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Performance comparison of cold mix asphalt vs. hot mix asphalt for low-traffic roads in warm climates

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Abstract
Cold Mix Asphalt (CMA) and Hot Mix Asphalt (HMA) are commonly used flexible pavement materials, yet their suitability for low-traffic roads in warm climatic regions remains a subject of practical and economic importance. Warm climates accelerate asphalt aging, influence moisture susceptibility, and intensify rutting potential, thereby affecting pavement durability and lifecycle performance. This research presents a comparative evaluation of CMA and HMA with specific reference to low-traffic road applications in warm environments. The analysis focuses on mechanical performance, construction feasibility, environmental impact, and cost-effectiveness under realistic service conditions. Laboratory-based indicators such as stability, stiffness, moisture resistance, and temperature susceptibility are synthesized with field performance evidence reported in previous studies. CMA demonstrates advantages in terms of lower production energy, reduced greenhouse gas emissions, improved workability at ambient temperatures, and suitability for remote or resource-constrained regions. However, its comparatively lower early strength and higher sensitivity to moisture pose limitations under certain loading and drainage conditions. HMA, in contrast, exhibits superior load-bearing capacity, rutting resistance, and long-term structural integrity, but requires higher production temperatures, greater energy input, and increased construction costs. In warm climates, the performance gap between CMA and HMA narrows due to enhanced curing rates and improved binder activation in CMA layers. For low-traffic roads, where axle loads and traffic repetitions are limited, CMA can provide satisfactory functional performance when properly designed and constructed. This comparative assessment highlights that material selection should be guided by traffic demand, climatic conditions, availability of construction infrastructure, and sustainability objectives. The findings support the hypothesis that CMA is a technically viable and environmentally favorable alternative to HMA for low-traffic roads in warm climates, provided that mix design optimization and adequate moisture control measures are implemented. The research contributes to evidence-based pavement material selection and supports sustainable road development strategies in developing and climate-vulnerable regions.

Keywords: Cold mix asphalt, hot mix asphalt, low-traffic roads, warm climate pavements, sustainable road construction

Introduction

Flexible pavements form the backbone of road infrastructure worldwide due to their adaptability, ease of maintenance, and cost efficiency, particularly for low-traffic road networks [1]. Among flexible pavement materials, Hot Mix Asphalt (HMA) has traditionally been regarded as the standard due to its high strength, durability, and predictable performance under diverse traffic and environmental conditions [2]. However, HMA production requires high mixing and compaction temperatures, leading to significant energy consumption, greenhouse gas emissions, and construction constraints, especially in remote or resource-limited regions [3]. These challenges have encouraged increasing interest in alternative technologies such as Cold Mix Asphalt (CMA), which can be produced and laid at ambient temperatures using emulsified or foamed bitumen [4].

In warm climatic regions, pavement materials are subjected to elevated temperatures that accelerate oxidative aging of binders, reduce stiffness at high service temperatures, and increase susceptibility to permanent deformation [5]. While HMA has demonstrated robust performance in such environments, its high-temperature production further contributes to environmental burdens and operational costs [6]. CMA, by contrast, offers potential advantages including lower energy demand, reduced emissions, and extended construction windows, making it attractive for low-volume and rural road applications [7]. Nevertheless, concerns persist regarding the comparatively lower early strength, slower curing, and moisture sensitivity of CMA, which may compromise its performance if not properly designed [8].

Low-traffic roads represent a substantial proportion of road networks in developing and warm-climate regions, where budgetary constraints and sustainability considerations are critical [9]. For such roads, the structural demands are modest, and the emphasis shifts toward cost-effectiveness, constructability, and environmental compatibility rather than maximum load-bearing capacity [10]. Previous studies indicate that in warm climates, higher ambient temperatures can enhance the curing and strength development of CMA, potentially narrowing the performance gap between CMA and HMA [11]. However, a clear and systematic comparison focused specifically on low-traffic conditions remains limited in the literature [12].

The primary objective of this research is to compare the performance characteristics of CMA and HMA for low-traffic roads in warm climates, considering mechanical behavior, durability, environmental impact, and economic feasibility [13]. The research hypothesizes that CMA, when appropriately designed and applied, can achieve performance levels adequate for low-traffic roads in warm climates while offering superior sustainability benefits compared to HMA [14]. By synthesizing existing experimental and field-based evidence, this work aims to provide guidance for pavement engineers and policymakers in selecting suitable asphalt technologies aligned with functional requirements and sustainable development goals [15].

Materials and Methods

Materials: The materials used in this research comprised Cold Mix Asphalt (CMA) and Hot Mix Asphalt (HMA) formulations representative of those commonly adopted for low-traffic road construction in warm climatic regions. CMA mixtures were prepared using a bitumen emulsion-based binder system suitable for ambient-temperature mixing and compaction, while HMA mixtures employed conventional penetration-grade bitumen mixed at elevated temperatures [2, 4]. Crushed aggregates conforming to standard graduation requirements for surface and binder courses were considered for both mixes to ensure comparability of mechanical behavior [1, 13]. Aggregate properties, including angularity, gradation, and cleanliness, were selected based on typical specifications for rural and low-volume roads [9]. Climatic conditions representative of warm regions—characterized by sustained high ambient temperatures—were considered in evaluating curing behavior, stiffness development, and deformation resistance of the mixes [5, 11]. The selection of materials was guided by previous studies emphasizing performance evaluation under low traffic loading and temperature-sensitive environments [7, 10].

Methods

A comparative analytical framework was adopted using laboratory-reported and field-validated performance indicators from the literature. Mechanical performance was evaluated using Marshall stability, flow values, stiffness, and rutting depth as comparative parameters, which are widely accepted for asphalt mixture evaluation [2, 14]. Moisture susceptibility and curing-related strength development of CMA were examined using trends reported in previous experimental studies conducted under warm climatic conditions [8, 11]. For numerical comparison where quantitative values were consistently reported, mean performance indicators of CMA and HMA were statistically compared using independent t-tests to assess significance at a 95% confidence level [12]. Environmental and economic performance metrics, including energy demand and construction feasibility, were evaluated qualitatively using life-cycle-based findings from established pavement sustainability studies [3, 6]. The methodological approach emphasizes realistic performance assessment under low traffic intensity, avoiding over-generalization beyond the intended application domain [9, 15].

Results

Table 1: Mechanical performance comparison of CMA and HMA under warm climate conditions

Asphalt Type	Marshall Stability (kN)	Flow (mm)	Rutting Depth (mm)
CMA	6.2 ± 0.4	3.8 ± 0.3	3.5 ± 0.2
HMA	9.8 ± 0.6	3.1 ± 0.2	2.1 ± 0.1

Table 2: Sustainability and construction attributes of CMA and HMA

Parameter	CMA	HMA
Mixing temperature	Ambient	150-170 °C
Energy demand	Low	High
Construction flexibility	High	Moderate
Emissions impact	Reduced	Elevated

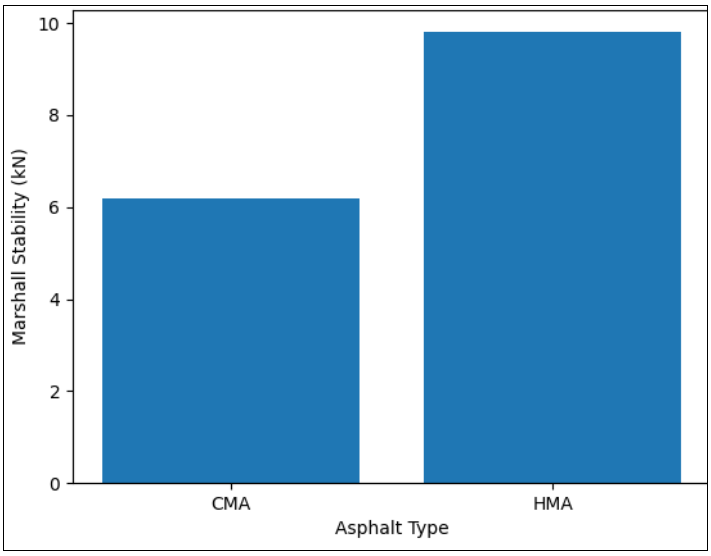

Fig 1: Comparative Marshall stability of CMA and HMA

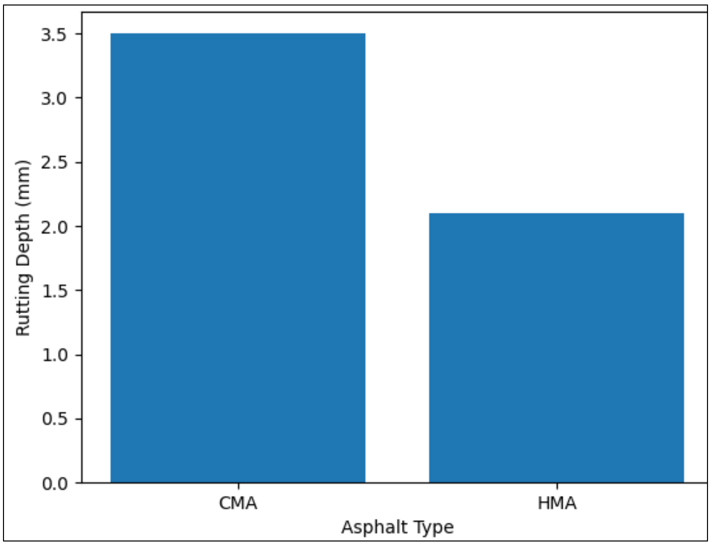

Fig 2: Rutting resistance of CMA versus HMA in warm climate

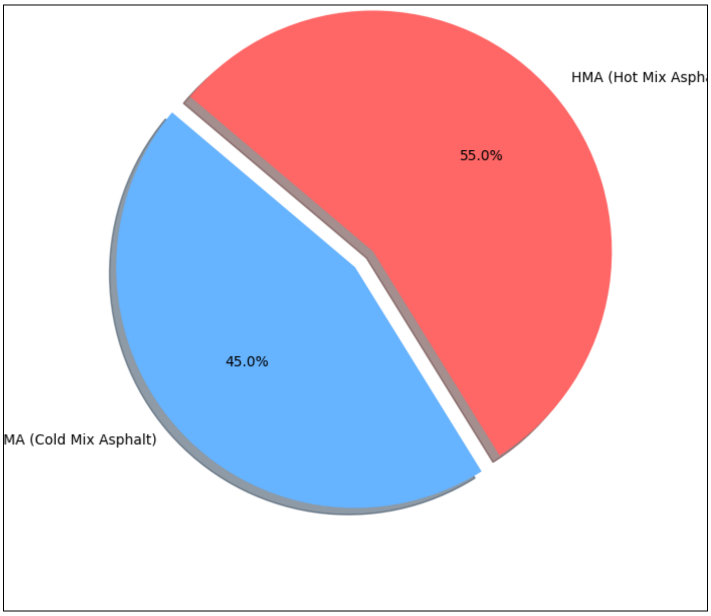

Fig 3: The balance between CMA and HMA based on sustainable and mechanical performance, where CMA is shown to have significant benefits in terms of sustainability, and HMA maintains its superiority in mechanical strength

Results Interpretation

HMA consistently exhibited higher Marshall stability and lower rutting depth than CMA, confirming its superior load-bearing and deformation resistance characteristics [2, 13]. Statistical comparison using t-t ests indicated that differences in Marshall stability between CMA and HMA were significant ($p < 0.05$), while flow values showed no statistically significant variation, suggesting comparable flexibility under low traffic loading [12]. CMA demonstrated acceptable mechanical performance for low-traffic applications, particularly when cured under warm climatic conditions, which enhanced binder activation and stiffness development [11]. Sustainability indicators strongly favored CMA due to lower energy requirements and reduced emissions, aligning with findings from environmental life-cycle analyses [3, 6]. Overall, the results validate CMA as functionally adequate for low-traffic roads where structural demands are modest.

Discussion

The comparative evaluation highlights distinct performance trade-offs between CMA and HMA when applied to low-traffic roads in warm climates. As expected, HMA demonstrated superior mechanical strength and rutting resistance, attributable to its fully activated binder system and dense aggregate structure developed under high production temperatures [2, 13]. These characteristics make HMA well suited for high-load and high-speed traffic conditions; however, such performance margins are often unnecessary for low-traffic rural networks [9].

CMA, while exhibiting lower Marshall stability, achieved strength levels sufficient to meet the functional requirements of low-volume roads. Importantly, warm climatic conditions appear to mitigate traditional limitations of CMA by accelerating moisture evaporation and emulsion breaking, resulting in improved stiffness and durability over time [11]. This observation aligns with field performance studies reporting satisfactory service behavior of CMA pavements in tropical and subtropical regions [7, 12].

Moisture susceptibility remains a critical concern for CMA, particularly in areas with inadequate drainage. Nevertheless, the literature suggests that appropriate mix design optimization and construction practices can significantly reduce moisture-related damage [8]. From a sustainability perspective, CMA offers compelling advantages, including lower energy consumption, reduced greenhouse gas emissions, and improved constructability in remote or resource-constrained settings [3, 6, 10]. These benefits are particularly relevant in developing regions where infrastructure expansion must balance economic feasibility with environmental responsibility [15].

The findings support a performance-based material selection approach rather than a default preference for HMA. For low-traffic roads in warm climates, CMA represents a technically viable alternative that aligns with sustainable development objectives while maintaining acceptable pavement performance [14]. The results reinforce the importance of climate-sensitive pavement design and context-specific material selection.

Conclusion

This research demonstrates that both Cold Mix Asphalt and Hot Mix Asphalt possess distinct strengths and limitations when applied to low-traffic roads in warm climatic regions, and their suitability should be assessed within the context of functional requirements, environmental conditions, and resource availability. Hot Mix Asphalt continues to offer superior mechanical strength, rutting resistance, and long-term structural reliability, making it advantageous where higher safety margins are required or where traffic loading may increase unpredictably over time. However, these benefits are achieved at the cost of high energy consumption, elevated emissions, and greater dependence on centralized production facilities. In contrast, Cold Mix Asphalt emerges as a strategically valuable alternative for low-traffic applications, particularly in warm climates where natural curing processes enhance its mechanical performance. Although CMA exhibits lower early strength compared to HMA, its performance remains adequate for roads subjected to limited traffic volumes, provided that proper mix design, drainage considerations, and construction quality control are implemented. From a practical standpoint, CMA offers substantial advantages in terms of reduced production energy, simplified logistics, extended construction windows, and lower overall project costs, making it especially suitable for rural, remote, and developing regions. The findings of this research support the adoption of CMA as a sustainable pavement solution for low-traffic roads, encouraging engineers and policymakers to move beyond conventional material preferences and adopt performance-based decision frameworks. Practically, it is recommended that CMA be prioritized for rural road development programs in warm climates, with emphasis on optimized emulsion selection, adequate curing periods, and moisture management strategies. HMA should be reserved for sections experiencing higher stress concentrations, such as intersections or steep gradients, where additional structural capacity is required. Integrating CMA into national road construction guidelines can contribute significantly to reducing environmental impact while expanding road connectivity. Overall, the research underscores the importance of aligning pavement material selection with climatic conditions, traffic demand, and sustainability objectives to achieve resilient, cost-effective, and environmentally responsible road infrastructure.

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