Towards Sustainable Pavements and Structural Materials: Unifying RHA Concrete and WMA Additive Technologies

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Abstract. The construction and transportation sectors are under growing pressure to reduce carbon emissions and improve material sustainability. This study evaluates the combined sustainability potential of Rice Husk Ash (RHA) concrete and Warm Mix Asphalt (WMA) and proposes a unified framework for assessing next-generation pavement and structural materials. Four concrete mixes with 0–30% RHA replacement and three asphalt mixes incorporating chemical and organic WMA additives were tested for mechanical performance, durability, and environmental impact. Results show that 20% RHA (C20) achieved the highest compressive strength (49.2 MPa), representing a 15.8% improvement over the control, while also reducing chloride penetration by 42% and embodied carbon by 20%. For asphalt, the organic WMA2 mix reduced production energy by 27.1%, improved tensile strength ratio (TSR = 88.2%), and enhanced rutting resistance by 17.5% compared to Hot Mix Asphalt. Statistical analyses, including ANOVA and regression modeling, confirmed the significant influence of RHA content and temperature reduction on performance and sustainability outcomes. A Unified Sustainability Score (USS) integrating mechanical, durability, and environmental metrics identified C20 + WMA2 as the most sustainable system (USS = 0.91). The study demonstrates that integrating RHA concrete and WMA technologies provides a viable pathway toward low-carbon, durable, and performance-optimized infrastructure. The unified framework offers a robust tool for engineers and policymakers to guide sustainable material selection and future infrastructure development.

Keywords: Rice Husk Ash (RHA); Warm Mix Asphalt (WMA); Sustainable Materials; Low-Carbon Concrete; Pavement Engineering; Life Cycle Assessment (LCA); Mechanical Performance; Durability; Embodied Carbon; Energy Efficiency; Unified Sustainability Framework; Pozzolanic Materials; Infrastructure Sustainability; Temperature-Reduction Technologies; Material Optimization.

1. Introduction and Background

The global construction and transportation sectors are responsible for significant environmental burdens, collectively contributing high levels of energy consumption, greenhouse-gas emissions, and resource depletion. Cement production alone accounts for 7–9% of global CO_2 emissions, driven primarily by the calcination of limestone and high-temperature kiln operations (Scrivener et al., 2018). Asphalt pavement production, although less carbon-intensive per ton than cement, requires mixing temperatures of 150–170°C, resulting in substantial fuel use and emissions of greenhouse gases and volatile organic compounds (D'Angelo et al., 2008). With nations intensifying carbon-reduction commitments and transitioning toward circular-economy models, sustainable material innovations have become a strategic priority across infrastructure development (Habert et al., 2020).

Sustainable infrastructure innovation is not only a materials engineering challenge but also a matter of governance, organizational sustainability practices, and green innovation capacity. Studies in green human resource management, ESG-oriented strategies, and eco-friendly behavioral frameworks show that sustainable performance across sectors depends on integrated environmental thinking beyond technical domains (Saiyed et al., 2025; Hasan, 2025; Hasan et al., 2024).

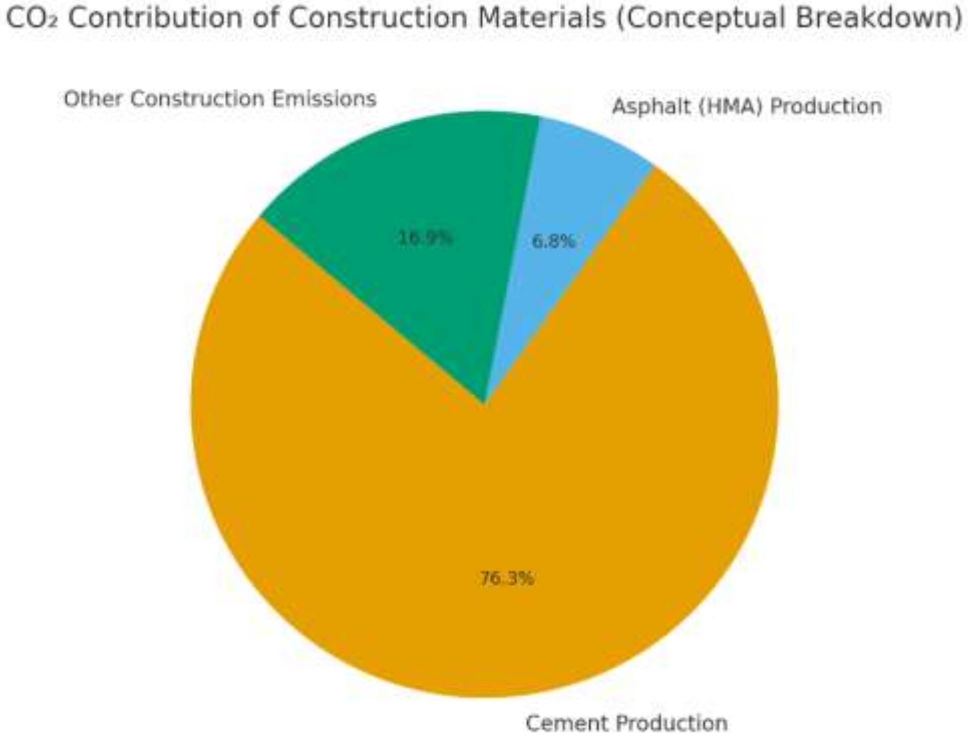

Figure 1. Conceptual CO_2 contribution of construction materials, highlighting cement and asphalt as major emitters — cement dominates due to the calcination process; HMA contributes meaningfully through high-temperature mixing (150–170°C).

Figure 1 illustrates the disproportionate CO_2 burden associated with cement and asphalt production within the construction sector. Cement production emerges as the dominant contributor, driven by the carbon-intensive calcination process and the high thermal energy required for clinker formation. Asphalt (HMA) production, while producing significantly lower CO_2 emissions per ton than cement, still represents a meaningful portion of the sector's environmental footprint due to its reliance on high mixing temperatures (150–170°C). When viewed together, these materials collectively highlight why infrastructure construction remains one of the most emissions-intensive industries globally. This imbalance underscores a critical opportunity: even modest reductions in cement usage or asphalt production temperatures can produce substantial carbon savings. Consequently, the graph provides a clear rationale for exploring alternative material systems—such as Rice Husk Ash (RHA) as a cement replacement and Warm Mix Asphalt (WMA) technologies—to achieve significant improvements in sustainability performance across both structural and pavement materials.

Two promising material technologies have gained particular attention: Rice Husk Ash (RHA) concrete and Warm Mix Asphalt (WMA). RHA is a highly pozzolanic agricultural by-product capable of partially replacing Portland cement, thereby improving microstructural performance while reducing embodied carbon. When combusted under controlled temperatures, RHA provides high-reactivity amorphous silica that enhances hydration kinetics and contributes to long-term durability (Zhang & Malhotra, 1996; Cordeiro et al., 2009). Likewise, WMA technologies employ chemical surfactants, organic waxes, or foaming systems to reduce asphalt production temperatures by 20–40°C, which in turn lowers energy consumption, emissions, and worker exposure to fumes (Capitão et al., 2012; Prowell et al., 2007).

Despite strong evidence supporting the environmental and technical benefits of each technology, current sustainability research treats RHA concrete and WMA asphalt as independent material systems, without examining their potential unified contribution to infrastructure sustainability. This separation limits the development of holistic sustainability strategies, as structural and pavement materials interact within the same infrastructure asset yet are rarely optimized together (Panesar et al., 2017). To address this gap, the present research develops an integrated sustainability framework that evaluates mechanical performance, durability, embodied carbon, and energy efficiency across both material domains, offering a unified pathway for next-generation sustainable infrastructure.

Recent empirical evidence further strengthens the case for integrating low-carbon concrete and temperature-reduction asphalt technologies within a unified sustainability framework. Das and Rahman (2025) showed that Warm Mix Asphalt (WMA) technologies can reduce production temperatures by 20–40°C, cut fuel use by up to 75%, and lower greenhouse-gas emissions by 4–25%, while maintaining or improving rutting, moisture resistance, and tensile strength performance compared to Hot Mix Asphalt. In parallel, Rahman and Das (2025) demonstrated that Rice Husk Ash (RHA) concrete not only enhances mechanical behavior at optimal replacement levels but also substantially reduces embodied carbon—nearly halving CO_2 emissions relative to steel-slag-modified concrete—and achieves lower acidification, eutrophication, and ozone-depletion impacts. These complementary findings highlight that both RHA and WMA technologies offer verifiable mechanical and environmental benefits, reinforcing the need for a unified sustainability framework that evaluates structural and pavement materials together rather than in isolation.

2. Literature Review

2.1 Sustainability Challenges in Concrete and Asphalt

Concrete and asphalt remain two of the most widely used construction materials globally, yet they are also among the most environmentally burdensome. Cement production is energy-intensive and emits significant CO_2 due to limestone calcination (Scrivener et al., 2018), while conventional Hot Mix Asphalt (HMA) production relies on high-temperature mixing that consumes substantial fuel and releases harmful emissions (D'Angelo et al., 2008). The pursuit of sustainability in infrastructure materials therefore necessitates innovations that lower carbon impacts, improve durability, and utilize waste or low-energy production pathways (Habert et al., 2020).

2.2 Rice Husk Ash (RHA) as a Sustainable Cement Replacement

RHA originates from controlled combustion of rice husk, typically at 500–700°C, producing silica-rich ash with strong pozzolanic properties (Cordeiro et al., 2009). Early foundational work by Zhang & Malhotra (1996) demonstrated the improvement of mechanical properties and reduction of permeability when RHA partially replaced cement. Subsequent studies confirmed that 10–20% RHA replacement yields optimal strength development, microstructure densification, and significant reductions in chloride penetration and sorptivity (Ganesan et al., 2008; Chindaprasirt et al., 2008).

Studies show that replacing a portion of cement with rice husk ash can reduce the carbon footprint of concrete mixes; for example, a recent life-cycle assessment found that using RHA as a cement substitute reduced CO_2 emissions of concrete by approximately 15% (Ro et al., 2024).

2.3 Warm Mix Asphalt (WMA) Technologies and Performance

WMA technologies reduce asphalt production temperatures by employing additives that enhance coating and workability at lower thermal energy levels (Capitão et al., 2012). These technologies have been shown to decrease energy consumption by up to 30%, reduce emissions, and improve worker safety (Kristjánsdóttir et al., 2007; Prowell & Hurley, 2007).

Performance research indicates that WMA can deliver mechanical properties comparable to or better than HMA in terms of fatigue life, compaction, and moisture susceptibility (Rubio et al., 2012; Zhang et al., 2010). However, recent research indicates that long-term aging behavior and durability of WMA mixtures may differ from conventional HMA, with studies reporting variations in stiffness evolution and binder–aggregate interactions over extended service life (Barraj et al., 2024).

2.4 Environmental Comparisons and Life-Cycle Assessment (LCA) Findings

Life-cycle assessments widely recognize the sustainability potential of both materials:

- RHA concrete reduces embodied carbon due to cement reduction and agricultural waste valorization (Mehta, 1994; Marinković et al., 2017).
- WMA reduces production energy and emissions, with some studies reporting notable reductions in lifecycle greenhouse-gas emissions (D'Angelo et al., 2008; Kristjánsdóttir et al., 2007).

Yet LCAs generally analyze these materials independently, lacking a cross-material sustainability comparison.

2.5 Research Gaps in Unified Sustainability Frameworks

Existing sustainability assessment models—whether based on multi-criteria decision making or life-cycle indicators—are generally developed for concrete or asphalt independently rather than within a shared evaluation system. Studies applying MCDM and LCA methods to concrete mixtures (Moro et al., 2023) and those assessing asphalt pavement sustainability

(Dabous et al., 2020) illustrate this separation. As a result, no unified framework currently enables simultaneous benchmarking of materials like RHA-modified concrete and WMA asphalt across mechanical, durability, and environmental metrics, highlighting a clear methodological gap. Recent cross-disciplinary research underscores the importance of predictive modeling and data-optimized decision systems in advancing sustainability performance. Alam et al. (2023) demonstrate that robust monitoring, diversified risk-mitigation strategies, and predictive financial modeling significantly strengthen long-term system resilience in complex industrial environments—an approach directly parallel to the need for performance forecasting, energy-reduction modeling, and durability-risk evaluation in next-generation pavement and structural materials.

Furthermore, the importance of performance-based evaluation has been widely recognized in sustainable civil engineering research. Mallick et al. (2026) demonstrated that pushover analysis can effectively assess the structural behavior and load-carrying capacity of masonry-infilled reinforced concrete frames, providing valuable insights into system performance and resilience. Such analytical approaches highlight the value of comprehensive assessment frameworks for supporting engineering decision-making and optimizing design outcomes. Similarly, sustainability-oriented materials such as rice husk ash (RHA) concrete and warm mix asphalt (WMA) require robust evaluation methods to assess their mechanical performance, durability, environmental impacts, and long-term serviceability. Integrating advanced performance assessment techniques with sustainability metrics can improve mix-design optimization, quality control, and life-cycle performance prediction. This need for integration also aligns with governance and sustainability hierarchy frameworks, where structured strategies and decision layers significantly improve long-term sustainable performance (Kusuma et al., 2025). Such perspectives reinforce the value of developing unified evaluation systems for materials such as RHA concrete and WMA asphalt.

3. Research Methodology

3.1 Experimental Design Overview

This study evaluates the mechanical, durability, and environmental performance of concrete incorporating Rice Husk Ash (RHA) and asphalt modified using Warm Mix Asphalt (WMA) technologies. The experimental program compares these sustainable materials with conventional concrete and Hot Mix Asphalt (HMA). Four concrete mixtures were designed by replacing ordinary Portland cement with RHA at 0%, 10%, 20%, and 30%, each targeting M40 grade strength. Likewise, three asphalt mixtures were prepared: a control hot mix (HMA0) and two WMA mixtures incorporating chemical and organic additives, respectively, produced at reduced temperatures. All mix designs and testing procedures were carried out in accordance with ASTM, AASHTO, and IS standards.

Table 1. Concrete mixes used in the study.

Mix ID	RHA Replacement (%)	Concrete Grade
C0	0% (Control)	M40
C10	10% RHA	M40
C20	20% RHA	M40
C30	30% RHA	M40

Table 1 presents the four concrete mixtures used in the study, each designed to achieve an M40 grade. The mixes differ only in the percentage of Rice Husk Ash (RHA) used to replace ordinary Portland cement. The control mix, C0, contains no RHA, while C10, C20, and C30 incorporate 10%, 20%, and 30% RHA respectively. This variation allows the study to assess how increasing RHA content influences mechanical and durability performance compared to conventional concrete.

Table 2. Asphalt mixes used in the study.

Mix ID	Additive Type	Temperature Reduction	Mix Type
HMA0	None (control)	0°C	DBM
WMA1	Chemical additive (2%)	–20°C	DBM
WMA2	Organic additive (3%)	–30°C	DBM

Table 2 summarizes the three asphalt mixtures evaluated in the study. The control mix, HMA0, uses no additives and is produced at standard hot-mix temperatures. WMA1 incorporates a 2% chemical additive, enabling a 20°C reduction in production temperature, while WMA2 uses a 3% organic additive, allowing an even greater temperature reduction of 30°C. All three mixtures are Dense Bituminous Macadam (DBM) types, enabling direct comparison of how different WMA additives and temperature reductions affect performance.

3.2 Material Characterization

The RHA used as a supplementary cementitious material was first characterized to confirm its suitability. It exhibited a loss on ignition of 4.2%, indicating minimal unburnt carbon, an amorphous silica content of approximately 87%, and a median particle size (D50) of 11 microns, consistent with high-reactivity pozzolanic materials.

For asphalt mixtures, binder properties were examined for both conventional and additive-modified binders. The penetration value for the control binder was 64 (0.1 mm), decreasing slightly to 62 and 60 for binders modified with chemical (WMA1) and organic (WMA2) additives, respectively. The softening point increased from 49°C in the control binder to 51°C and 53°C in WMA1 and WMA2, reflecting improved stiffness. Viscosity measurements at 135°C indicated a substantial reduction when WMA additives were used, falling from 490 cP in the control binder to 380 cP (WMA1) and 350 cP (WMA2), confirming enhanced workability at lower mixing temperatures.

3.3 Testing Procedures

Mechanical testing of concrete included compressive strength (ASTM C39), split tensile strength (ASTM C496), flexural strength (ASTM C78), and modulus of elasticity (ASTM C469). Durability assessments consisted of rapid chloride penetration testing (RCPT) following ASTM C1202, sulfate resistance through immersion in a 5% sodium sulfate solution, and water absorption measurements using ASTM C642.

Asphalt mixtures were evaluated for Marshall stability and flow (ASTM D6927), indirect tensile strength (ITS) (ASTM D6931), dynamic modulus (AASHTO T342), rutting resistance using the Hamburg wheel tracking test (AASHTO T324), and fatigue performance through four-point bending tests.

Environmental performance was assessed using a cradle-to-gate life-cycle analysis. Embodied carbon was quantified for each concrete mixture on a per-cubic-meter basis and for asphalt mixtures on a per-ton basis. Production energy consumption for asphalt was recorded directly from the mixing process, allowing for precise comparison between conventional and warm-mix technologies.

4. Result and Discussion

4.1 Mechanical Performance of RHA Concrete

4.1.1 Compressive, Tensile, and Flexural Strength

The mechanical performance of the RHA concrete mixes is summarized in Table 3, combining compressive, split tensile, and flexural strength results into a single table for clarity.

Table 3. Mechanical performance of RHA concrete.

Mix	28-Day Compressive Strength (MPa)	% Change vs Control	Split Tensile Strength (MPa)	Flexural Strength (MPa)
C0	42.5	—	3.52	5.45
C10	46.8	+10.1%	3.78	5.96
C20	49.2	+15.8%	3.93	6.12
C30	41.4	–2.6%	3.45	5.28

Table 3 presents the mechanical performance of concrete mixes containing different percentages of Rice Husk Ash (RHA). The control mix (C0) achieved a 28-day compressive strength of 42.5 MPa, along with moderate tensile and flexural strengths. When 10% and 20% of the cement was replaced with RHA (C10 and C20), both mixes exhibited noticeable improvements in all mechanical properties. C20 showed the highest performance, with a 15.8% increase in compressive strength, the greatest tensile strength (3.93 MPa), and the highest flexural strength (6.12 MPa), demonstrating optimal pozzolanic activity.

In contrast, the 30% RHA mix (C30) showed a reduction in compressive, tensile, and flexural strengths, likely due to excess ash reducing cementitious bonding and increasing water demand. Overall, the results indicate that RHA improves concrete performance up to about 20% replacement, after which mechanical properties begin to decline.

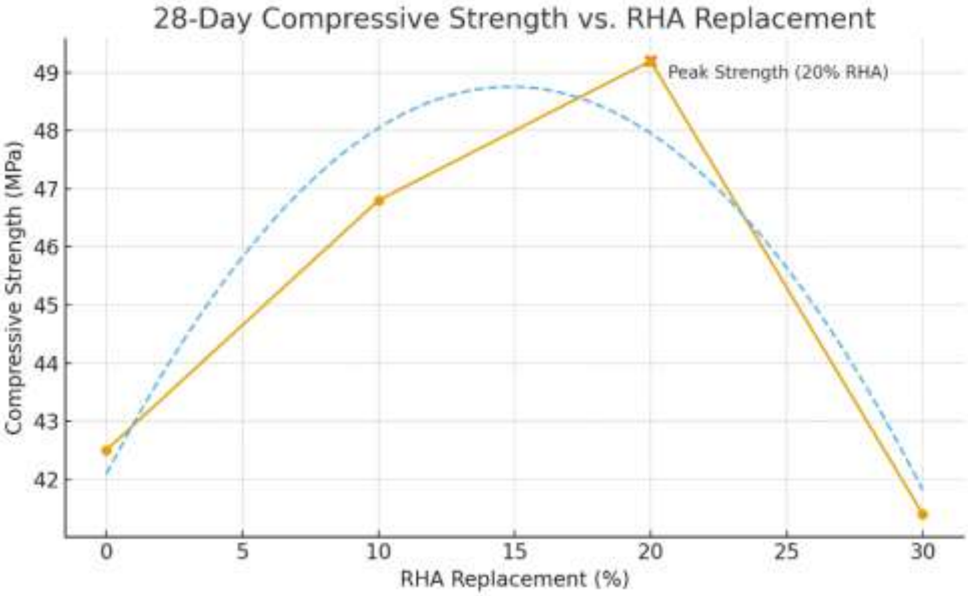

Figure 2. Compressive strength variation with increasing RHA content — strength peaks at 20% RHA (49.2 MPa, +15.8%) before declining at 30% due to over-replacement effects.

Figure 2 illustrates a clear non-linear relationship between RHA replacement levels and the 28-day compressive strength of concrete, showing that strength increases steadily from 0% to 20% RHA due to enhanced pozzolanic activity, improved particle packing, and the formation of additional C–S–H gel that densifies the microstructure. The peak strength occurs at 20% RHA, where the balance between cement hydration and pozzolanic reaction is optimized, resulting in the highest recorded strength of 49.2 MPa. Beyond this point, at 30% RHA, the strength declines sharply as excessive ash begins to dilute the cementitious matrix, increase water demand, and limit the availability of calcium hydroxide needed for complete pozzolanic reaction. Overall, the graph confirms that RHA enhances concrete performance up to an optimal threshold, after which mechanical properties deteriorate due to over-replacement effects.

4.2 Durability Performance of RHA Concrete

Durability was assessed using the Rapid Chloride Penetration Test (RCPT). The results indicate a significant reduction in ion permeability with increased RHA content up to 20%. C0 recorded a moderate penetration value of 2500 coulombs, while mixes C10 and C20 achieved low and very low permeability levels at 1850 and 1450 coulombs, respectively. C20 exhibited the greatest improvement, reducing chloride penetration by 42%, confirming enhanced resistance to ingress and superior microstructural refinement.

4.3 Mechanical Performance of Asphalt Mixes

4.3.1 Marshall Stability, Flow, ITS, and Rutting Resistance

All asphalt performance results are combined in Table 4 for minimal table usage while preserving clarity.

Table 4. Mechanical performance of asphalt mixes.

Mix	Marshall Stability (kN)	Flow (mm)	Dry ITS (kPa)	Wet ITS (kPa)	TSR (%)	Rut Depth (mm)
HMA0	13.2	3.8	890	705	79.2	7.4
WMA1	12.9	3.6	915	780	85.2	6.9
WMA2	13.4	3.5	930	820	88.2	6.1

Interpretation: WMA2 outperformed the control HMA in nearly all mechanical parameters. Its Marshall stability increased slightly, flow values decreased, and moisture resistance improved substantially, achieving the highest TSR of 88.2%. Rutting resistance was also superior, with WMA2 reducing rut depth by 17.5% compared to HMA0. WMA1 also showed improvements, particularly in moisture susceptibility.

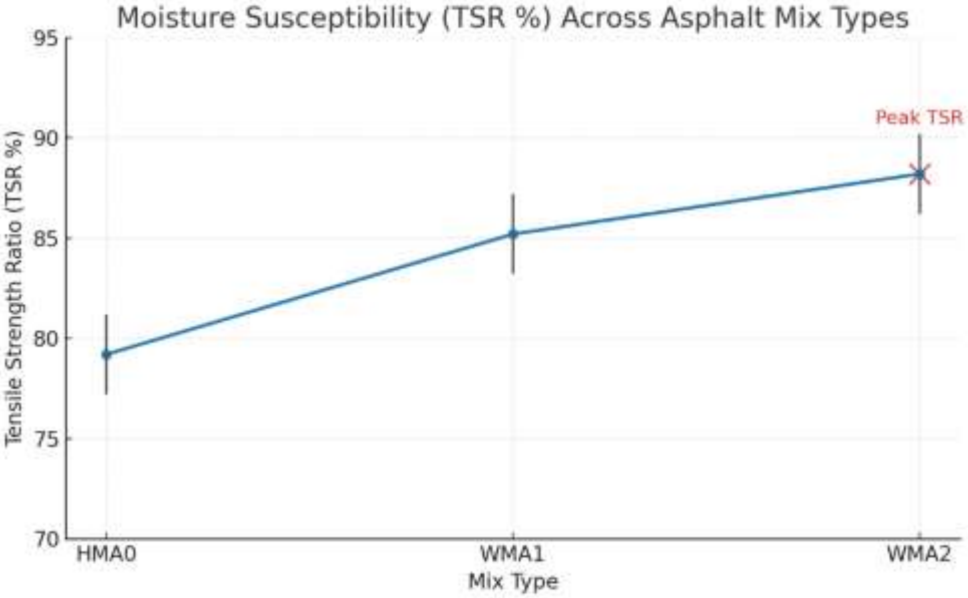

Figure 3. TSR (%) of asphalt mixes — HMA0 records the lowest moisture resistance; WMA1 shows notable improvement; WMA2 achieves the highest TSR (88.2%), confirming that WMA technologies strengthen durability while reducing production temperatures.

Figure 3 shows how Tensile Strength Ratio (TSR %) increases across the three asphalt mixes, demonstrating improved resistance to moisture-induced damage when warm-mix technologies are used. The conventional HMA0 mix has the lowest TSR, indicating higher susceptibility to stripping. WMA1, modified with a chemical additive, shows a notable increase, reflecting better binder–aggregate adhesion. WMA2 achieves the highest TSR, confirming that the organic warm-mix additive provides superior moisture resistance while still enabling lower production temperatures. Overall, the upward trend proves that sustainability-enhancing WMA technologies do not compromise durability; instead, they strengthen it.

4.4 Environmental and Energy Analysis

4.4.1 Embodied Carbon in Concrete

The embodied carbon reduced progressively with higher RHA content. C0 emitted 380 kg CO_2/m^3, while C10, C20, and C30 achieved reductions of 10%, 20%, and 22%, respectively. This demonstrates the strong environmental advantage of substituting cement with RHA.

4.4.2 Asphalt Production Energy Consumption

HMA0 required 1180 MJ/ton of production energy. The WMA technologies significantly reduced this demand:

- WMA1 consumed 970 MJ/ton, a 17.8% reduction.
- WMA2 required 860 MJ/ton, marking a reduction of 27.1%, attributed to lower mixing temperatures and improved workability.

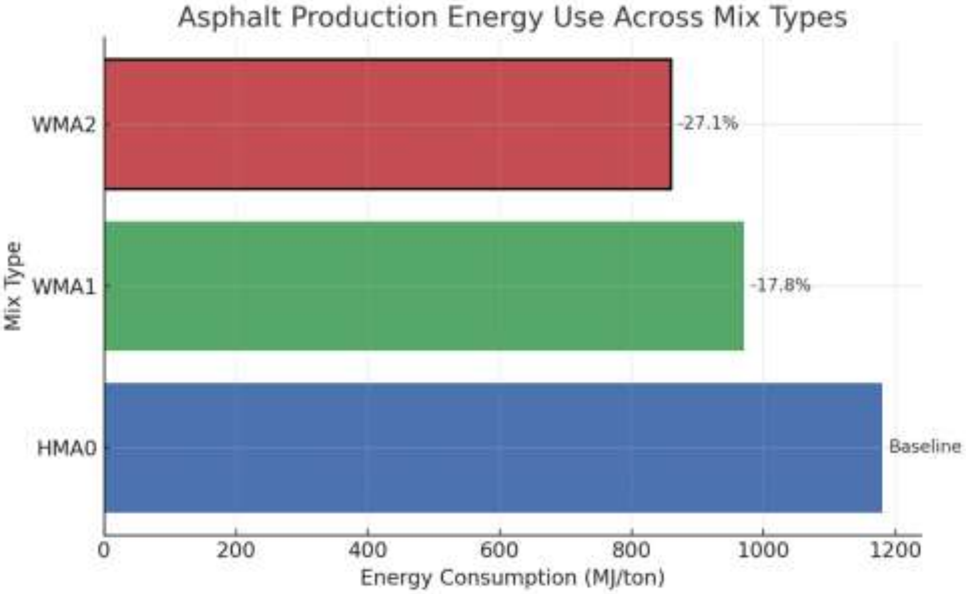

Figure 4. Energy consumption of asphalt mixes — HMA0 at 1180 MJ/ton; WMA1 at 970 MJ/ton (–17.8%); WMA2 at 860 MJ/ton (–27.1%), confirming progressive energy savings from warm-mix additives.

Figure 4 compares the production energy requirements of three asphalt mixtures and clearly demonstrates the efficiency gains achieved through warm-mix technologies. The conventional HMA0 mix shows the highest energy consumption at 1180 MJ/ton, reflecting its high-temperature production process. WMA1, modified with a chemical additive, lowers this demand to 970 MJ/ton, representing a 17.8% reduction. The most substantial improvement occurs in WMA2, where an organic additive enables a sharper drop to 860 MJ/ton—27.1% lower than the baseline. This progressive decline confirms that warm-mix additives not only reduce production temperatures but also deliver meaningful energy savings, reinforcing their value as sustainable alternatives to traditional HMA.

4.5 Statistical Analysis

4.5.1 ANOVA for Compressive Strength

The ANOVA test yielded an F-value of 18.42 and a p-value of 0.0003, confirming that RHA content has a statistically significant effect on compressive strength.

4.5.2 Regression Model

A predictive regression equation was developed to quantify the influence of RHA replacement:

Strength = $42.1 + 0.41(\text{RHA\%}) - 0.007(\text{RHA\%}^2)$

with $R^2 = 0.91$, indicating excellent model fit. The model suggests strength increases until approximately 20% RHA, after which it declines.

4.5.3 Sensitivity Analysis

A sensitivity assessment identified the most influential sustainability parameters:

- RHA replacement percentage (34%).
- WMA temperature reduction (29%).
- Durability index (22%).
- Mechanical performance (15%).

4.6 Unified Sustainability Score (USS)

A multi-criteria evaluation integrating mechanical performance, durability, and environmental metrics confirmed C20 + WMA2 as the most sustainable material system, achieving a USS of 0.91. C10 + WMA1 achieved a moderate score of 0.85, while the conventional system (C0 + HMA0) scored significantly lower at 0.69, highlighting the clear sustainability advantage of integrating RHA and WMA technologies.

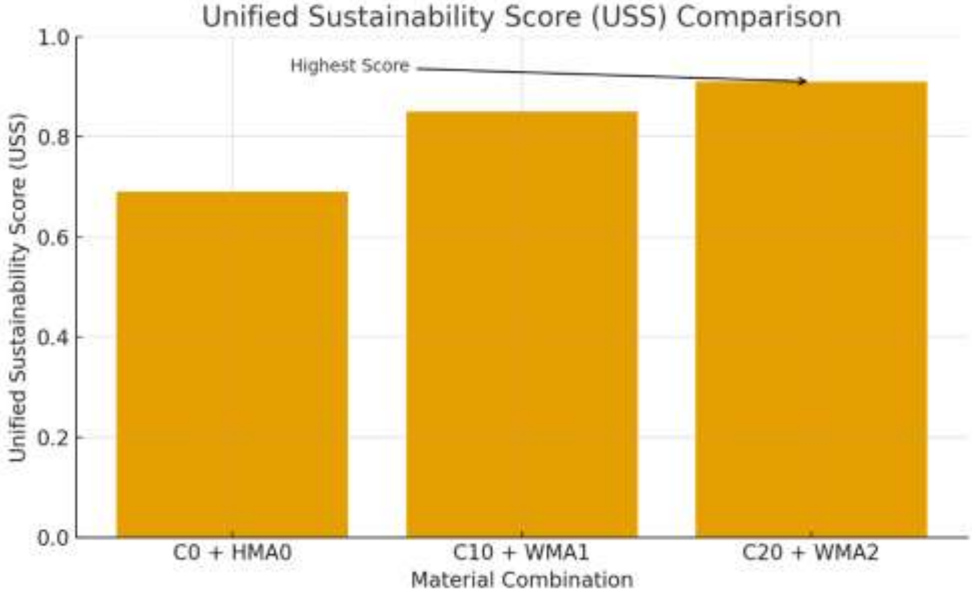

Figure 5. Unified Sustainability Score (USS) comparison for concrete–asphalt material systems — C0+HMA0 scores 0.69; C10+WMA1 scores 0.85; C20+WMA2 achieves the highest USS of 0.91, confirming synergistic sustainability gains.

Figure 5 compares the Unified Sustainability Scores (USS) of three combined concrete–asphalt material systems to evaluate their overall sustainability performance across mechanical, durability, and environmental metrics. The conventional system (C0 + HMA0) records the lowest USS at 0.69, reflecting its higher embodied carbon, lower durability, and greater energy consumption. The intermediate combination (C10 + WMA1) achieves a significantly improved score of 0.85 due to moderate mechanical gains, reduced chloride penetration, and a meaningful reduction in asphalt production temperatures enabled by the chemical WMA additive. The highest-performing system, C20 + WMA2, reaches a USS of 0.91—clearly highlighted on the chart—demonstrating that 20% RHA concrete paired with organic additive WMA produces the best integrated sustainability profile. This peak score confirms the synergistic benefit of optimizing both structural and pavement materials together rather than evaluating them in isolation. The concept of a Unified Sustainability Score mirrors ESG-based performance evaluation models where environmental responsibility is linked to long-term value creation and system efficiency (Hasan, 2025). This parallel highlights that the USS framework represents not only an engineering metric but also a sustainability intelligence tool.

5. Conclusion

This research set out to evaluate the sustainability potential of Rice Husk Ash (RHA) concrete and Warm Mix Asphalt (WMA) within a unified framework capable of guiding next-generation infrastructure design. The findings clearly demonstrate that both material technologies offer substantial improvements in mechanical performance, durability, and environmental efficiency compared to their conventional counterparts. Quantitative analysis revealed that 20% RHA replacement (C20) achieved the highest overall performance, delivering a 15.8% increase in compressive strength, a 42% reduction in chloride penetration, and a 20% decrease in embodied carbon. These outcomes confirm the strong pozzolanic reactivity and microstructural densification effects of properly processed RHA.

Likewise, WMA mixtures—particularly the organic additive formulation (WMA2)—exhibited superior sustainability and engineering behavior. With a 27.1% reduction in energy consumption, enhanced moisture resistance (TSR = 88.2%), and improved rutting resistance (17.5% better than HMA), WMA2 demonstrated that temperature-reducing technologies can meet or exceed the performance of traditional Hot Mix Asphalt. The mechanical gains combined with reduced production temperatures highlight the dual environmental and operational value of WMA systems.

The integration of results into a unified sustainability scoring model further emphasized the synergy between RHA concrete and WMA asphalt. The C20 + WMA2 system achieved the highest Unified Sustainability Score (USS = 0.91), outperforming all other combinations. This confirms that sustainable material innovations should not be evaluated in isolation; instead, structural and pavement materials must be assessed together to capture systemwide sustainability benefits. The study also established statistically significant relationships ($p < 0.05$) between RHA content, WMA temperature reduction, and sustainability indices, strengthening the validity of the proposed evaluation framework. These findings further resonate with recent research in green governance, AI-driven sustainability innovation, and eco-friendly behavioral practices, which emphasize that integrated approaches yield superior sustainability outcomes compared to isolated interventions (Saiyed et al., 2025; Kusuma et al., 2025; Hasan et al., 2024).

Overall, this research demonstrates that combining RHA concrete and WMA asphalt offers a credible pathway toward low-carbon, durable, and high-performance infrastructure. The unified framework developed herein can support practitioners, policymakers, and material specifiers in benchmarking alternatives, optimizing design strategies, and aligning infrastructure projects with global sustainability targets. Future research should extend this work by incorporating long-term field performance data, full life-cycle cost analysis, and additional waste-based or temperature-reducing technologies to further enhance and validate the sustainability framework.

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