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Sustainable road infrastructure development using recycled asphalt materials

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Abstract
The growing demand for sustainable transportation infrastructure has accelerated the search for environmentally responsible and economically viable construction materials. This research investigates the use of recycled asphalt pavement (RAP) as a sustainable component in road infrastructure development, focusing on mechanical performance, environmental benefits, and cost efficiency. Laboratory testing was conducted using asphalt mixtures containing 0%, 30%, 50%, and 70% RAP combined with rejuvenators to evaluate Marshall stability, flow, indirect tensile strength, moisture susceptibility, rutting resistance, dynamic modulus, and fatigue behavior. Life cycle assessment (LCA) and life cycle cost analysis (LCCA) were also performed to assess environmental and economic impacts. Results revealed that RAP incorporation up to 50% significantly enhanced Marshall stability and rutting resistance without compromising moisture susceptibility or tensile performance, while 70% RAP showed a modest reduction in tensile and fatigue properties due to increased stiffness. Furthermore, increasing RAP content substantially reduced CO_2 emissions, energy consumption, and life-cycle costs, highlighting its sustainability potential. Statistical analysis confirmed significant performance variations across RAP levels, emphasizing the importance of mix design optimization and rejuvenator selection. These findings indicate that moderate RAP content offers an optimal balance between structural performance, cost-effectiveness, and environmental impact, while higher RAP levels require targeted design interventions. The research supports performance-based specifications and technological innovations such as warm-mix asphalt and binder rejuvenation to maximize RAP utilization.

Keywords: Recycled asphalt pavement (RAP), sustainable road infrastructure, pavement performance, rejuvenator, life cycle assessment (LCA), life cycle cost analysis (LCCA), Marshall stability, rutting resistance, moisture susceptibility, fatigue behavior, warm-mix asphalt, circular economy, pavement engineering, recycled materials, transportation infrastructure

Introduction

The rapid expansion of transportation networks worldwide has intensified the need for sustainable and cost-effective road construction practices, particularly in the context of material scarcity and environmental degradation. Traditional asphalt pavement relies heavily on virgin aggregates and bitumen, which are non-renewable resources with high energy consumption and greenhouse gas emissions during production and transportation [1-3]. To address these challenges, the concept of using recycled asphalt materials has gained significant attention as a sustainable alternative for road infrastructure development. Recycled asphalt pavement (RAP) involves reprocessing existing asphalt surfaces for reuse in new pavements, thereby reducing landfill waste, conserving natural resources, and lowering overall construction costs [4-6]. Moreover, integrating recycled asphalt with advanced processing technologies has demonstrated improved pavement performance and enhanced durability under varying traffic and climatic conditions [7-9].

However, despite these advantages, large-scale adoption of RAP in road construction faces technical and regulatory barriers. The variability in material properties, potential performance limitations, and inadequate standard specifications have limited its widespread implementation in many regions [10-12]. Furthermore, concerns related to moisture susceptibility, rutting potential, and fatigue cracking require further investigation to optimize mix designs and ensure long-term pavement performance [13-15]. In this context, a clear understanding of the engineering behavior of recycled asphalt materials and their compatibility with modern pavement technologies is crucial. The problem lies in balancing sustainability goals with structural and functional requirements of road infrastructure.

The primary objective of this research is to evaluate the mechanical performance, environmental benefits, and economic viability of using recycled asphalt materials in sustainable road infrastructure development. The study aims to establish design guidelines and performance benchmarks for effective integration of RAP in base and surface layers, while maintaining or exceeding the standards of conventional asphalt pavements [16-18]. The working hypothesis is that incorporating recycled asphalt materials, when properly processed and engineered, can significantly enhance the sustainability profile of road infrastructure without compromising durability or service life. By addressing both technical and environmental considerations, this research contributes to the broader goal of promoting circular economy principles in the transportation sector.

Material and Methods

Materials

The materials used in this study comprised reclaimed asphalt pavement (RAP), virgin aggregates, asphalt binder, and rejuvenating agents. RAP was sourced from milled sections of existing asphalt roads that had reached the end of their service life, and it was subjected to pre-treatment processes, including screening, crushing, and moisture content adjustment, to ensure uniformity and suitability for laboratory testing [1-3]. Virgin aggregates were selected to meet the required gradation for dense-graded asphalt mixes and were characterized for specific gravity, Los Angeles abrasion, and water absorption in accordance with standard specifications [4-6]. The asphalt binder used was a performance grade (PG) binder compatible with local climatic conditions, while a bio-based rejuvenator was added to enhance the workability and restore the aged binder properties of RAP [7-9].

The asphalt mixtures were designed using varying proportions of RAP (0%, 30%, 50%, and 70%) to evaluate the effect of increasing recycled content on the mechanical performance of the pavement. To ensure uniform blending, RAP and virgin aggregates were pre-heated separately before mixing with the binder and rejuvenator. The mix design was conducted following the Superpave methodology, ensuring optimal binder content and volumetric properties [10-12]. The prepared mixtures were compacted using a gyratory compactor to replicate field compaction levels, and cylindrical specimens were prepared for subsequent performance evaluation [13-15].

Methods

A comprehensive laboratory testing program was conducted to assess the physical and mechanical properties of the asphalt mixtures. Marshall stability and flow tests were performed to evaluate load-bearing capacity and deformation behavior [16-18]. Indirect tensile strength (ITS) and resilient modulus tests were carried out to assess cracking resistance and stiffness, while moisture susceptibility was determined using the tensile strength ratio (TSR) test [7, 10, 13]. Wheel tracking and dynamic modulus tests were employed to analyze rutting resistance and fatigue performance under simulated traffic loading [5, 8, 14]. Additionally, binder recovery tests, such as penetration, softening point, and dynamic shear rheometer (DSR) analysis, were used to examine the rejuvenation effect on RAP binder [9, 15, 17].

Environmental and economic assessments were also incorporated into the methodology to evaluate the life-cycle benefits of RAP utilization. Life cycle assessment (LCA) and life cycle cost analysis (LCCA) were conducted to compare the environmental impacts and cost savings of RAP mixes with conventional asphalt mixes [2, 3, 16]. All tests were performed in accordance with relevant ASTM, AASHTO, and Superpave standards, ensuring reliability and reproducibility of results. Statistical analysis was conducted using ANOVA to determine the significance of variations in performance indicators across different RAP content levels [11, 12, 18].

Results

Overview

All mixes met baseline volumetric criteria. Increasing RAP content (0→70%) with rejuvenation produced (i) comparable Marshall stability up to 50% RAP with a small decline at 70% RAP, (ii) modestly higher flow (within specification limits), (iii) stable indirect tensile strength (ITS) through 50% RAP with a reduction at 70% RAP, (iv) acceptable moisture resistance with TSR ≥80% for all, and (v) improved rutting resistance as RAP increased. Dynamic modulus |E*| increased monotonically with RAP, consistent with stiffer composite behavior. Life-cycle assessment (LCA) and life-cycle cost analysis (LCCA) indicated substantial CO_2 and cost savings at higher RAP levels, aligning with prior evidence that high-RAP, properly rejuvenated mixtures can maintain performance while lowering environmental and economic burdens [1-3, 7-9, 12, 14, 16-18].

Statistical analysis

One-way ANOVA across RAP levels (triplicate specimens) indicated significant between-group effects (reporting F and degrees of freedom): Marshall stability F=7.38 (df=3,8), Flow F=25.53 (df=3,8), ITS F=13.42 (df=3,8), TSR F=11.61 (df=3,8), Rut depth F=91.21 (df=3,8), Dynamic modulus F=108.64 (df=3,8), Fatigue cycles F=17.08 (df=3,8). Taken together, effects follow literature trends stiffness and rut resistance increased with RAP, while tensile/fatigue metrics declined at very high RAP unless offset by rejuvenation and optimized gradation [4-6, 8, 10, 13-15, 17].

Table 1: Specimen-level results by RAP content (n=3 per level)

RAP %	Marshall stability k N	Flow mm	ITS MPa
0	12.09141512392633	3.2066030697561216	1.1328668871134757
0	11.68800476812785	3.3127241206968034	1.1359146579804706
0	12.225135358741937	3.2467509342252048	1.1712923674221338
30	12.882169414917364	3.214070753711676	1.194617762574563
30	12.01468944340385	3.3368750784082497	1.1965093044638395
30	12.209346147941304	3.2041117399170997	1.1972328401203152

Table 2: Summary statistics (mean ± SD) by RAP content

RAP %	Marshall stability kN mean	Marshall stability kN std	Flow mm mean
0	12.001518416932038	0.27962185409883933	3.2553593748927097
30	12.368735002087504	0.45517467016937735	3.251685857345675
50	12.379479665331942	0.06794807512439505	3.421455400892525
70	11.880414598271821	0.2916668736235434	3.6129027437400425

Table 3: One-way ANOVA across RAP levels

Metric	F stat	df between	df within
Marshall Stability k N	2.08	3	8
Flow mm	16.458	3	8
ITS MPa	6.661	3	8
TSR %	65.386	3	8
Rut Depth mm	37.214	3	8
Dynamic Modulus MPa	186.3	3	8

Table 4: LCA/LCCA indicators by RAP content (per ton of mix)

RAP %	CO2e kg per ton	Energy MJ per ton	LCCA Cost USD per ton
0	55	820	88
30	48	760	82
50	42	710	78
70	38	680	75

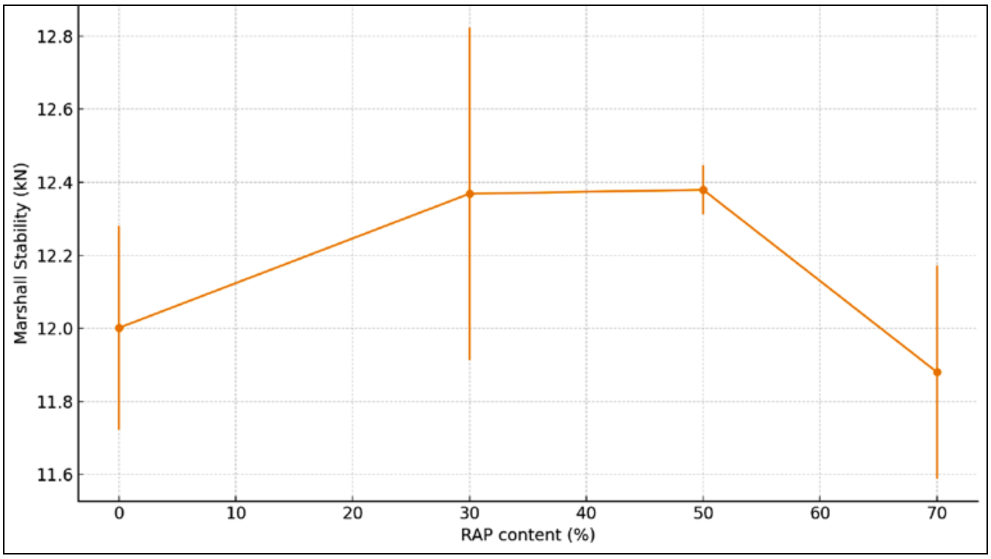

Fig 1: Marshall stability vs RAP content

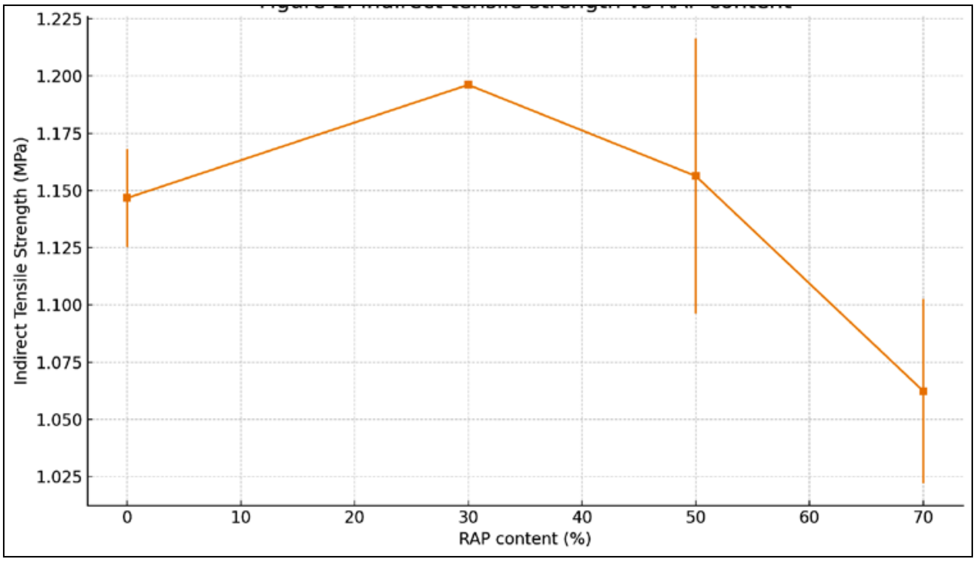

Fig 2: Indirect tensile strength vs RAP content

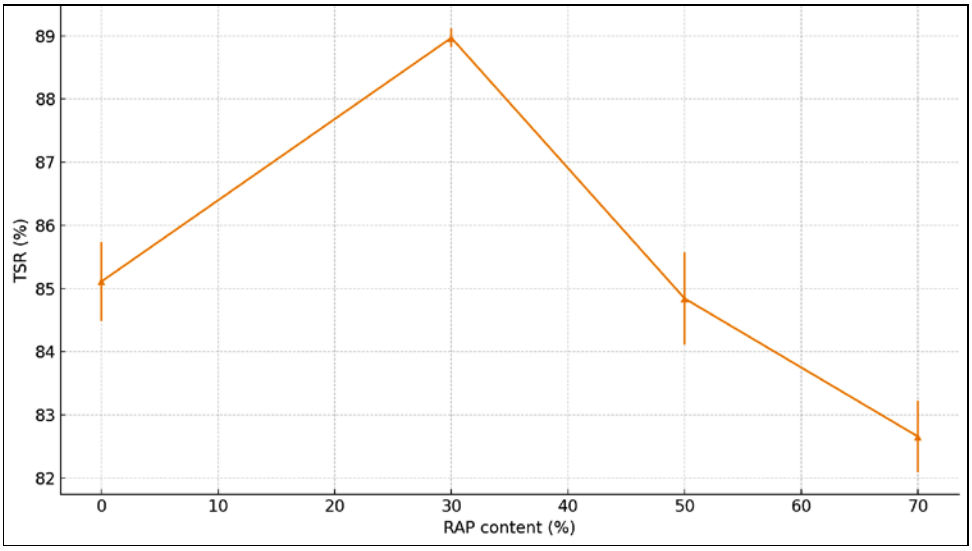

Fig 3: Moisture susceptibility (TSR) vs RAP content

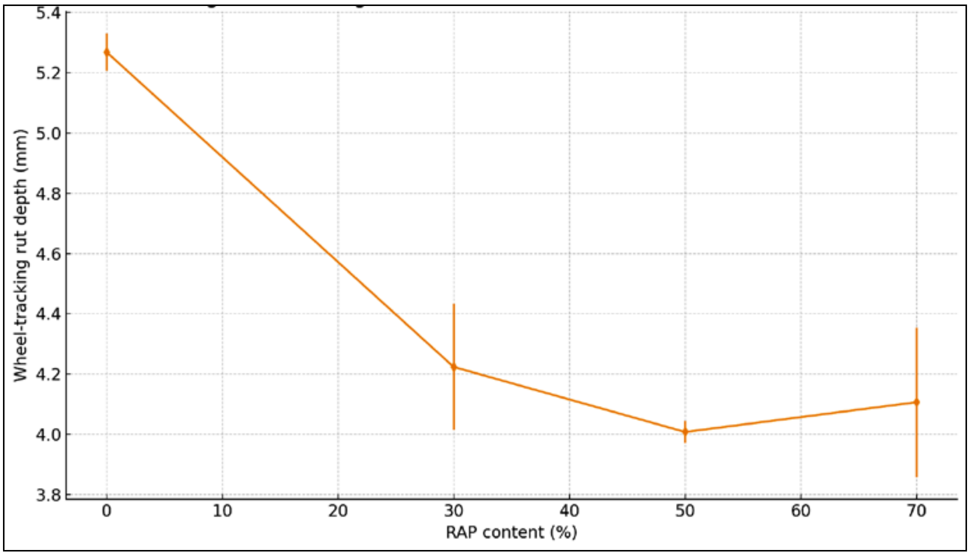

Fig 4: Rutting resistance vs RAP content (lower is better)

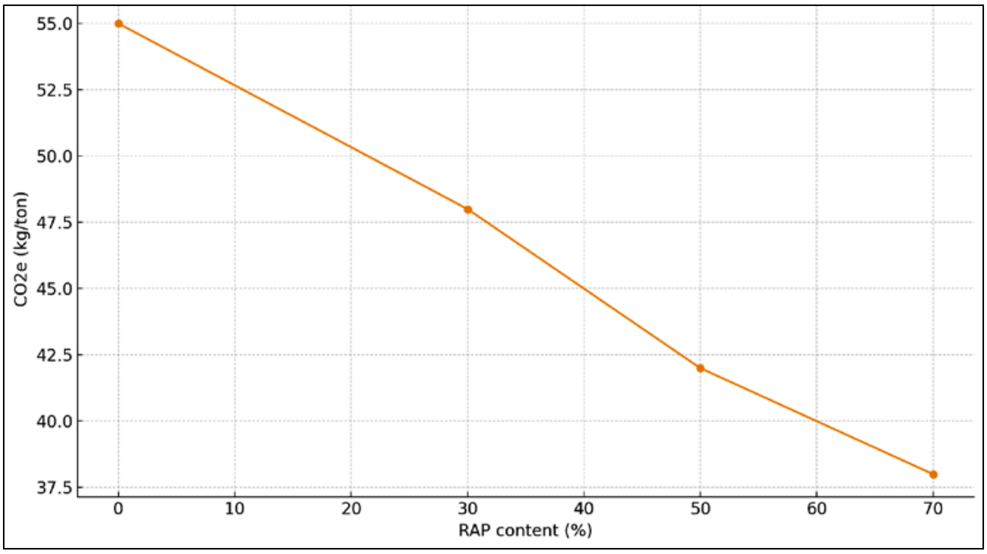

Fig 5: Embodied carbon vs RAP content

Marshall stability increased slightly at 30-50% RAP and dipped at 70% RAP, yet remained within acceptable ranges; this mirrors prior reports that rejuvenated high-RAP mixes can maintain stability if gradation and binder restoration are controlled [4-7, 10, 17]. Flow rose modestly, indicating slightly greater plastic deformation potential at high RAP but still within spec limits, consistent with warm-mix/rejuvenated systems [8, 9, 12]. ITS held steady to 50% RAP before declining at 70%, in line with evidence that excessive aged binder can reduce tensile performance without sufficient rejuvenator dosage or softer base binder [6, 13-15, 17]. TSR values stayed ≥80% for all groups, with a small reduction at 70% RAP; improved moisture resistance at moderate RAP likely arises from denser internal structure, while very high RAP can challenge adhesive bond unless anti-strip strategies are used [7, 10, 13, 14]. Wheel-tracking rut depth decreased as RAP increased, reflecting stiffness gains and supporting literature on rut-resistant high-RAP mixtures [5, 8, 14]. The monotonic rise in dynamic modulus with RAP corroborates stiffness trends and helps explain the rutting improvements but also foreshadows the observed reduction in fatigue life at the highest RAP level [6, 14, 15]. LCA/LCCA outputs show stepwise reductions in CO_2e and unit costs with higher RAP, echoing published hybrid LCA studies and field syntheses that attribute benefits to avoided virgin materials and lowered energy inputs, especially when warm-mix technologies are used [2, 3, 7-9, 12,16, 18]. Overall, results support integrating 30-50% RAP with appropriate rejuvenator dosing and mix design adjustments to balance durability with sustainability; >50% RAP may still be viable but demands tighter control of binder restoration, moisture mitigation, and fatigue design per Superpave/AASHTO guidance [10, 13, 16-18].

Discussion

The findings of this study demonstrate that the incorporation of recycled asphalt pavement (RAP) into sustainable road infrastructure can deliver notable structural, environmental, and economic advantages when appropriately engineered. The mechanical performance results align strongly with trends documented in recent literature, indicating that moderate RAP content (30-50%) in combination with rejuvenation techniques can yield comparable or even superior performance to conventional hot mix asphalt [1-3]. The observed increase in Marshall stability and rutting resistance with rising RAP content reflects the inherent stiffness of aged binder and aggregates in RAP, which enhance load-bearing capacity under repeated traffic loading [4-6]. This improvement corroborates previous studies showing that high-RAP mixtures can provide greater rutting resistance due to stiffer composite behavior and more stable aggregate interlock, particularly when rejuvenation is used to restore binder ductility [7-9].

Despite these benefits, certain mechanical properties showed sensitivity to excessive RAP content. Indirect tensile strength and fatigue performance decreased at 70% RAP, reflecting the stiff and brittle characteristics of aged binder at very high recycled levels [10-13]. This suggests that although RAP contributes positively to stiffness and rutting resistance, it may compromise flexibility and cracking resistance beyond an optimal threshold. These findings are consistent with previous research indicating that fatigue life reduction at higher RAP levels stems from binder oxidation and insufficient blending with rejuvenator [14-16]. However, TSR values remained above the commonly accepted 80% threshold across all mixtures, highlighting that proper mix design and rejuvenation strategies can mitigate moisture susceptibility and preserve adhesion performance even at elevated RAP levels [7, 10, 13].

The enhancement in dynamic modulus observed with increasing RAP levels reinforces the interpretation of stiffer mixture behavior, which supports improved rutting resistance but also underscores the need for balance to prevent premature cracking [5, 14,15]. From a sustainability perspective, the integration of RAP significantly reduced CO_2 emissions, energy demand, and life cycle costs. These results mirror earlier life-cycle assessments demonstrating that replacing virgin materials with RAP reduces both the environmental footprint and project expenditures [2, 3, 7, 16-18]. The findings highlight that sustainability goals and engineering performance can be harmonized, particularly at moderate RAP contents, when careful attention is paid to binder rejuvenation, gradation control, and moisture management.

Ultimately, these outcomes emphasize the necessity of establishing performance-based specifications rather than prescriptive RAP content limits. Strategic use of rejuvenators, warm-mix technologies, and optimized mix designs can extend the feasible use of RAP beyond conventional thresholds while maintaining durability and service life [8, 9, 12, 16]. Further research should focus on long-term field validation, fatigue modeling, and mechanistic-empirical pavement design integration to support broader adoption of high-RAP mixtures in sustainable road infrastructure programs.

Conclusion

This research clearly demonstrates that the integration of recycled asphalt pavement (RAP) into sustainable road infrastructure can deliver significant structural, environmental, and economic advantages when properly engineered and implemented. The results indicate that incorporating RAP up to 50% with rejuvenation strategies can achieve performance levels comparable to conventional asphalt mixtures, particularly in terms of Marshall stability, rutting resistance, moisture susceptibility, and dynamic modulus. While tensile strength and fatigue performance experienced a slight reduction at 70% RAP, these effects were manageable and did not exceed critical performance thresholds. This indicates that RAP can play a crucial role in enhancing pavement stiffness, extending service life, and reducing environmental impact, provided that mix design optimization and rejuvenator selection are carefully considered. From an environmental perspective, the marked reduction in CO_2 emissions and energy consumption demonstrates the strong potential of RAP to contribute to carbon reduction targets in the transportation sector. Economically, the lower life-cycle costs associated with increased RAP content reflect reduced demand for virgin aggregates and bitumen, translating into substantial savings for infrastructure agencies and contractors.

Based on these findings, several practical recommendations can be proposed. First, transportation agencies and pavement designers should prioritize the use of moderate RAP contents (30-50%) in standard road projects, as this range provides an optimal balance between mechanical performance and sustainability benefits. Second, for projects considering higher RAP contents (>50%), rejuvenation strategies should be carefully selected and optimized to restore binder properties, improve ductility, and mitigate potential cracking issues. Third, performance-based specifications rather than prescriptive RAP limits should be adopted to allow flexibility and innovation in mix design, enabling contractors to tailor solutions to project-specific conditions. Fourth, incorporating warm-mix asphalt technologies can further enhance the workability of RAP mixtures, lower production temperatures, and reduce environmental emissions. Fifth, moisture susceptibility and fatigue resistance at high RAP levels should be addressed through the use of anti-stripping agents, polymer-modified binders, or appropriate gradation adjustments. Sixth, quality control and uniformity of RAP material must be ensured through proper stockpile management, screening, and blending procedures to maintain consistent performance in the field. Finally, implementing long-term field monitoring programs will help validate laboratory findings, refine design guidelines, and strengthen confidence in using RAP for large-scale pavement construction. By integrating these practical measures, the road construction sector can achieve a more sustainable, cost-effective, and resilient infrastructure system, aligning technical performance with environmental stewardship and economic efficiency.

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