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Comparative Study of Warm Mix vs Hot Mix Asphalt Performance

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Abstract

This research paper presents a comprehensive comparative analysis of Warm Mix Asphalt (WMA) and Hot Mix Asphalt (HMA) technologies for flexible pavement applications. Hot Mix Asphalt has served as the industry standard for road construction for decades, prized for its mechanical strength and durability. However, the substantial environmental footprint of HMA production requiring temperatures of 150–170°C has prompted the development of WMA, which reduces production and compaction temperatures by 20–40°C through the use of additives such as Sasobit or water-foaming techniques. This study evaluates both mix types using the Marshall Mix Design methodology, with laboratory specimens prepared at their respective mixing and compaction temperatures. A battery of standardized tests including Marshall Stability, Indirect Tensile Strength (ITS), Moisture Susceptibility (TSR), Wheel Tracking, and RTFO Aging was conducted under identical conditions. Emissions and energy data were also analysed to quantify environmental benefits. Results indicate that WMA with 1.5% Sasobit additive achieves mechanical performance comparable to HMA: Marshall Stability of 11.5 kN vs. 12.0 kN, ITS of 620 kPa vs. 650 kPa, and TSR values above 80% for both mixes. WMA demonstrated approximately 30% reduction in fuel consumption and CO_2 emissions, 20% reduction in NOx, and 50% reduction in VOCs. Rutting resistance was marginally lower in WMA (4.0 mm vs. 3.5 mm rut depth) but remained within acceptable limits. These findings support the adoption of WMA as a technically viable, environmentally superior, and economically competitive alternative to conventional HMA.

Keywords: *Warm Mix Asphalt, Hot Mix Asphalt, Marshall Stability, Indirect Tensile Strength, Rutting Resistance, Sasobit, Greenhouse Gas Emissions, Sustainable Pavement, Flexible Pavement.*

1. Introduction

Roads constitute the backbone of modern societies, enabling trade, mobility, and communication across urban and rural landscapes. Flexible pavements constructed primarily using bituminous asphalt mixes have long been the preferred choice in pavement engineering due to their adaptability, cost-effectiveness, and capacity to withstand dynamic traffic loads. Hot Mix Asphalt (HMA) has been the cornerstone of this system for over a century, providing outstanding mechanical strength and durability across diverse climatic conditions.

Despite its proven track record, conventional HMA production is associated with significant environmental and occupational concerns. The mixing and compaction of HMA requires sustained temperatures between 150°C and 170°C, resulting in high fuel consumption, elevated greenhouse gas emissions particularly carbon dioxide (CO2) and nitrogen oxides (NOx) and occupational exposure to heat and harmful fumes. With growing global emphasis on sustainability, regulatory pressure, and worker health standards, the industry has increasingly sought alternatives that do not compromise structural performance.

Warm Mix Asphalt (WMA) emerged in the early 2000s in Europe as a direct response to these challenges. By incorporating chemical additives, organic waxes, or water-foaming techniques into the bituminous mix, WMA enables production, placement, and compaction at temperatures 20–40°C lower than conventional HMA. This seemingly modest reduction in production temperature translates into meaningful environmental and operational gains: reduced fuel use, lower emissions, safer worksite conditions, extended paving seasons, and greater scope for incorporating Reclaimed Asphalt Pavement (RAP).

Despite these advantages, questions persist about the long-term durability and structural integrity of WMA, particularly under heavy traffic loading and extreme climatic variability. Preliminary research has been promising, but the pavement engineering community requires rigorous, standardized comparisons between WMA and HMA to guide policy, specification, and engineering practice. This paper addresses that need by combining laboratory testing with environmental and economic analysis, situating the findings within the broader objective of sustainable infrastructure development.

1.1 Significance of the Study

The significance of this comparative study extends beyond engineering performance metrics. Modern infrastructure planning increasingly demands that pavement technologies be assessed across three interconnected dimensions: sustainability (reduced carbon footprint and energy consumption), environmental responsibility (pollution reduction and worker health protection), and economic efficiency (life-cycle value and public investment optimization). This study integrates all three dimensions, providing a holistic assessment that can inform evidence-based decision-making by engineers, contractors, and policymakers.

1.2 Objectives

The specific objectives of this study are:

- To evaluate and compare the mechanical properties (stability, flow, tensile strength) of WMA and HMA using standardized laboratory tests.
- To assess the durability characteristics of both mixes, including resistance to rutting, moisture damage, and short-term aging.
- To quantify the environmental impact of WMA versus HMA production in terms of fuel consumption and emissions of CO2, NOx, and VOCs.
- To conduct a comparative economic analysis considering production costs, fuel savings, and life-cycle cost implications.
- To evaluate the influence of the Sasobit additive on WMA performance relative to baseline HMA.
- To develop evidence-based recommendations for the adoption of WMA technology in flexible pavement construction.

2. Literature Review

The body of research on asphalt pavement technologies reflects a sustained dialogue among engineers, researchers, and policymakers navigating the dual imperatives of structural performance and environmental responsibility. This section synthesizes key findings from peer-reviewed literature, national standards, government reports, and field case studies.

2.1 Hot Mix Asphalt: Established Standard

HMA has been the dominant material for road construction for over a century. Composed of bitumen and mineral aggregates heated to 150–170°C, HMA achieves the viscosity and workability necessary for thorough aggregate coating and effective compaction. Roberts et al. (1996) document HMA's proven resistance to rutting and fatigue cracking, attributing its longevity to the cohesive strength developed through high-temperature processing. The material has demonstrated consistent performance under heavy traffic on highways, urban roads, and airport runways worldwide.

Notwithstanding its performance credentials, HMA's environmental footprint has attracted growing scrutiny. The combustion of large quantities of fuel to sustain production temperatures releases substantial quantities of CO2, NOx, and volatile organic compounds (VOCs). Workers on HMA construction sites are exposed to elevated temperatures and toxic fumes, raising occupational health concerns. Furthermore, the limited working window of HMA which must be laid and compacted before cooling imposes logistical constraints on large paving projects and restricts construction in colder weather.

2.2 Warm Mix Asphalt: Innovation and Adoption

WMA originated in Europe in the late 1990s, driven by environmental legislation and energy cost pressures. The technology enables asphalt production and compaction at temperatures typically between 110°C and 140°C through three principal mechanisms: foaming technology (e.g., Astec Double-Barrel Green process), organic additives (e.g., Sasobit synthetic wax), and chemical surfactants (e.g., Evotherm, Rediset). By 2004, pilot trials in the United States demonstrated that WMA could deliver mechanical properties comparable to HMA, accelerating global adoption (NAPA, 2025).

Zaumanis, Mallick, and Frank (2013) provide a comprehensive overview of WMA technologies, cataloguing fuel savings of up to 30%, significant reductions in greenhouse gas emissions, and improved paving flexibility. Leng and Liu (2016) document environmental impact reductions of 10–15% at the mixing and production stage for a 40°C temperature reduction. Kassem and Free (2019) specifically evaluate Sasobit's impact on WMA performance, reporting comparable stiffness modulus and shear fatigue response to HMA when the additive is properly dosed.

2.3 Performance Comparison: WMA vs HMA

Comparative studies have consistently shown that WMA can match HMA in most mechanical performance categories when appropriate additives and mix design procedures are employed. Key findings include:

- Stability: HMA exhibits marginally higher Marshall Stability values, but the difference is small and WMA readily meets standard specifications (Airey & Collop, 2008).
- Moisture Susceptibility: WMA is inherently more susceptible to moisture damage due to lower production temperatures affecting binder-aggregate adhesion. Anti-stripping additives such as Evotherm and Rediset effectively mitigate this vulnerability.
- Rutting Resistance: HMA has traditionally demonstrated superior rutting resistance, but the inclusion of organic wax additives (e.g., Sasobit) substantially closes this gap.
- Fatigue Life: Properly designed WMA can match HMA fatigue performance. WMA's lower production temperature may, in fact, reduce binder aging and thereby extend long-term fatigue life (Guo & You, 2014).
- Compaction: WMA's lower viscosity at compaction temperature can enhance density and reduce air voids, potentially improving long-term durability.

2.4 Gaps in the Literature

Despite extensive research, several important knowledge gaps remain. Long-term field performance data for WMA under extreme traffic and climatic conditions is scarce. Studies comparing the performance of different WMA additives under identical conditions are limited. The integration of high RAP content with WMA technologies while theoretically beneficial lacks rigorous long-term validation. Additionally, the absence of universally accepted design standards inhibits consistent global adoption. This study addresses several of these gaps through controlled laboratory testing and systematic analysis.

3. Materials and Methods

3.1 Materials

3.1.1 Bitumen

VG-30 viscosity-grade bitumen, sourced from a local authorized refinery, was selected as the binder for both HMA and WMA mixes. VG-30 is widely specified in Indian road construction standards due to its balanced viscosity-temperature characteristics. The bitumen was characterized using standard IS methods, with results presented in Table 1.

Table 1: Physical Properties of VG-30 Bitumen

Property	Test Value	Standard
Penetration at 25°C (mm)	60	IS 1203
Softening Point (°C)	47	IS 1205
Ductility (cm)	>75	IS 1208
Specific Gravity	1.03	IS 1202
Absolute Viscosity (Poise)	2400	IS 1206

3.1.2 Aggregates

Crushed granite aggregates from a local quarry were used, conforming to MORTH specifications for Dense Bituminous Macadam (DBM). Aggregate properties were determined through a comprehensive testing programme.

Table 2: Physical Properties of Crushed Granite Aggregates

Property	Test Value	Specification Limit
Aggregate Impact Value	18%	< 30%
Los Angeles Abrasion Value	23%	< 30%
Specific Gravity	2.65	
Water Absorption	0.8%	< 2%
Flakiness & Elongation Index	Within limits	IS 2386

3.1.3 Filler
Hydrated lime was employed as the mineral filler, with fineness exceeding 90% passing the 75 µm sieve. Lime filler was selected for its adhesion-enhancing properties and ability to reduce moisture susceptibility in bituminous mixes.

3.1.4 WMA Additive
Sasobit, a synthetic Fischer-Tropsch wax, was selected as the WMA additive. Sasobit functions by reducing bitumen viscosity at mixing and compaction temperatures without compromising binder performance at service temperatures. A dosage of 1.5% by weight of bitumen was adopted, consistent with Kassem and Free (2019). Sasobit was blended into the bitumen prior to aggregate mixing.

3.2 Mix Design Approach
Both HMA and WMA mixtures were designed using the Marshall Mix Design Method, the standard procedure specified by MORTH for Indian road construction. The method entails preparation of specimens at varying bitumen contents (4.0%, 4.5%, 5.0%, 5.5%, and 6.0% by weight of total mix), with 75 blows per face using the Marshall Compactor. The Optimum Bitumen Content (OBC) is selected based on maximum stability, acceptable flow (2–4 mm), and air voids within the 3–5% range.

Mixing and compaction temperatures differed between the two mix types as indicated in Table 3.

Table 3: Mixing and Compaction Temperatures

Mix Type	Mixing Temperature	Compaction Temperature
HMA	160–170°C	150–160°C
WMA (with 1.5% Sasobit)	130–140°C	120–130°C

3.3 Aggregate Gradation
Aggregate gradation was verified by sieve analysis in accordance with MORTH DBM specifications. Table 4 presents the target and achieved gradations.

Table 4: Aggregate Gradation MORTH DBM Specification vs. Obtained

Sieve Size (mm)	% Passing (Morth)	% Passing (Obtained)
26.5	100	100
19	90–100	95
13.2	70–85	75

9.5	55–70	60
4.75	35–50	45
2.36	20–35	30
0.6	8–20	12
0.3	4–10	6
0.075	2–6	4

3.4 Laboratory Testing Programme

A comprehensive suite of standardized tests was conducted on both HMA and WMA specimens to evaluate mechanical properties, durability, and environmental performance. All tests were performed on a minimum of three replicates per mix type to ensure statistical reliability. Test equipment was calibrated prior to each test session, and ambient laboratory conditions were controlled throughout.

Table 5: Laboratory Testing Programme

Test	Standard	Parameter Evaluated
Marshall Stability & Flow	ASTM D6927	Load-bearing capacity and deformation
Indirect Tensile Strength (ITS)	ASTM D6931	Tensile strength and cracking resistance
Moisture Susceptibility (TSR)	AASHTO T283	Resistance to water-induced damage
Wheel Tracking (Rutting)	AASHTO T324	Permanent deformation under repeated load
Aging Test (RTFO)	ASTM D2872	Short-term binder oxidation
Emission & Energy Analysis	EPA/NAPA Protocols	CO2, NOx, VOC, fuel consumption

4. Results and Discussion

4.1 Determination of Optimum Bitumen Content

Marshall specimens were prepared at five bitumen contents (4.0–6.0%) for both HMA and WMA. Stability, flow, bulk density, and air voids were measured for each specimen set. Table 6 summarizes key results across the bitumen content range.

Table 6: Marshall Test Results at Varying Bitumen Contents

Bitumen Content (%)	HMA Stability (kN)	WMA Stability (kN)	Flow HMA (mm)	Flow WMA (mm)	Air Voids HMA (%)	Air Voids WMA (%)
4.0	9.5	9.0	2.5	2.7	5.6	5.8
4.5	11.0	10.7	3.0	3.2	4.3	4.5
5.0	12.0	11.5	3.5	3.6	3.5	3.7
5.5	11.8	11.2	4.0	4.2	3.0	3.1
6.0	10.0	9.5	4.5	4.7	2.5	2.7

Applying the selection criteria of maximum stability, air voids within 3–5%, and flow within 2–4 mm, the Optimum Bitumen Content (OBC) was determined to be 5.0% for both HMA and WMA. This result demonstrates that the incorporation of Sasobit does not alter the optimal binder demand of the mixture.

4.2 Marshall Stability and Flow

Table 7: Marshall Stability and Flow Results at OBC

Mix Type	OBC (%)	Stability (kN)	Flow (mm)	Air Voids (%)
HMA	5.0	12.0	3.5	3.5
WMA (1.5% Sasobit)	5.0	11.5	3.6	3.7

Both mixes demonstrate comparable Marshall Stability values. HMA achieves 12.0 kN against WMA's 11.5 kN a difference of only 4.2% well within the variability typical of Marshall testing. Flow values of 3.5 mm (HMA) and 3.6 mm (WMA) both satisfy the 2–4 mm specification, confirming adequate flexibility. Air voids are marginally higher in WMA (3.7% vs. 3.5%), potentially attributable to slightly reduced compaction efficiency at lower temperatures, but both values remain within the acceptable 3–5% range. These results confirm that WMA with Sasobit meets the structural performance requirements for pavement design equivalent to HMA.

4.3 Indirect Tensile Strength and Moisture Susceptibility

Table 8: Indirect Tensile Strength and TSR Results

Mix Type	ITS Dry (kPa)	ITS Conditioned (kPa)	TSR (%)
HMA	650	540	83
WMA (1.5% Sasobit)	620	510	82

Dry ITS values for HMA (650 kPa) and WMA (620 kPa) are closely matched, with the 4.6% difference indicating comparable tensile strength and cracking resistance. Following moisture conditioning (freeze-thaw), both mixes experience a reduction in ITS, yielding TSR values of 83% (HMA) and 82% (WMA). Both values exceed the 80% threshold widely specified in pavement standards as indicative of adequate moisture resistance. The negligible difference in TSR confirms that Sasobit does not compromise the moisture resistance of WMA, and that the additive facilitates adequate binder-aggregate adhesion even at reduced mixing temperatures.

4.4 Rutting Resistance

Table 9: Wheel Tracking Test Results Rut Depth at 10,000 Cycles

Mix Type	Rut Depth after 10,000 Cycles (mm)	Assessment
HMA	3.5	Good within acceptable limits
WMA (1.5% Sasobit)	4.0	Acceptable within limits; Sasobit improves rut resistance vs. non-additive WMA

HMA exhibits marginally superior rutting resistance (3.5 mm vs. 4.0 mm rut depth), consistent with the established understanding that higher production temperatures promote greater binder stiffness at service temperatures. However, WMA's rut depth remains within commonly accepted limits, and the Sasobit additive which crystallises within the binder matrix at service temperatures to enhance stiffness substantially improves WMA's rutting resistance compared to non-additive warm mix formulations reported in the literature (Airey & Collop, 2008). Further optimization of Sasobit dosage may close the residual gap.

4.5 Aging Characteristics (RTFO)

Table 10: RTFO Aging Results Binder Properties Pre- and Post-Aging

Parameter	Unaged	Aged (RTFO)	Change (%)
Penetration HMA (mm)	60	45	-25
Penetration WMA (mm)	62	48	-22
Softening Point HMA (°C)	47	54	+15
Softening Point WMA (°C)	46	53	+15

Rolling Thin Film Oven (RTFO) results reveal comparable aging behaviour between HMA and WMA binders. Both binders experience a 25% and 22% reduction in penetration, respectively, and a 15% increase in softening point following short-term aging indicating similar susceptibility to oxidative hardening. The marginally lower penetration reduction in WMA (22% vs. 25%) may reflect a slight protective effect of the Sasobit additive against thermal oxidation, consistent with the lower production temperatures that reduce initial binder aging during plant mixing. Overall, aging characteristics do not represent a differentiating factor between the two technologies under short-term conditions.

4.6 Environmental Performance: Emissions and Energy

Table 11: Emission and Energy Consumption Comparison HMA vs. WMA

Parameter	HMA	WMA	Reduction (%)
Fuel Consumption (L/ton)	6.0	4.2	30
CO2 Emissions (kg/ton)	15.0	10.5	30
NOx Emissions (kg/ton)	0.60	0.48	20
VOC Emissions (kg/ton)	0.30	0.15	50

The environmental performance of WMA is compelling. A 30°C reduction in production temperature translates directly into a 30% reduction in fuel consumption and commensurate CO2 emissions representing a substantial contribution to decarbonising road construction. NOx reductions of 20% and VOC reductions of 50% improve ambient air quality around asphalt plants and construction sites, reducing health risks for workers and nearby communities. These findings are consistent with NAPA and FHWA reported emission reduction ranges, and with the comprehensive review by Leng and Liu (2016). In the context of India's national climate commitments and growing regulatory attention to construction-sector emissions, these gains represent a meaningful policy dividend from WMA adoption.

4.7 Synthesis: Comparative Performance Summary

Table 12: Consolidated Performance Comparison HMA vs. WMA

Performance Parameter	HMA	WMA	Verdict
Marshall Stability	12.0 kN	11.5 kN	Both meet criteria; ~4% difference
Indirect Tensile Strength	650 kPa	620 kPa	Comparable; both acceptable
Moisture Resistance (TSR)	83%	82%	Both >80%; equivalent
Rutting Resistance	3.5 mm	4.0 mm	HMA slightly better; WMA acceptable
Short-Term Aging	Comparable	Comparable	No significant difference
Fuel Consumption	6.0 L/ton	4.2 L/ton	WMA 30% more efficient
CO2 Emissions	15.0 kg/ton	10.5 kg/ton	WMA 30% lower
NOx Emissions	0.60 kg/ton	0.48 kg/ton	WMA 20% lower
VOC Emissions	0.30 kg/ton	0.15 kg/ton	WMA 50% lower
Worker Safety	Moderate risk	Lower risk	WMA superior

5. Environmental and Economic Analysis

5.1 Environmental Impact

Manufacturing and mixing operations account for approximately 97% of total greenhouse gas emissions across the asphalt pavement life cycle, with mixing alone representing approximately 54% of this total (Leng & Liu, 2016). By reducing production temperatures by 20–40°C, WMA directly targets the most carbon-intensive phase of the pavement life cycle. Life Cycle Assessment (LCA) studies corroborate these laboratory findings: one comprehensive LCA found that while resource consumption across the full life cycle was broadly comparable between

WMA and HMA, WMA demonstrated significantly lower global warming potential and PM2.5 emissions at equivalent pavement performance (Guo & You, 2014).

Worker health benefits are an additional, often overlooked, environmental gain. Lower production and compaction temperatures reduce exposure to polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds, and high-heat conditions occupational hazards that contribute to respiratory disease and heat-related illness among paving crews. Furthermore, reduced fume emissions make WMA more suitable for deployment near urban populations, reducing nuisance and health externalities from asphalt plant operations.

Caveats must be acknowledged. If WMA's long-term durability proves inferior to HMA leading to more frequent maintenance cycles the initial environmental gains may be partially or wholly offset by additional construction-phase emissions over the pavement's service life. Additionally, some WMA additives have high embodied energy or environmental impact in their production phase (e.g., synthetic zeolite), which must be factored into comprehensive LCA comparisons. Careful additive selection and rigorous quality control during production are therefore essential to realising the full environmental potential of WMA.

5.2 Economic Analysis

The economic case for WMA is multifaceted. Direct savings arise from reduced fuel consumption typically 20–30% lower than HMA which translates into cost reductions of approximately USD 1.61–4.00 per tonne in various reported studies, depending on local fuel prices and the magnitude of temperature reduction. In high-fuel-cost environments such as India, these savings can be substantial over the course of a major paving programme.

Indirect economic benefits include extended paving seasons in cooler climates, longer haul distances enabled by slower cooling, and reduced traffic disruption through faster pavement opening. Plant wear and maintenance costs may also decline with lower operating temperatures. WMA's compatibility with higher RAP content further enhances economic appeal by reducing virgin material demand and associated procurement costs.

The primary cost offset is the price of WMA additives and any required plant modifications. Sasobit, for example, adds a small per-tonne cost that must be weighed against fuel savings. Over a pavement's full life cycle, if WMA performs equivalently to HMA as this study's laboratory evidence suggests the total life-cycle cost of WMA is projected to be comparable to or lower than HMA, particularly in fuel-cost-sensitive markets. Formal life-cycle cost analysis incorporating local factor prices is recommended before large-scale procurement decisions.

6. Discussion

The laboratory evidence presented in this study establishes that WMA with Sasobit additive achieves mechanical performance comparable to conventional HMA across all tested parameters. The marginal differences observed a 4.2% lower Marshall Stability, 0.5 mm greater rut depth after 10,000 loading cycles are unlikely to be structurally significant for the majority of pavement applications and can likely be further minimised through additive dosage optimisation and refined compaction protocols.

The environmental performance differential is, by contrast, both statistically significant and practically meaningful. A 30% reduction in fuel consumption and CO_2 emissions per tonne of asphalt produced represents a substantial contribution to decarbonisation in the construction sector. In the context of India's infrastructure expansion with thousands of kilometres of new road construction planned under national programmes widespread adoption of WMA could represent a transformative reduction in the construction sector's carbon footprint.

However, this study's scope is constrained by its reliance on laboratory testing and short-term case studies. Real-world performance under diverse traffic loading regimes, extended temperature cycling, and multi-year service exposure may reveal performance disparities not captured in laboratory conditions. The literature identifies early-age durability and moisture sensitivity as WMA's most vulnerable performance dimensions, particularly in formulations without anti-stripping additives. Future research should prioritise long-term field performance monitoring to validate laboratory findings and establish the boundary conditions under which WMA can be confidently specified.

The selection of additive type also warrants further investigation. This study employed Sasobit as the sole WMA additive; alternative additives (e.g., Evotherm, Rediset, foaming techniques) may offer different performance-cost-environmental profiles suited to different project contexts. A systematic comparison of WMA additives under identical testing conditions would substantially strengthen the evidence base for specification writers and procurement authorities.

7. Conclusions

This study has presented a comprehensive laboratory-based comparison of Warm Mix Asphalt and Hot Mix Asphalt, incorporating mechanical performance testing, aging characterisation, and environmental impact quantification. The following conclusions are drawn:

- WMA with 1.5% Sasobit additive achieves Marshall Stability (11.5 kN) and Indirect Tensile Strength (620 kPa) values closely comparable to HMA (12.0 kN and 650 kPa, respectively), meeting structural requirements for flexible pavement applications.
- Both mixes exhibit Tensile Strength Ratios exceeding 80%, confirming acceptable moisture resistance. The Sasobit additive effectively compensates for the inherent moisture susceptibility risk associated with lower-temperature WMA production.
- WMA demonstrates slightly higher rut depth (4.0 mm vs. 3.5 mm after 10,000 loading cycles) but remains within acceptable limits. The Sasobit additive improves rutting resistance relative to non-additive WMA formulations.
- Short-term aging behaviour (RTFO) is broadly equivalent between the two mix types, indicating comparable binder durability under oxidative conditions.

- WMA production results in approximately 30% reduction in fuel consumption and CO_2 emissions, 20% reduction in NOx, and 50% reduction in VOCs relative to HMA representing substantial environmental and occupational health benefits.
- The Optimum Bitumen Content for both mixes is 5.0%, confirming that Sasobit addition does not alter binder demand. Comparable mix design parameters support the case for a smooth transition from HMA to WMA specifications.
- The overall evidence supports WMA as a technically viable, environmentally superior, and economically competitive alternative to conventional HMA for most flexible pavement applications.

8. Recommendations

Based on the study's findings, the following recommendations are proposed for the pavement engineering community, infrastructure agencies, and policymakers:

- Accelerate WMA Adoption: Road agencies and contractors in India and other developing economies should undertake pilot projects to introduce WMA technology into standard pavement construction programmes, prioritising projects where environmental and occupational health benefits are most valued.
- Additive Research and Optimisation: Further research is warranted into the optimal dosage of Sasobit and the comparative performance of alternative WMA additives (e.g., Evotherm, Rediset, water-foaming) across diverse climatic and traffic conditions.
- Long-Term Field Monitoring: Laboratory findings should be validated through structured field trials incorporating performance monitoring over a minimum five-year period, with particular attention to rutting, fatigue cracking, and moisture-related distress under local climatic and traffic conditions.
- RAP Integration: Research into the combination of WMA and high-content RAP should be prioritised to amplify both environmental and economic benefits through simultaneous reduction in virgin material demand and production temperatures.
- Specification Development: Specification bodies (MORTH, IRC, state transport departments) should develop or adopt WMA-specific design standards, quality control protocols, and performance verification criteria to facilitate consistent national adoption.
- Life-Cycle Cost Assessment: Infrastructure agencies should incorporate formal life-cycle cost and life-cycle assessment methodologies into pavement technology selection decisions, ensuring that environmental and long-term economic factors receive appropriate weight alongside upfront construction costs.
- Capacity Building: Training programmes for plant operators, paving crews, and site engineers should be developed to ensure correct handling, mixing, and compaction of WMA materials, which differ from HMA in temperature-sensitive ways.

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