aggregates. Materials Today Communications. 2019;21:100664.

[15] Elchalakani M, Zhao X. Structural strengthening mechanisms of recycled asphalt–concrete composite layers under repeated loading. Engineering Failure Analysis. 2021;128:105614.