RESWARA: Jurnal Riset Ilmu Teknik
2024, Vol. 2, No. 4, pp. 125-132
E-ISSN: 3025-9444

Sustainable Pavement Design Using Recycled Asphalt Materials

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Abstract: *The increasing environmental burden associated with conventional asphalt pavement construction has accelerated the need for sustainable alternatives. Recycled asphalt materials, particularly reclaimed asphalt pavement (RAP), have emerged as a promising solution to reduce virgin material consumption, greenhouse gas emissions, and lifecycle costs. This study aims to analyze the performance, environmental, and economic implications of sustainable pavement design incorporating recycled asphalt materials based on a systematic literature-based assessment. A qualitative systematic review and comparative synthesis were conducted using 25 peer-reviewed studies published between 2016 and 2025. The selected studies were analyzed to evaluate mechanical performance, durability, environmental impact, and cost efficiency of pavements incorporating RAP and other recycled materials such as waste polymers, steel slag, and fly ash. The results indicate that RAP contents between 30% and 50% provide optimal performance while significantly reducing carbon emissions and lifecycle costs. Advanced recycling techniques such as warm-mix asphalt and cold recycling further enhance sustainability by lowering energy demand and emissions. Life cycle assessment results consistently demonstrate environmental impact reductions ranging from 30% to 50% compared to conventional pavements. This study confirms that sustainable pavement design using recycled asphalt materials is technically feasible, environmentally beneficial, and economically viable. The findings support the wider adoption of recycled materials in pavement engineering and provide evidence-based guidance for policymakers and practitioners toward achieving carbon-neutral infrastructure development.*

Article history:
Received: 25 August 2024
Revised: 16 September 2024
Accepted: 21 October 2024
Published: 29 October 2024

Keyword:
sustainable pavement, reclaimed asphalt pavement, life cycle assessment, recycled materials, green infrastructure

How to cite: Pratama, A. F., Zhao, W. F., & Oreto, C. (2024). Sustainable Pavement Design Using Recycled Asphalt Materials. *RESWARA: Jurnal Riset Ilmu Teknik*, *2*(4), 125-132. https://doi.org/10.70716/reswara.v2i4.374

INTRODUCTION

The global expansion of road infrastructure has significantly increased the consumption of natural resources, energy, and fossil-based materials while simultaneously intensifying greenhouse gas emissions and environmental degradation associated with pavement construction and maintenance. Conventional asphalt pavements rely heavily on virgin aggregates and petroleum-based binders, both of which require extensive extraction, processing, and transportation activities that contribute substantially to climate change and resource depletion (Assaf & Abu Abdo, 2022; Wu et al., 2024). As transportation systems continue to grow, the environmental footprint of pavement engineering has become a critical concern, prompting the need for sustainable alternatives that reduce ecological impacts without compromising technical performance or serviceability.

Sustainable pavement design has emerged as a strategic response to these challenges by integrating environmental, economic, and technical considerations into the planning and implementation of road infrastructure. This approach emphasizes minimizing lifecycle environmental impacts, optimizing material efficiency, and promoting circular economy principles through the reuse

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and recycling of construction materials (Zhao & Yang, 2023a; Oreto et al., 2021). Among the various strategies proposed, the use of recycled asphalt materials, particularly reclaimed asphalt pavement (RAP), has gained increasing attention due to its potential to significantly reduce virgin material consumption, landfill disposal, and greenhouse gas emissions while maintaining satisfactory mechanical performance (Naik et al., 2024; Firoozi & Firoozi, 2023).

Reclaimed asphalt pavement consists of milled or removed asphalt layers from existing pavements that can be reprocessed and incorporated into new asphalt mixtures. Numerous studies have demonstrated that RAP-based mixtures can achieve stiffness, strength, and durability comparable to conventional asphalt when appropriately designed (Georgiou & Loizos, 2021; Sajid et al., 2024). Empirical evidence suggests that RAP contents in the range of 30% to 50% provide an optimal balance between sustainability benefits and mechanical reliability, whereas higher contents require careful control of binder properties and mixture design (Rabihati et al., 2025; Sajid et al., 2024). These findings confirm that RAP is not merely a waste material but a valuable secondary resource for sustainable pavement systems.

Life cycle assessment has become a central analytical framework for quantifying the environmental benefits of recycled materials in pavement engineering. Several studies report substantial reductions in energy consumption, greenhouse gas emissions, and resource depletion when RAP and other recycled materials are incorporated into pavement structures (Zhao & Yang, 2023a; Oreto et al., 2021; Araneda et al., 2022). For example, cold recycled asphalt pavements and warm-mix asphalt technologies reduce production temperatures and fuel requirements, thereby lowering emissions by up to 50% compared to conventional hot-mix asphalt (Araneda et al., 2022; Elshahat & Shafik, 2024). These technologies enhance the environmental performance of pavement systems while maintaining construction feasibility and quality.

Beyond RAP, a wide range of recycled and industrial by-products such as waste plastics, fly ash, steel slag, and reclaimed asphalt shingles have been integrated into asphalt mixtures to further improve sustainability outcomes (Colbert et al., 2016; Oreto et al., 2021). The combined use of RAP and waste polyethylene terephthalate has been shown to improve moisture resistance and rutting performance while simultaneously reducing material costs and carbon emissions (Sajid et al., 2024). Similarly, the incorporation of steel slag and industrial solid waste into high-RAP mixtures has demonstrated improved mechanical stability and long-term durability (Zhao & Yang, 2023b; Georgiou & Loizos, 2021). These findings indicate that multi-material recycling strategies can amplify the benefits of sustainable pavement design.

Despite the demonstrated advantages, several technical and institutional challenges continue to limit the widespread adoption of recycled asphalt materials. Variability in RAP quality, aging and stiffening of recycled binders, and the absence of harmonized design standards remain major barriers to consistent performance and regulatory acceptance (Wu et al., 2024; Caires Pereira Pessoa, 2024). High RAP content mixtures often require rejuvenating agents or modified binders to restore flexibility and mitigate cracking susceptibility, which introduces additional design complexity and cost considerations (Rabihati et al., 2025; Casaux et al., 2024). Moreover, differences in local material availability and construction practices necessitate context-specific design approaches.

Another critical issue concerns the integration of sustainability assessment into pavement design decision-making. While life cycle assessment and life cycle cost analysis provide valuable quantitative insights, they are not yet systematically embedded into routine engineering practice or policy frameworks (Moins, 2024; Casaux et al., 2024). The lack of standardized sustainability metrics and performance thresholds limits the comparability of studies and the translation of research findings into regulatory guidelines. As a result, many infrastructure projects continue to prioritize short-term economic efficiency over long-term environmental performance.

Therefore, a comprehensive synthesis of existing empirical evidence is necessary to support informed decision-making and promote the effective implementation of sustainable pavement technologies. This study aims to systematically review and analyze recent research on sustainable pavement design using recycled asphalt materials, with a particular focus on reclaimed asphalt pavement and complementary recycled materials. The objectives are to evaluate their technical performance, environmental benefits, and economic implications, and to identify key challenges and enabling factors for practical implementation. By consolidating multidisciplinary findings, this study seeks to provide an evidence-based foundation for engineers, policymakers, and researchers working toward environmentally responsible and resilient transportation infrastructure.

RESEARCH METHOD

Research Design

This study employed a qualitative systematic literature review design with comparative analytical synthesis. The approach was selected to integrate and critically examine empirical findings from peer-reviewed studies on sustainable pavement design using recycled asphalt materials. The focus was on synthesizing existing evidence related to technical performance, environmental impacts, and economic implications of reclaimed asphalt pavement and associated recycled materials without generating new experimental data. This design allows for structured comparison and interpretation across multiple studies while maintaining consistency with established research methodologies in sustainable infrastructure assessment.

Data Sources and Selection Criteria

The data sources consisted of 25 peer-reviewed journal articles and book chapters published between 2016 and 2025 that explicitly addressed sustainable pavement design and the use of recycled asphalt materials. These studies were selected based on the following inclusion criteria: relevance to pavement engineering and sustainability, explicit use of reclaimed asphalt pavement or related recycled materials, availability of performance, environmental, or economic evaluation results, and publication in reputable scientific outlets. Studies focusing solely on theoretical modeling without empirical or applied relevance were excluded to maintain practical applicability.

The selection process followed a structured screening procedure. Titles and abstracts were initially reviewed to assess relevance. Full-text screening was then conducted to ensure alignment with the study objectives and consistency with the sustainability indicators discussed in the literature. Only studies that met all inclusion criteria were retained for analysis.

Data Extraction and Classification

From each selected study, data were systematically extracted on key variables including the type and proportion of recycled materials used, mixture design approaches, reported mechanical performance indicators, environmental impact measures derived from life cycle assessment, and economic indicators such as lifecycle costs or cost savings. These data were organized into thematic categories corresponding to technical performance, environmental sustainability, and economic efficiency. This classification facilitated comparative analysis and pattern identification across studies while preserving the integrity of the original findings.

Analytical Framework

A comparative synthesis framework was applied to integrate the extracted data. This framework involved cross-study comparison of reported outcomes to identify consistent trends, optimal design ranges, and recurring challenges associated with recycled asphalt materials. Particular attention was given to the relationships between recycled material content and performance outcomes, as well as the environmental and economic trade-offs identified through life cycle assessment and life cycle cost analysis.

The synthesis did not involve statistical meta-analysis due to the heterogeneity of study designs, measurement methods, and reporting formats across the reviewed literature. Instead, a narrative comparative approach was used to interpret findings within their respective methodological contexts and to ensure that conclusions remained grounded in the original empirical evidence.

Reliability and Validity Considerations

To enhance the reliability of the synthesis, data extraction and categorization were conducted using a standardized template to minimize subjective interpretation. Cross-checking was performed to ensure consistency in classification and interpretation of findings. The use of peer-reviewed sources further ensured the credibility and scientific rigor of the data.

Validity was addressed by maintaining strict adherence to the inclusion criteria and by preserving the contextual meaning of reported results. Findings were interpreted within the methodological limitations of each study, and no extrapolation beyond the original scope of the data was performed.

Ethical Considerations

This study did not involve human participants, animals, or primary data collection. All data were derived from publicly available academic sources. Proper citation and acknowledgment of original authors were maintained throughout the analysis to ensure academic integrity and avoid plagiarism.

RESULTS AND DISCUSSION

Technical Performance of Recycled Asphalt Pavements

The reviewed studies consistently report that reclaimed asphalt pavement can be incorporated into asphalt mixtures without compromising structural performance when appropriate design controls are applied. Naik et al. (2024), Firoozi and Firoozi (2023), and Georgiou and Loizos (2021) showed that RAP-based mixtures exhibit stiffness, rutting resistance, and fatigue behavior comparable to conventional asphalt mixtures. Sajid et al. (2024) further demonstrated that the addition of waste polyethylene terephthalate enhances moisture resistance and rutting performance in RAP mixtures.

Rabihati et al. (2025) reported that RAP contents between 30% and 50% provide an optimal balance between mechanical performance and sustainability, while higher RAP contents require rejuvenating agents to mitigate binder aging effects. Zhao and Yang (2023b) confirmed that pavements using 100% RAP combined with industrial solid waste can achieve high-temperature stability and durability comparable to or exceeding conventional pavements.

Table 1. Reported RAP Content and Performance Outcomes

Study	RAP Content	Key Performance Findings
Naik et al. (2024)	30–50%	Comparable stiffness and durability
Sajid et al. (2024)	40% RAP + 6% PET	Improved rutting and moisture resistance
Rabihati et al. (2025)	30–50%	Optimal sustainability-performance balance
Zhao & Yang (2023b)	100%	High-temperature stability and durability
Georgiou & Loizos (2021)	25–50%	Equivalent or better performance than HMA

Environmental Impact Reduction

Life cycle assessment results consistently indicate substantial environmental benefits associated with recycled asphalt materials. Zhao and Yang (2023a) and Oreto et al. (2021) reported reductions in lifecycle environmental impacts ranging from 30% to 50% compared to conventional pavements. Araneda et al. (2022) showed that cold recycled asphalt pavements reduce emissions by approximately 50% relative to hot-mix asphalt.

Assaf and Abu Abdo (2022) and Wu et al. (2024) confirmed that recycled materials significantly reduce energy consumption, greenhouse gas emissions, and natural resource depletion. These findings demonstrate that environmental benefits are not marginal but structurally embedded in sustainable pavement systems.

Table 2. Reported Environmental Benefits

Study	Method	Main Environmental Outcome
Zhao & Yang (2023a)	LCA	~45% reduction in emissions and energy
Oreto et al. (2021)	LCA	~31% reduction in lifecycle impacts
Araneda et al. (2022)	Comparative LCA	~50% lower emissions
Assaf & Abu Abdo (2022)	LCA	Reduced energy, emissions, water use

Economic Implications

From an economic perspective, the reviewed studies report substantial lifecycle cost savings. Moins (2024) demonstrated that incorporating RAP reduces lifecycle costs through lower material extraction and reduced energy use. Sajid et al. (2024) reported significant cost reductions associated with reduced virgin material demand. Casaux et al. (2024) highlighted that the use of local recycled materials further enhances economic efficiency by reducing transportation costs and associated emissions.

These results indicate that sustainability and economic efficiency are not competing objectives but mutually reinforcing outcomes in pavement design.

Challenges and Design Considerations

Despite the benefits, several limitations remain. Wu et al. (2024) and Caires Pereira Pessoa (2024) emphasized the lack of standardized guidelines, variability in RAP quality, and uncertainty in long-term performance. Rabihati et al. (2025) highlighted the necessity of rejuvenators for high-RAP mixtures to prevent brittleness and cracking. Casaux et al. (2024) noted that mechanistic-empirical design approaches improve reliability but require higher technical capacity.

These challenges underscore the importance of integrated technical, environmental, and regulatory frameworks to ensure consistent implementation.

Synthesis and Implications

Overall, the findings confirm that sustainable pavement design using recycled asphalt materials is technically feasible, environmentally beneficial, and economically viable. The integration of recycled materials supports circular economy principles and contributes directly to climate mitigation goals (Firoozi & Firoozi, 2023; Plati & Cliatt, 2018). However, achieving these benefits at scale requires standardized quality control, appropriate design methodologies, and institutional support.

CONCLUSION

This study confirms that sustainable pavement design using recycled asphalt materials, particularly reclaimed asphalt pavement, is a technically feasible, environmentally beneficial, and economically viable approach for modern road infrastructure. The reviewed evidence demonstrates that RAP can replace a substantial proportion of virgin materials while maintaining mechanical performance and structural reliability when appropriate mixture design and quality control are applied.

The synthesis shows that RAP contents in the range of 30% to 50% consistently achieve an effective balance between performance and sustainability, while higher replacement levels are possible under controlled conditions and with complementary materials or technologies. Life cycle assessments consistently report significant reductions in greenhouse gas emissions, energy consumption, and resource depletion, confirming that recycled asphalt materials contribute meaningfully to environmental impact mitigation. Life cycle cost analyses further indicate that these environmental benefits are accompanied by economic advantages through reduced material extraction, lower energy requirements, and minimized waste disposal.

However, the findings also highlight persistent challenges, including variability in recycled material quality, aging of reclaimed binders, and the absence of harmonized design and sustainability standards. Addressing these issues requires the integration of mechanistic-empirical design approaches, consistent quality control protocols, and standardized sustainability assessment frameworks.

Overall, this study provides consolidated evidence supporting the systematic adoption of recycled asphalt materials in pavement engineering and underscores the importance of aligning technical practices with sustainability objectives to achieve resilient and environmentally responsible transportation infrastructure.

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