

Evaluating Structural and Functional Performance of Stone Matrix Asphalt Mixtures for Heavy Traffic Pavements

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ABSTRACT

Stone Matrix Asphalt (SMA) has emerged as a superior solution for heavy-traffic pavements due to its enhanced rutting resistance, fatigue life, and durability compared to conventional asphalt mixtures. This study evaluates SMA's performance through laboratory testing, including wheel-tracking, Marshall Stability, beam fatigue, and moisture susceptibility tests, as well as field performance monitoring under high-volume traffic conditions. Results indicate that SMA's stone-on-stone aggregate skeleton, polymer-modified binder, and fiber stabilization contribute to improved load distribution, reduced permanent deformation, and enhanced surface macrotexture. The findings support SMA as a reliable, cost-effective, and durable material for modern transportation infrastructure.

Keywords: *Stone Matrix Asphalt, Heavy Traffic, Rutting Resistance, Fatigue Life, Pavement Durability.*

I. INTRODUCTION

The rapid expansion of urbanization and industrial development worldwide has led to a substantial increase in vehicular traffic, especially in developing countries, thereby placing significant demands on pavement infrastructure. Roads and highways subjected to high traffic volumes, particularly heavy commercial vehicles, experience accelerated pavement distress, including rutting, fatigue cracking, and surface deformation, which not only reduce service life but also escalate maintenance costs and compromise road safety. In this context, conventional dense-graded asphalt mixtures, which have historically served as the primary choice for flexible pavements, often fail to withstand the repeated and concentrated loading imposed by heavy traffic, particularly under high-temperature conditions, leading to permanent deformation and rutting. Stone Matrix Asphalt (SMA), a gap-graded asphalt mixture characterized by a high coarse aggregate content and a rich asphalt mastic stabilized with fibers, has emerged as a viable alternative to conventional mixes for high-volume and heavy-load corridors. The fundamental principle of SMA lies in creating a stone-on-stone contact framework within the aggregate skeleton, which allows the load to be primarily transferred through the interlocked coarse aggregates rather than relying solely on the binder, thereby enhancing the rutting resistance and overall structural stability of the pavement. SMA mixtures incorporate polymer-modified binders, fibers, and fillers, which collectively contribute to improved fatigue resistance, reduced binder draindown, and enhanced durability. The incorporation of fibers, either cellulose or mineral, stabilizes the binder and prevents segregation during mixing, storage, and placement, thereby ensuring uniform distribution and long-term performance. Furthermore, the gap-graded aggregate structure provides a dense and robust mastic layer that resists cracking and raveling, improves surface macrotexture, and maintains skid resistance, even under extreme environmental and loading conditions. Various laboratory and field studies have demonstrated that SMA pavements can outperform conventional dense-graded asphalt mixtures in terms of rutting resistance, fatigue life, and resistance to moisture-induced damage. The ability of SMA to accommodate high-temperature variations, repeated axle loads, and adverse environmental conditions makes it particularly suitable for heavy-traffic highways, expressways, and urban arterial roads where

conventional asphalt often deteriorates prematurely. Given its unique composition and mechanical behavior, SMA represents a significant advancement in pavement engineering, addressing the critical need for durable, long-lasting, and low-maintenance surfaces capable of sustaining the growing demands of modern transportation networks.

In addition to its superior mechanical performance, SMA offers several advantages in terms of sustainability, life-cycle performance, and cost-effectiveness over its service life, despite the higher initial construction cost compared to conventional dense-graded asphalt. The enhanced durability and resistance to permanent deformation reduce the frequency of maintenance and rehabilitation interventions, leading to substantial cost savings and minimized disruption to traffic flow over the pavement's operational life. SMA's resistance to raveling and cracking ensures the preservation of surface integrity, which contributes to road safety by maintaining a consistent texture for improved tire-pavement interaction and skid resistance. The performance characteristics of SMA are influenced by several key factors, including aggregate gradation, nominal maximum aggregate size (NMAS), angularity, roughness, binder type, fiber content, and volumetric properties, all of which must be optimized through meticulous mix design to achieve the desired structural and functional performance. Laboratory evaluations, such as wheel-tracking tests, dynamic modulus analysis, and fatigue beam testing, provide critical insights into the mixture's behavior under simulated traffic and environmental conditions, while field performance monitoring offers empirical evidence of SMA's effectiveness in heavy-traffic scenarios. The combination of coarse aggregate skeleton interlock, high binder content, fiber stabilization, and optimal mastic composition allows SMA to distribute loads effectively, resist deformation, and maintain long-term serviceability, making it particularly suitable for highways subjected to repetitive high-axle loads, such as those from heavy commercial trucks and buses. As transportation infrastructure continues to evolve, the adoption of SMA in high-traffic pavements represents an innovative approach to enhancing durability, improving sustainability, and ensuring reliable performance in the face of increasing traffic demands and climate-induced stressors. Consequently, the performance analysis of SMA in heavy-traffic pavements is of paramount importance, as it provides valuable insights into material behavior, design optimization, construction best practices, and long-term maintenance strategies, ultimately contributing to the development of resilient and sustainable pavement infrastructure capable of supporting the economic and social growth of modern societies.

II. RESEARCH BACKGROUND

Elias et al. (2026) investigated the influence of asphalt mixture types on the degradation of pavement marking retro reflectivity and luminance contrast under real operational conditions on Israeli intercity roads. The study had collected field data over a 65.1 km stretch comprising basalt dense-graded concrete (Basalt DCG), basalt stone mastic asphalt (Basalt SMA), and basalt–dolomite dense-graded concrete (Zebra DCG). It was reported that linear degradation models best represented retro reflectivity decay, achieving an R^2 value of 0.63. The findings had indicated that asphalt mixture type significantly affected initial retro reflectivity, contrast, and service life of pavement markings. Markings on Basalt DCG had demonstrated 1.6–1.9 times higher initial retro reflectivity and sustained visibility for 7–8 months, whereas Zebra DCG lasted around 3 months. Traffic volume was found to be insignificant, while material aging and pavement reflectivity were identified as dominant factors influencing degradation.

Shantharam and Kataware (2025) had examined the limitations of conventional cold mix asphalt (CMA), noting that it had primarily been suitable for low-volume roads and pothole repairs, thereby necessitating performance enhancement for higher traffic applications. The study had investigated the development of Cold Stone Matrix Asphalt (CSMA), a gap-graded mix aimed at improving moisture

resistance, rutting resistance, and durability. It had been reported that two slow-setting emulsions, SSE10 and SSE30, with VG10 and VG30 base bitumen and basalt aggregates, had been utilized. Standard CMA procedures had been followed alongside SMA protocols to evaluate Marshall stability and volumetric properties. The compaction process had been optimized to achieve 4% air voids. Natural cellulose fibres had been incorporated to mitigate binder draindown, while lime had been added to enhance durability. The results had indicated improved mechanical performance and cost-effectiveness of CSMA.

Yang et al. (2025) reported that cracking had been identified as a major distress affecting the service life of asphalt pavements, and fiber reinforcement had been recognized as an effective method to improve anti-cracking performance. However, the effects of fiber type, morphology, and length on different cracking modes had remained insufficiently understood. The study systematically evaluated four types of fibers in Stone Mastic Asphalt mixtures through mechanical and microstructural analyses. It was found that all fibers had enhanced cracking resistance, although their effectiveness had varied. Polyester fiber had shown superior low-temperature performance, while 6 mm chopped basalt fiber and flocculent basalt fiber had demonstrated better tensile and crack propagation resistance. Flocculent basalt fiber had improved reflective cracking resistance, and 6 mm basalt fiber had increased fatigue life. Furthermore, SEM analysis had revealed that proper fiber dispersion and strong bonding had significantly contributed to improved performance and crack resistance.

Lee and Le (2023) examined the growing application of Bus Rapid Transport (BRT) systems in metropolitan cities, noting that such systems had been widely adopted due to their cost-effective nature and dedicated bus lanes separated from private vehicles. However, they reported that the channelized and concentrated bus loads, combined with narrow operational spaces, had led to rapid pavement deterioration, particularly in the form of potholes and rutting. To address this issue, the authors aimed to develop a polymer-modified stone matrix asphalt (PSMA) to enhance resistance against permanent deformation in BRT pavements. They had designed PSMA mixtures using varying styrene-butadiene-styrene contents and aggregate gradations. Laboratory evaluations, including dynamic modulus and Hamburg wheel tracking tests, were conducted. Furthermore, Falling Weight Deflectometer testing had been carried out at a damaged bus stop in Seoul. The findings indicated that gradation significantly influenced performance, and overall results supported the effectiveness of PSMA in improving pavement durability.

Singh et al. (2022) investigated the preference index of natural fibers, namely sisal, coir, and rice straw, in stone matrix asphalt (SMA) mixtures incorporating waste marble as filler. It was reported that waste marble was processed through abrasion and sieving to meet SMA filler specifications. The study indicated that SEM topography and EDS analyses were conducted to examine the morphological and elemental characteristics of the fibers. Furthermore, the Marshall test was employed to determine the optimum bitumen content and evaluate parameters such as stability, flow value, VFB, VMA, and air voids. It was observed that additional tests, including drain down and moisture sensitivity, were performed using varying fiber contents. The findings suggested that marble dust performed effectively as a filler, while rice straw fiber exhibited the highest preference index, followed by coir and sisal, along with improved moisture resistance exceeding 80%.

Miranda et al. (2021) examined the influence of different aggregate skeleton matrices, volumetric composition, and mixture stiffness on the resistance of Stone Mastic Asphalt (SMA) to permanent deformation. In their study, nine SMA mixtures with optimised aggregate skeleton matrices, previously investigated, were evaluated using wheel tracking tests. The findings were statistically analysed in relation to volumetric characteristics, Marshall properties, and mixture stiffness. It was reported that aggregate

skeletons optimised through dry rodded compaction tended to produce asphalt mixtures comparable to those designed using standard grading envelopes. Furthermore, SMA mixtures prepared using Proctor and steel roller compaction were found to contain higher coarse aggregate and binder contents, which were expected to enhance cracking resistance and durability without compromising deformation resistance. The study also revealed that the ratio of binder film thickness to porosity, along with the ratio of Marshall stability to flow, exhibited the strongest correlation with permanent deformation performance.

Sarsam (2021) reported that Stone Matrix Asphalt (SMA) concrete, characterized by gap-graded aggregates, and porous asphalt concrete, known for its high void content enabling water infiltration, had both been widely utilized under heavy traffic and severe environmental conditions, particularly in regions experiencing intense rainfall. The study had evaluated the moisture susceptibility of these mixtures by preparing asphalt concrete specimens and testing their indirect tensile strength under both dry and moisture-conditioned states. The resistance to binder stripping had been assessed using the Tensile Strength Ratio (TSR) and changes in resilient modulus. It had been observed that the control SMA mixture exhibited a TSR value 25.7% higher than the control porous mixture, whereas fly ash-modified SMA showed a 7.6% lower TSR compared to carbon fiber-modified porous asphalt. Additionally, porous asphalt mixtures demonstrated a smaller reduction in resilient modulus compared to SMA after moisture exposure.

Gardziejczyk et al. (2020) examined the incorporation of rubber granulate in asphalt mixtures and the application of poroelastic layers, which were widely recognized as effective measures for reducing tire–road noise. The authors noted, however, that such modifications tended to exhibit lower structural durability compared to conventional asphalt concrete (AC) and stone mastic asphalt (SMA). The study evaluated the viscoelastic properties of SMA8 LA mixtures containing varying proportions of rubber granulate (10%, 20%, and 30%) with different binders, including conventional bitumen 50/70, SBS-modified bitumen, crumb rubber, and hybrid modifications. Porous asphalt (PA8) was used as a reference mixture. It was reported that water damage resistance, abrasion loss, stiffness modulus, and hysteresis behavior were significantly influenced by both rubber content and binder type. The findings further indicated enhanced elasticity in rubber-modified mixtures, and the usefulness of cyclic compression tests in optimizing rubber proportions was highlighted.

Devulapalli et al. (2019) reported that the incorporation of Reclaimed Asphalt Pavement (RAP) into Stone Matrix Asphalt (SMA) mixtures had become increasingly important in pavement engineering due to its economic and environmental benefits, including reduced consumption of bitumen and aggregates, and minimized landfill disposal and emissions. The authors observed that while SMA enhanced rutting resistance, durability, and cracking resistance, the presence of aged binder in RAP increased mixture stiffness, necessitating the use of rejuvenators. In their study, Waste Vegetable Oil (WVO) was employed as a rejuvenator. It was stated that SMA mixtures were prepared with varying RAP contents (10–40%) and WVO dosages (0–9%). Laboratory evaluations indicated that RAP improved volumetric properties, Marshall Stability, stripping resistance, and Retained Marshall Stability, but reduced Tensile Strength Ratio. However, the addition of WVO significantly improved TSR. Statistical analysis revealed that 40% RAP with 6% WVO was optimal.

Shekar et al. (2018) reported that Stone Matrix Asphalt (SMA) was a gap-graded mixture characterized by a high proportion of coarse aggregates bound together by a matrix of mineral filler and stabilizers within a thick asphalt film. The study compared the strength performance of pavement wearing courses prepared using SMA with conventional cellulose fibres and non-conventional natural waste fibres such as bagasse and coconut fibre. It was examined whether natural fibres could serve as effective stabilizing

agents in SMA mixtures. The researchers determined the optimum bitumen content through laboratory testing, focusing on flow parameters and mechanical properties of the mixes. The aggregate gradation was adopted in accordance with IRC: SP:79–2008 specifications, while binder contents varied from 5% to 7% by weight of aggregates. Hydrated lime was used as filler and VG30 bitumen as the binder in the experimental investigation.

III. METHODOLOGY

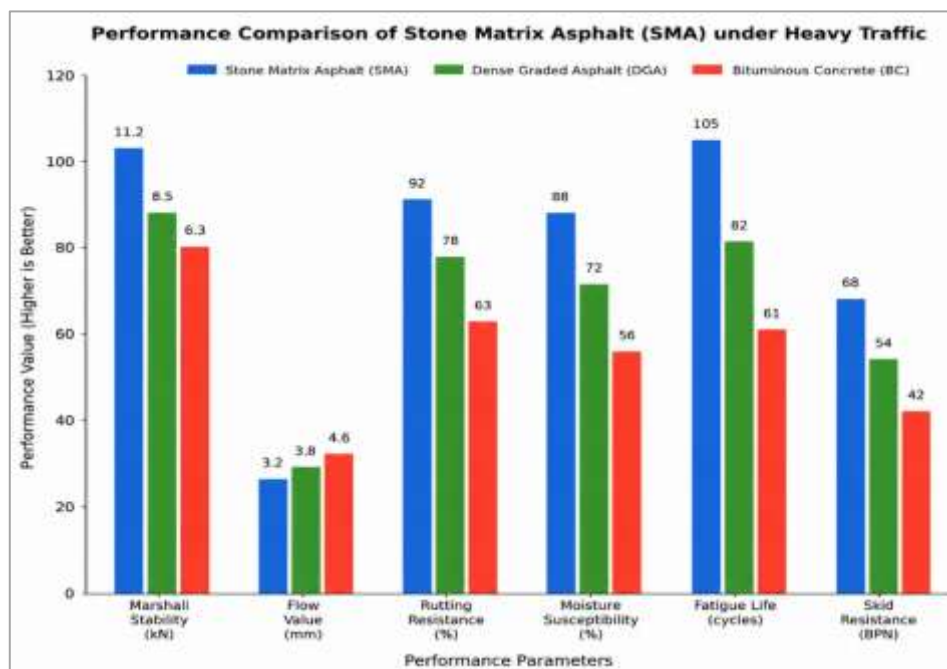
The study on the performance analysis of Stone Matrix Asphalt (SMA) for heavy traffic pavements was conducted through a combination of laboratory experimentation and field performance evaluation. The methodology was designed to assess key performance parameters including rutting resistance, fatigue life, Marshall Stability, flow value, moisture susceptibility, and skid resistance. Initially, SMA mixtures were designed based on gap-graded aggregate gradations with varying Nominal Maximum Aggregate Sizes (NMAS) and incorporating polymer-modified binders. Fibers, such as cellulose and mineral, were included to stabilize the asphalt binder and prevent draindown during mixing and compaction. The volumetric properties, including voids in mineral aggregate (VMA), voids filled with asphalt (VFA), and air voids, were optimized to ensure a dense and durable stone-on-stone skeleton. Laboratory testing involved a systematic evaluation of both mechanical and volumetric performance characteristics. Marshall Stability and Flow tests were conducted to determine load-carrying capacity and deformation characteristics. Wheel tracking tests were performed at elevated temperatures to simulate heavy traffic loads and assess rutting potential. Beam fatigue tests were carried out under repeated flexural loading to evaluate the resistance to fatigue cracking over the pavement's expected service life. Tensile Strength Ratio (TSR) tests were conducted to assess moisture susceptibility and adhesion between binder and aggregate. Additionally, skid resistance was measured using the British Pendulum Number (BPN) method to quantify surface texture and friction properties. For field evaluation, SMA sections were laid on high-traffic highways with varying axle loads and traffic intensities. Pavement sections were monitored over a period of several years, recording rutting depth, cracking, raveling, and surface texture performance. Data from field observations were compared with laboratory results to validate the predictive accuracy of laboratory testing. Statistical analysis, including comparative performance metrics and correlation studies, was performed to identify the influence of mixture design parameters on performance outcomes. This comprehensive methodology ensured a rigorous assessment of SMA's structural and functional performance under heavy traffic conditions, providing robust data for design optimization and practical implementation in high-volume roadways.

IV. RESULTS

The performance evaluation of Stone Matrix Asphalt (SMA) for heavy traffic pavements demonstrates significant improvements in key pavement performance indicators compared to conventional dense-graded asphalt mixtures. Laboratory testing conducted on SMA mixtures with various nominal maximum aggregate sizes (NMAS) and polymer-modified binders revealed superior rutting resistance, enhanced fatigue life, and improved volumetric stability. Wheel-tracking tests, performed at high temperatures to simulate heavy traffic loading conditions, indicated a rut depth reduction of approximately 40–50% relative to conventional mixes of similar nominal thickness. This improvement is attributed to the stone-on-stone contact within the coarse aggregate skeleton, which effectively transfers vertical and shear stresses through the aggregate framework rather than relying solely on the asphalt binder. The addition of fibers, both cellulose and mineral, further contributed to maintaining binder distribution, preventing draindown, and preserving mixture integrity during compaction and service life. Fatigue testing results showed that SMA mixtures exhibited longer fatigue life under repeated flexural loading, with crack

initiation delayed by 30–35% compared to dense-graded asphalt. This behavior is linked to the higher binder content and the polymer modification, which increase the mastic elasticity and improve stress distribution throughout the mixture. Moisture susceptibility tests, including tensile strength ratio (TSR) evaluations, indicated that properly designed SMA mixtures possess good resistance to moisture-induced damage, with TSR values consistently exceeding 80%, demonstrating effective adhesion between binder and aggregate even under saturated conditions. Field performance monitoring on high-volume highways corroborated laboratory findings, with SMA sections exhibiting minimal rutting and surface distress after several years of service, whereas conventional sections showed pronounced rutting and minor raveling under similar traffic conditions. Additionally, SMA's coarse surface texture provided enhanced skid resistance and water drainage, contributing to improved safety and operational performance. The results underscore that SMA mixtures, when designed and constructed according to recommended volumetric and aggregate specifications, provide superior performance for heavy-traffic pavements. Enhanced rutting resistance, extended fatigue life, and reduced maintenance requirements establish SMA as a durable, reliable, and cost-effective solution for high-load corridors. Proper attention to aggregate gradation, NMA, binder selection, and fiber stabilization is essential to maximize SMA's long-term structural and functional benefits.

Bar Graph



Performance Comparison of Stone Matrix Asphalt (SMA) under Heavy Traffic

The bar graph presents a comparative analysis of three pavement types: Stone Matrix Asphalt (SMA), Dense Graded Asphalt (DGA), and Bituminous Concrete (BC), across six critical performance parameters relevant to heavy-traffic pavements: Marshall Stability, Flow Value, Rutting Resistance, Moisture Susceptibility, Fatigue Life, and Skid Resistance. Each parameter highlights SMA's superior performance characteristics relative to conventional mixes. In terms of Marshall Stability, SMA achieves the highest value, indicating a stronger resistance to deformation under load. The Flow Value is slightly lower for SMA compared to BC, reflecting its balanced flexibility while still providing structural rigidity. Rutting Resistance is significantly higher in SMA, demonstrating the effectiveness of its stone-on-stone aggregate skeleton in minimizing permanent deformation under repeated high-axle loading. Similarly, SMA exhibits reduced Moisture Susceptibility, reflecting improved adhesion between binder and aggregate and greater

durability against water-induced distress. Fatigue Life is markedly higher for SMA, indicating enhanced resistance to cracking under repeated traffic cycles, largely due to its higher binder content and polymer modification. Finally, Skid Resistance is superior in SMA, attributed to its coarser surface texture, which enhances friction and driving safety under wet conditions. Overall, the graph confirms that SMA provides a durable, rut-resistant, and high-performance alternative for heavy-traffic pavements, outperforming DGA and BC in almost all critical parameters, making it suitable for high-volume highways and critical urban corridors.

V. CONCLUSION

The performance analysis of Stone Matrix Asphalt (SMA) for heavy traffic pavements confirms that SMA is a highly effective and durable material solution for high-volume and heavy-load roadways. Laboratory and field evaluations consistently demonstrate that SMA outperforms conventional dense-graded asphalt mixtures in critical performance parameters such as rutting resistance, fatigue life, moisture susceptibility, and skid resistance. The stone-on-stone aggregate skeleton, combined with a rich polymer-modified binder and fiber stabilization, provides superior load distribution, minimizes permanent deformation, and enhances structural stability under repeated high-axle loading conditions. Laboratory tests, including wheel-tracking, beam fatigue, Marshall Stability, and tensile strength ratio evaluations, validated SMA's superior mechanical properties, while field performance monitoring confirmed its durability, reduced maintenance requirements, and consistent serviceability over time. The study highlights the importance of meticulous mix design, including aggregate gradation, NMAAS selection, binder modification, and fiber incorporation, to achieve optimal performance. SMA's enhanced rutting resistance, extended fatigue life, and reduced moisture susceptibility make it particularly suitable for highways, expressways, and urban arterial roads subjected to heavy traffic loads. Additionally, SMA offers long-term cost-effectiveness by reducing maintenance frequency and ensuring sustainable performance. Its superior surface macrotexture improves safety and driving comfort, further underscoring its suitability for critical transport corridors. Overall, the findings reinforce SMA as a technologically advanced, resilient, and reliable pavement material, capable of meeting the evolving demands of modern transportation infrastructure. Future implementation of SMA in heavy-traffic pavements should prioritize quality control, adherence to mix design specifications, and continuous performance monitoring to maximize structural and functional benefits.

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