Research Article

Biochar as a Sustainable Additive: Performance Evaluation in Stone Matrix Asphalt and Bituminous Concrete Mix Designs

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ABSTRACT

This study investigates coconut shell biochar as a full replacement for mineral filler in Stone Matrix Asphalt (SMA, 9%) and Bituminous Concrete (BC, 2%), designed in accordance with Indian Roads Congress and MoRTH standards. Performance was assessed using indirect tensile strength (ITS), Marshall stability, resilient modulus, rutting, and moisture susceptibility tests, with statistical analysis confirming the significance of observed variations. BC mixes retained tensile strength above 93% under freeze–thaw and 98% under humid conditioning, while SMA remained above the 80% threshold. Rut depths were within permissible limits for both mixes (11 mm for BC; 13 mm for SMA after 20,000 passes). Binder-level analyses (FTIR and SEM) confirmed improved bitumen–biochar interactions at 10–15% replacement, explaining the observed mechanical improvements and BC's superior performance. Although stone dust provided marginally higher strength, biochar demonstrated strong technical feasibility along with added environmental benefits by valorising agricultural waste. Future studies should focus on fatigue testing, long-term field trials, and life-cycle assessment, where IoT-based bitumen fume monitoring can provide real-time emissions data to strengthen sustainability evaluations.

Keywords: Biochar, Sustainable pavement, Stone matrix asphalt, Bituminous concrete, Mechanical performance, Cost-benefit analysis

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Introduction

Sustainability and the circular economy have become central to global infrastructure development, with governments, researchers, and industries emphasizing the need to conserve natural resources while meeting rising construction demands [1]. Sustainability calls for fulfilling present needs without compromising future generations, while the circular economy extends beyond recycling to regeneration through reducing, reusing, repairing, and recycling [2, 3]. These approaches are particularly relevant in road construction one of the largest consumers of raw materials where the depletion of aggregates and the environmental costs of conventional binders pose urgent challenges.

Road infrastructure underpins economic growth, yet flexible pavements, which constitute nearly three-quarters of global road networks, demand vast quantities of aggregates and bitumen [4]. Transitioning towards eco-friendly practices is therefore essential to reduce dependence on virgin resources and mitigate environmental burdens. As a sustainable addition to asphalt mixes, biochar a carbon-rich, porous byproduct of biomass pyrolysis is a potential innovation [5].

Produced from agricultural and forestry residues such as coconut shells, rice husks, or wood waste under limited oxygen, biochar is carbon-neutral, capable of long-term carbon sequestration, and supports waste valorization [6, 7]. Its lightweight, porous, and hydrophilic nature makes it suitable for asphalt applications, particularly in "stone matrix asphalt (SMA) and bituminous concrete (BC)". In addition, biochar production transforms organic residues into value-added products, simultaneously addressing solid waste disposal and greenhouse gas reduction [8].

The environmental rationale for biochar adoption is compelling. Transport accounts for over 20% of global energy-related CO_2 emissions, while pavements contribute significantly during both construction and maintenance [9]. Mining of aggregates, volatile organic compound (VOC) emissions during bitumen heating, and leaching of pollutants exacerbate sustainability concerns. Biochar helps mitigate these impacts: it can reduce VOC emissions from binders by up to 76% depending on feedstock [10] and sequester up to 64.40 Mg CO_2 per hectare in soil systems [11]. When incorporated into road construction, biochar therefore represents both a performance-enhancing additive and a potential carbon sink.

From a performance perspective, mineral fillers are essential in improving stiffness, resistance against to rutting and longevity of asphalt mixtures [12]. Traditionally, lime, fly ash, and cement have been used. Biochar, however, offers unique physico-chemical advantages: its porous surface improves binder adhesion, increases viscosity, and enhances resistance to rutting and ageing [13]. Laboratory studies have confirmed that biochar-modified binders exhibit superior oxidation resistance, fatigue life, and stiffness compared to conventional fillers [14]. Recent studies further support its potential. For instance, coconut shell biochar improved rutting resistance [15], while reduced moisture sensitivity was reported in porous asphalt [16]. Boraah et al. emphasized the influence of pyrolysis temperature on surface chemistry and compatibility with bitumen [17].

Despite these advances, several critical gaps remain. Most biochar–asphalt studies are confined to laboratory trials, with limited field-oriented validation. Statistical methods such as ANOVA are seldom employed to confirm significance of improvements. Links between microstructural alterations (via FTIR and SEM) and mechanical performance are not consistently established. Comprehensive cost−benefit analyses, policy considerations, and acceptance barriers are also underexplored. Moreover, while biochar has often been studied as a partial replacement for mineral filler, the feasibility and implications of its full replacement remain largely untested despite offering the highest sustainability benefits. In addition to these technical challenges, barriers related to industry adoption, regulatory approval, and public perception must also be addressed to ensure successful implementation of biochar-based pavements in practice.

This study addresses these gaps by evaluating coconut shell biochar as a complete substitute for conventional mineral filler in BC and SMA mixtures. Experimental trials assess its influence on rutting resistance, tensile strength, resilient modulus, and moisture susceptibility. Advanced characterization techniques, including “Fourier-transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM)”, are integrated to link microstructural features with performance. Statistical validation using ANOVA confirms the significance of observed differences. Finally, a preliminary cost−benefit analysis evaluates the economic feasibility within circular economy goals.

This work therefore contributes to both sustainability and performance enhancement of asphalt pavements, while highlighting biochar’s potential as a carbon-negative, cost-effective alternative to conventional fillers. Future research directions include long-term field trials, integration of IoT-based fume monitoring for life-cycle assessment, and exploration of other biomass-derived fillers that could complement biochar in sustainable pavement engineering.

Objectives

Building on these research gaps, this study aims to:

- Examine the viability of completely substituting coconut shell biochar for traditional mineral filler in bituminous concrete (BC) and stone matrix asphalt (SMA), paying particular attention to important mechanical characteristics as moisture susceptibility, tensile strength, resilient modulus, and rutting resistance.
- Use “scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR)” to establish microstructure−performance correlations, with statistical confirmation provided by ANOVA.
- Assess the economic and environmental potential of biochar adoption through a preliminary cost−benefit analysis within the circular economy framework.

Materials and Methods

Materials

Aggregates, filler, and binder were characterized to ensure conformity with MoRTH (2013) [18], IS:73 [19], IS:2386 [20], and IRC: SP:79-2008 [21] specifications. Locally available crushed granite was used as coarse and fine aggregates, with sharp sand included to improve packing density.

Crushed granite stone dust served as the control filler, while coconut shell biochar was investigated as the sustainable alternative. Tests for porosity, particle size distribution, and specific gravity were used to assess the aggregates' morphological and physical characteristics. Filler porosity was evaluated using the German filler test and Rigden voids, and clay content was ascertained using the methylene blue value. Hydrophilic coefficient and pH were measured to evaluate filler−binder affinity. A chemical analysis of the binder was assessed by SARA fractionation (“saturates, aromatics, resins, and asphaltenes”) following the Corbett method [22].

Aggregates

The nominal maximum size of crushed granite used for Bituminous Concrete (BC) and Stone Matrix Asphalt (SMA) combinations was 16 mm. A 6 mm downsize fraction served as the fine aggregate. All aggregates were tested in accordance with MoRTH (2013) [18] and IRC: SP:79-2008 [21] requirements. The combined gradations for SMA and BC were established based on particle size distribution and appear in Figure 1. The corresponding physical characteristics of aggregates are summarized in Table 1, while the raw materials employed in mixture preparation are presented in Figure 2.

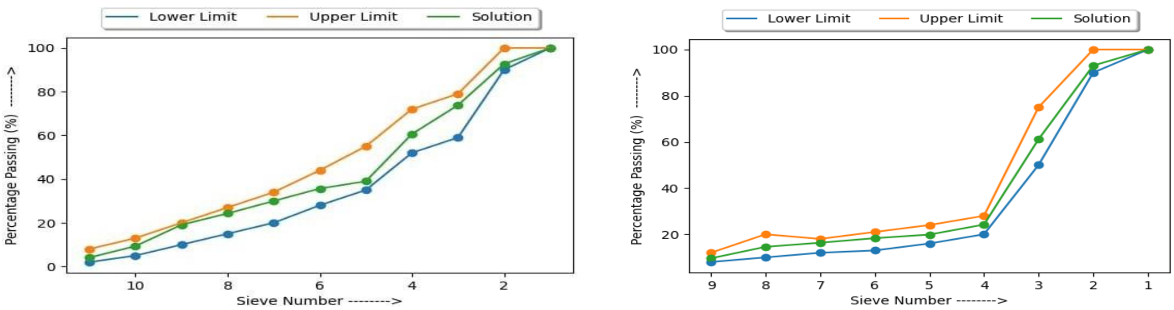

Figure 1 Combined aggregate gradation for Gap Graded Stone Matrix Asphalt (SMA) and Dense Graded Bituminous Concrete (BC).

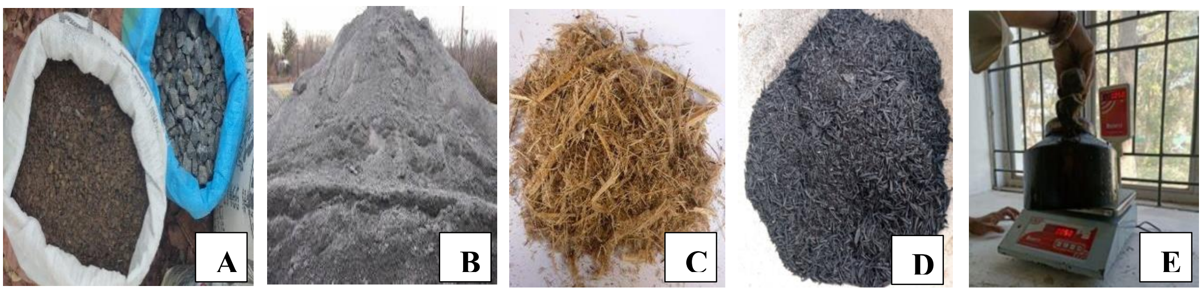

Figure 2 Raw materials for bituminous mixture preparation: A) Coarse aggregate B) Fine aggregate C) Stabilizing additive D) Raw biochar from muffle furnace E) Bitumen.

Biochar

Coconut shell biochar was produced by slow pyrolysis at 400 ^{o}C for 2 h. The resulting material was washed, oven-dried, ground, and sieved to pass a 0.075 mm sieve before use. The preparation process and potential applications are illustrated in Figures 3a and 3b. Thermogravimetric analysis verified good heat stability with 95% mass loss taking place at 699 ^{o}C. The filler was characterized in accordance with standardized procedures. The Rigden Void (RV) content was determined following BS EN 1097-4 (2008) [23], and the German Filler (GF) test quantified oil absorption. Clay contamination was assessed by the "Methylene Blue Value" (MBV) test using International Slurry Seal Association (ISSA, 2007) guidelines [24], confirming results below the permissible 10 g/kg threshold. Bulk density was measured by the IDF method (IS:2386 Part III, 1963) [20]. Hydrophilic coefficient testing evaluated filler affinity for water versus bitumen, while pH and electrical conductivity were determined using a 1:9 filler-to-water suspension. The biochar exhibited alkaline characteristics (pH >7), indicating good compatibility with bitumen. To assure accuracy and repeatability, every test was run three times.

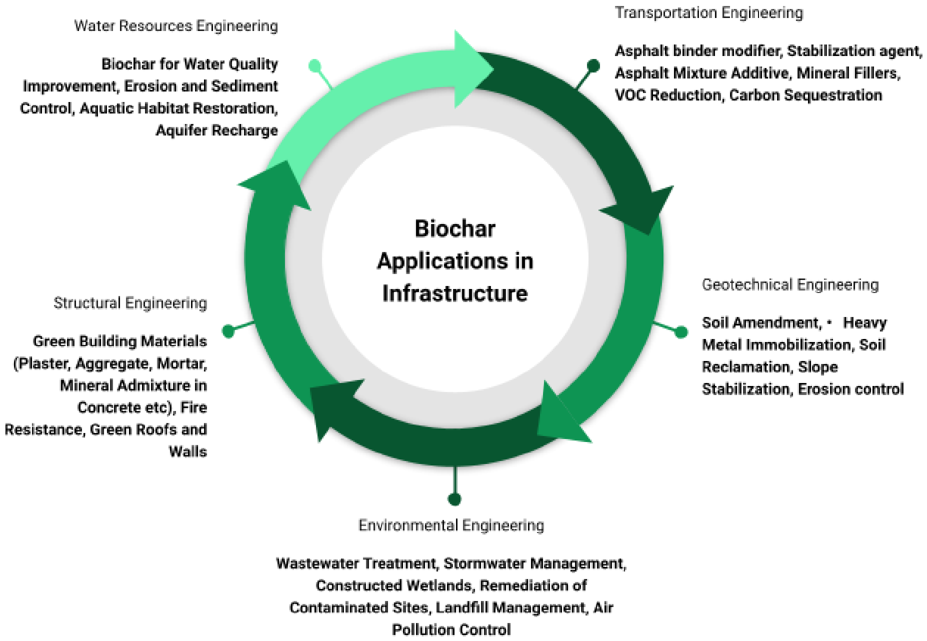

Figure 3a Biochar applications in the construction industry.

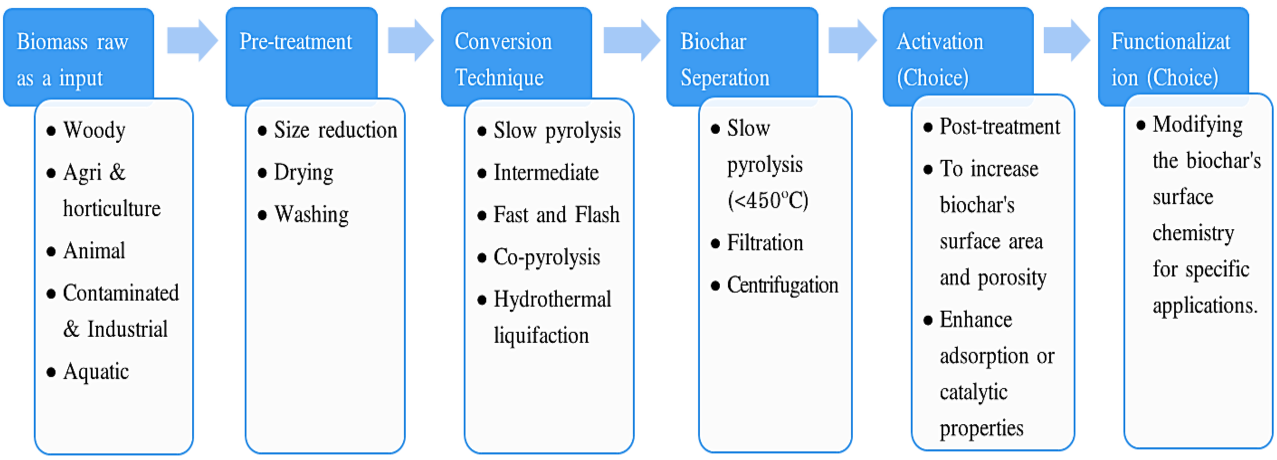

Figure 3b Making biochar and separating it with a slow pyrolysis method.

Bitumen

VG-40 grade bitumen, supplied by Tikitar Industries, Visakhapatnam (India), was used as the binder. The material conformed to IS 73:2013 requirements [19], and Table 1 provides a summary of its physical characteristics. To characterize chemical composition, the binder was fractionated into maltenes and asphaltenes using the Corbett method (ASTM D2007; Corbett, 1969) [22]. In this procedure, asphaltenes were precipitated using n-heptane, while the remaining solution constituted the maltene fraction. The maltene-to-asphaltene ratio was used to provide a baseline for evaluating the influence of biochar modification on binder performance.

Materials Characterisation

“Fourier transform infrared spectroscopy analysis”:

FTIR was employed to evaluate inorganic changes in base and biochar-modified binders, with particular attention to the carbonyl index (CI), a marker of oxidative ageing. A lower CI in biochar-modified binders suggests reduced susceptibility to oxidation, improving flexibility and crack resistance [7, 9].

Morphology analysis:

Surface morphology was examined using SEM (Tisscan Mira model) at magnifications from 100× to 5000×. Biochar-modified binders displayed rougher textures with well-dispersed porous particles compared to smoother control binders, indicating stronger physical interlocking and enhanced adhesion [10, 14, 15].

Mix Design Methodology

Bituminous concrete (BC) and Stone Matrix Asphalt (SMA) were selected due to their widespread use in road construction and durability [25, 26]. To reduce reliance on virgin materials, mineral filler was fully replaced with coconut shell biochar. The experimental framework (Figure 4) outlines the process from material preparation to performance evaluation. Marshall’s mix design approach was adopted for its reliability and standardization [27]. Biochar was introduced at 9% (SMA) and 2% (BC) as complete filler replacements.

Aggregate Blending Optimization (STAB Software tool)

Aggregate blending was carried out using the STAB approach in conjunction with the maximum density line concept. The blend proportions are detailed in Section 2.1.1. Gradation curves confirmed compliance with MoRTH (2013) [18] and IRC: SP:79-2008 [21] specifications.

Table 1 Pavement materials characterization for BC and SMA.

Material test		Method	Result obtained	Specification
Tests on Bitumen	Penetration at 25^{o}C	IS 1203	43	Min 45
	Softening point,	IS 1205	47	Min 47
	Ductility (5 cm/min) at 25^{o}C	IS 1208	76.7	Min 40
	Bitumen's specific gravity	IS 1202	0.972	0.9-1.02
	SARA analysis by Corbett separation	ASTM D4124	Asphaltenes: 20.28% Maltenes: 79.72%	Asphaltenes: 10% to 30% Maltenes: 70-90%
Tests on Coarse Aggregates	Combined Flakiness & Elongation	IS 2386 part-1	25.76%	<30%
	Los Angeles abrasion	IS 2386 part-4	17.68%	<25%
	Aggregate Impact	IS 2386 part-4	13.71%	<15%
	Water absorption	IS 2386 part-3	0.52%	<2%
	Specific gravity of 16mm aggregate	IS 1202	2.67	2.5-3.0
	13mm aggregate specific gravity	IS 1202	2.65	2.5-3.0
	Fine aggregate's specific gravity	IS 1202	2.4	2.4-3.0
Tests on Filler's	Rigden void (RV) content	ASTM D7064		Biochar: 35.48% Stone dust: 29%
	Methylene Blue (MB)	ASTM C837-09		Biochar: 9ml Stone dust: 4ml
	German filler (GF) test	EN 12697-1	10g/kg	Biochar: 35g Stone dust: 40g
	Hydrophilic coefficient	ASTM D6088	<1	Biochar: 0.95 Stone dust:1.19
	pH & conductivity (affinity)	Ana R. Pasandín et.al.(2015)		Biochar: 8.45 & 990 ΔS(Affinity); 9.09 & 260 ΔS(Direct) Stone dust: 9.67 & 872 ΔS(Affinity); 7.85 & 7.9 and 160 ΔS(Direct)

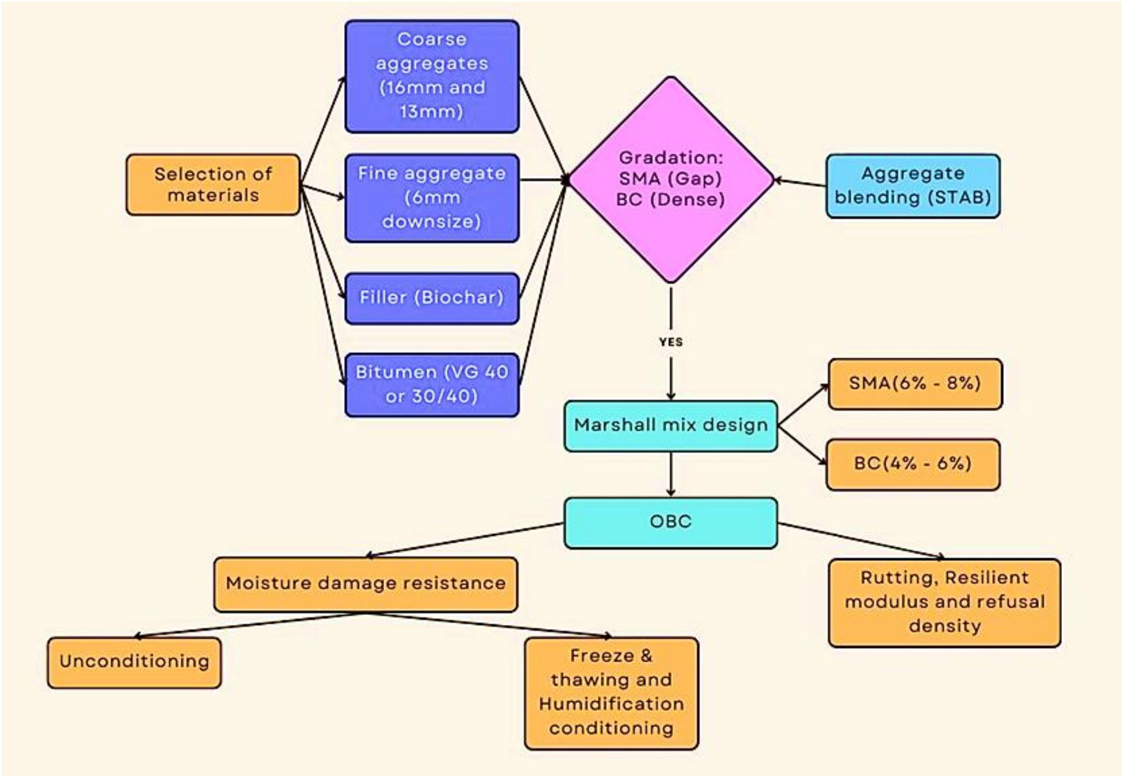

Figure 4 A road map for SMA and BC mix design and evaluation.

Gradation Verification (Bailey's Method)

The Bailey method was applied to validate aggregate packing and gradation compatibility [28]. Three parameters were calculated based on particle size distribution:

CA ratio: (PP Half-sieve−PP pcs)/(100−PP Half-sieve)

FAc ratio: PP scs/PP pcs

FAf ratio: PP tcs/PP scs

Here, PP represents the percentage passing a given sieve, PCS is the primary control sieve (2.36 mm), SCS is the secondary control sieve (0.60 mm), TCS is the tertiary control sieve (0.150 mm), and the half sieve corresponds to 4.75 mm. The nominal maximum particle size (NMPS) was defined as 13 mm in accordance with IRC: SP:79-2008 [21]. For SMA, the estimated ratios were 0.274 (CA), 0.676 (FAc), and 0.706 (FAf), all within the recommended bounds, confirming a well-balanced aggregate skeleton. For BC, the CA ratio was below 0.50, which is consistent with the dense-graded nature of the mix. These results verified the suitability of the selected blends for subsequent mix design.

Performance Testing

Marshall Compaction Test (Optimum Bitumen Content)

The optimal bitumen content (OBC) for Bituminous Concrete (BC) and Stone Matrix Asphalt (SMA) mixes was ascertained using the Marshall mix design process. The methodology followed the guidelines specified in ASTM D6927 [27] and IS: 1201 – 1220. Approximately 1200 g of aggregate, preheated to 175-190^{o}C, was blended with plain or biochar-modified bitumen, which had been separately heated to 121-138^{o}C. Mixing was performed at about 154^{o}C to ensure uniform coating of aggregates. A normal Marshall hammer was then used to compact the heated mixture with 50 blows on each face after it had been moved to preheated Marshall moulds. Trial specimens were prepared at varying binder contents: 6-8% (by weight of aggregates) for SMA and 4 - 6% for BC. The compacted specimens were cooled and conditioned for 24 hours before testing. Stability and flow values were determined by subjecting the specimens to loading at a constant deformation rate of 50.8 mm/min. Marshall stability was defined as the greatest load supported prior to failure, and flow value (measured in 0.25 mm increments) was defined as the corresponding deformation. These values were used to identify the OBC that achieves an optimal balance between strength, durability, and workability. Three replicates were tested at each binder level, and mean values were analysed. The theoretical maximum specific gravity (Gmm) of the asphalt mixtures was determined according to ASTM D2041. Triplicate measurements were performed for each mix to evaluate air voids and other volumetric properties, providing a baseline to assess the impact of biochar modification.

Optimum Bitumen Content (OBC) Determination

The optimum bitumen content (OBC) for the mixtures was determined using the Marshall mix design method according to IS 129-2019. The selection was based on three criteria: (i) compliance with the recommended air voids range (4±1%), (ii) attainment of maximum Marshall stability and bulk density, and (iii) satisfaction of flow values and volumetric requirements. Three replicates at each binder content were tested, and the binder content meeting all criteria was chosen as the OBC. For the control mix with conventional stone dust filler, the OBC was 5.7%, which was then applied to biochar-containing mixtures for comparative performance evaluation.

Performance Evaluation Tests:

Resistance to moisture damage

In compliance with ASTM D6931-12 [29], the Indirect Tensile Strength (ITS) test was used to evaluate the mixtures' moisture susceptibility. At 25°C and a loading rate of 50.8 mm/min, specimens with around 7% air spaces were compressed using steel strips. The ITS was calculated using:

$$ITS = 2000P / \pi DT$$

where D is the specimen diameter (mm), T is the thickness (mm), and P is the maximum load (N).

Moisture conditioning followed AASHTO T283 [24]. Specimens were divided into dry and saturated groups, with the latter subjected to partial vacuum saturation (55–80%), 16 hours of freezing at -18°C, 24 hours of immersion at 60°C, and 2 hours of conditioning at 25°C. The following was the Tensile Strength Ratio (TSR) calculated:

$$TSR = (ITS_{Wet} / ITS_{Dry}) \times 100$$

Better resilience to moisture-induced damage was indicated by a higher TSR. Three replicates per condition (dry and conditioned) were tested.

Rutting Resistance (Proportional Rut Depth)

Rutting performance was evaluated using predictive models proposed by Zieliński [25]:

$$(WTS) = 198925 * ITS^{-2.309}, \quad (PRD) = 48220 * ITS^{-1.443}$$

where WTS is the wheel tracking speed (mm/1000 cycles) and PRD is the proportional rut depth. Higher WTS and lower PRD values reflected better rutting resistance.

Experimental verification was carried out using an immersed wheel tracking test following BS EN 12697-33 [30]. Slab specimens (~6000 cm^3) compacted by a roller compactor were tested under a 710 N wheel load (47 mm width) moving at 72 passes/min in 50°C water. Rut depths were monitored using an LVDT. Biochar-modified mixes exhibited improved resistance compared to control mixes. Three replicate slabs were tested for each mix.

Modulus of Resilience

Asphalt mixes' elastic response to repeated stress is represented by the resilient modulus (M_R). Testing was performed per ASTM D7369 [31] at 35°C using the Indirect Tensile Test (IDT). Specimens were subjected to haversine-shaped loading pulses (0.1 s load, 0.9 s rest) at 10% of their ITS failure load. LVDTs were used to measure both horizontal and vertical deformations. The resilient modulus was calculated using:

$$M_r = \frac{P(0.27 + \mu)}{t.\ \Delta h}$$

$$\mu = 3.59 \frac{\Delta h}{\Delta v} - 0.27$$

where μ is Poisson's ratio, Δh is horizontal deformation, Δv is vertical deformation, t is specimen thickness (mm), and P is the applied load (N). Higher M_R values in biochar-modified mixtures indicated enhanced structural stiffness and load-bearing capacity. Three replicates were tested per mix.

Refusal Density Determination

Refusal density testing was performed to assess the densification properties of the blends, in accordance with BS EN 12697-33 [30]. Specimens were compacted using 50, 75, and 100 blows of the Marshall hammer until no further reduction in air voids was observed, indicating that the mixture had reached its maximum achievable density. This method ensures that the designed mixture maintains adequate void content even under heavy traffic compaction, thereby preventing premature rutting or bleeding in service. Three replicates were tested per compaction level.

Statistical Analysis

To ensure the reliability of experimental results and minimize the risk of random errors, statistical validation was performed on all measured parameters, including Marshall stability, indirect tensile strength (ITS), resilient modulus, and rutting resistance [24, 27, 29, 31]. Each test condition was conducted with a minimum of three replicate specimens, in line with ASTM [27, 29, 31] and IRC [21] recommendations. The mean values were compared using one-way Analysis of Variance (ANOVA) [32] for control (stone dust filler) and biochar-modified mixtures. The null hypothesis (H_0) assumed no significant difference between control and modified mixes, while the alternative hypothesis (H_1) indicated significant improvement due to biochar incorporation. The ANOVA was conducted in Minitab software at a 90% confidence level ($p < 0.10$), consistent with pavement engineering practice where slightly relaxed thresholds are often adopted to capture practical material effects [33]. Pairwise differences across mix types and binder contents were evaluated using Tukey's Honest Significant Difference (HSD) post-hoc test [34] when an ANOVA revealed significant differences. In addition, descriptive statistics (mean, standard deviation, coefficient of variation) were reported for each parameter to highlight data consistency. Effect size (η^2) was also calculated to quantify the practical impact of biochar substitution beyond statistical significance. This combined approach ensured that the observed improvements in performance parameters were both statistically valid and practically meaningful.

Results and Discussion

"Scanning Electron Microscopy (SEM)" was used to investigate the microstructural modifications in base and biochar-modified bitumen (Figure 5). The base binder displayed a relatively smooth surface with minor irregularities and micro-cracks, indicative of inherent brittleness and susceptibility to thermal and mechanical stresses. Incorporation of 5% biochar began to fill micro-voids and increase surface roughness, suggesting a denser and more homogeneous microstructure. At 10–15% biochar, the particles were uniformly dispersed, forming a porous interlocking network that improved adhesion and stiffness, enhancing resistance to rutting and thermal cracking. At 20% biochar, surface morphology became highly textured, showing signs of particle agglomeration that may lead to localized brittleness under low-temperature conditions. Fourier Transform Infrared (FTIR) spectroscopy supported these observations, showing that the carbonyl index (CI), a marker of oxidative ageing, initially increased at 10% due to the biochar's oxygenated groups. However, CI values at 15–20% were lower than the base binder, indicating that higher biochar content reduces susceptibility to oxidation and enhances long-term flexibility (Figure 6). Refusal density tests confirmed that biochar-modified BC and SMA specimens-maintained air voids above the recommended 4% threshold, even under higher compaction efforts of 100–150 blows. This indicates resistance to secondary compaction from heavy traffic, ensuring durability and preventing premature rutting.

Indirect tensile strength (ITS) results demonstrated that under unconditioned conditions, SMA exhibited an ITS of 1.80 N/mm^2, slightly lower than BC at 1.85 N/mm^2. After freeze–thaw cycles, BC retained 1.75 N/mm^2, whereas SMA decreased to 1.45 N/mm^2. Under humid conditions, BC maintained 1.85 N/mm^2, while SMA reduced to 1.60 N/mm^2. The corresponding Tensile Strength Ratio (TSR) values (Figure 7) showed BC achieving 93% under freeze–thaw and 98% in humid environments, while SMA recorded 81% and 86%, respectively. Both mixes exceeded the 80% minimum threshold recommended by the Indian Roads Congress (IRC), with BC demonstrating superior durability. ANOVA confirmed that the differences in ITS and TSR between BC and SMA were statistically significant ($p < 0.10$). Resilient modulus (M_R) measurements indicated that BC consistently outperformed SMA under all testing conditions. Comparison with predictive model values showed less than 10% variation, confirming the reliability of laboratory and theoretical estimates. Enhanced stiffness in BC is attributed to improved binder–biochar interactions and optimized filler packing.

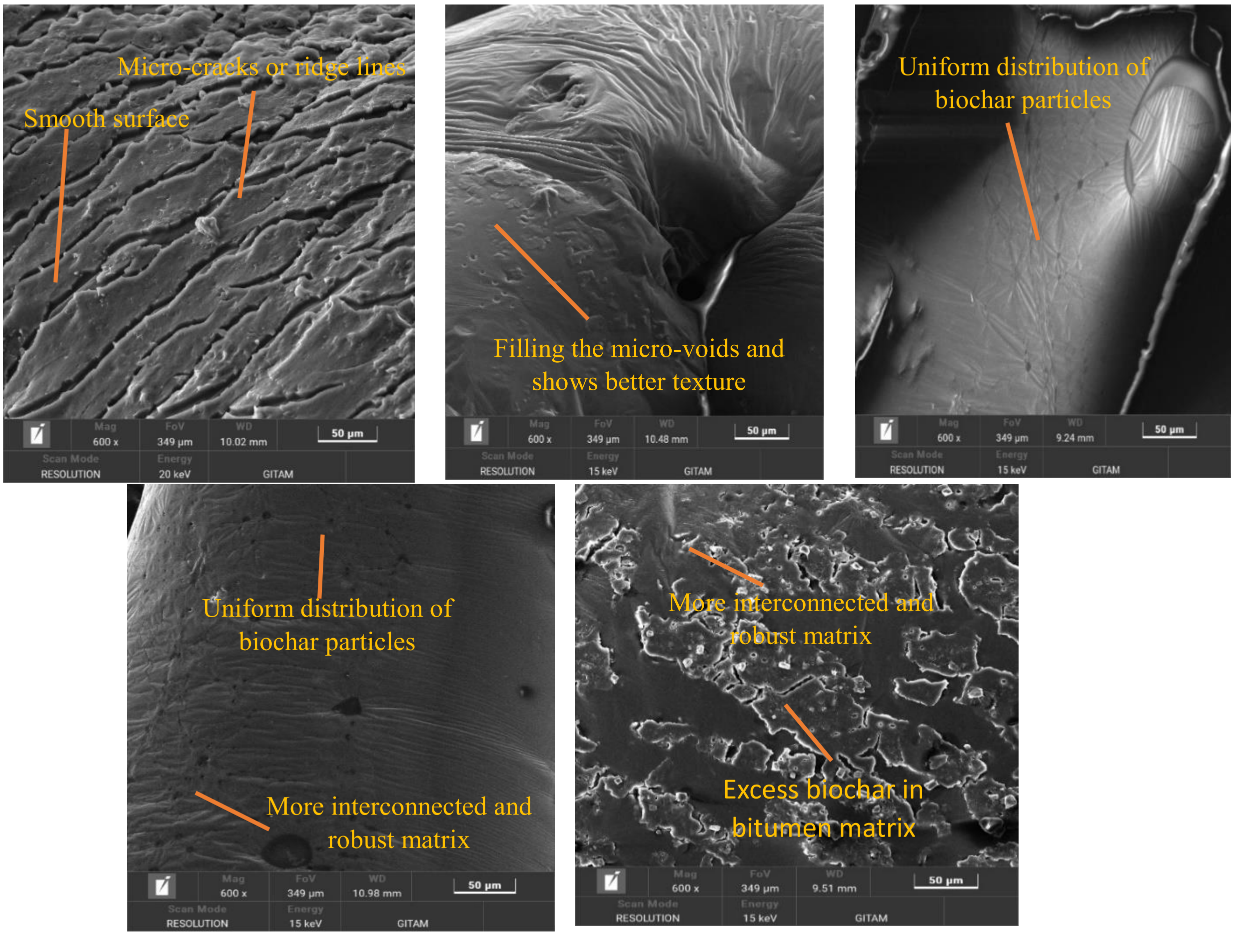

Figure 5 SEM analysis for biochar-based bitumen samples with Base bitumen, 5% biochar, 10% biochar, 15% biochar and 20% biochar at 600x magnification.

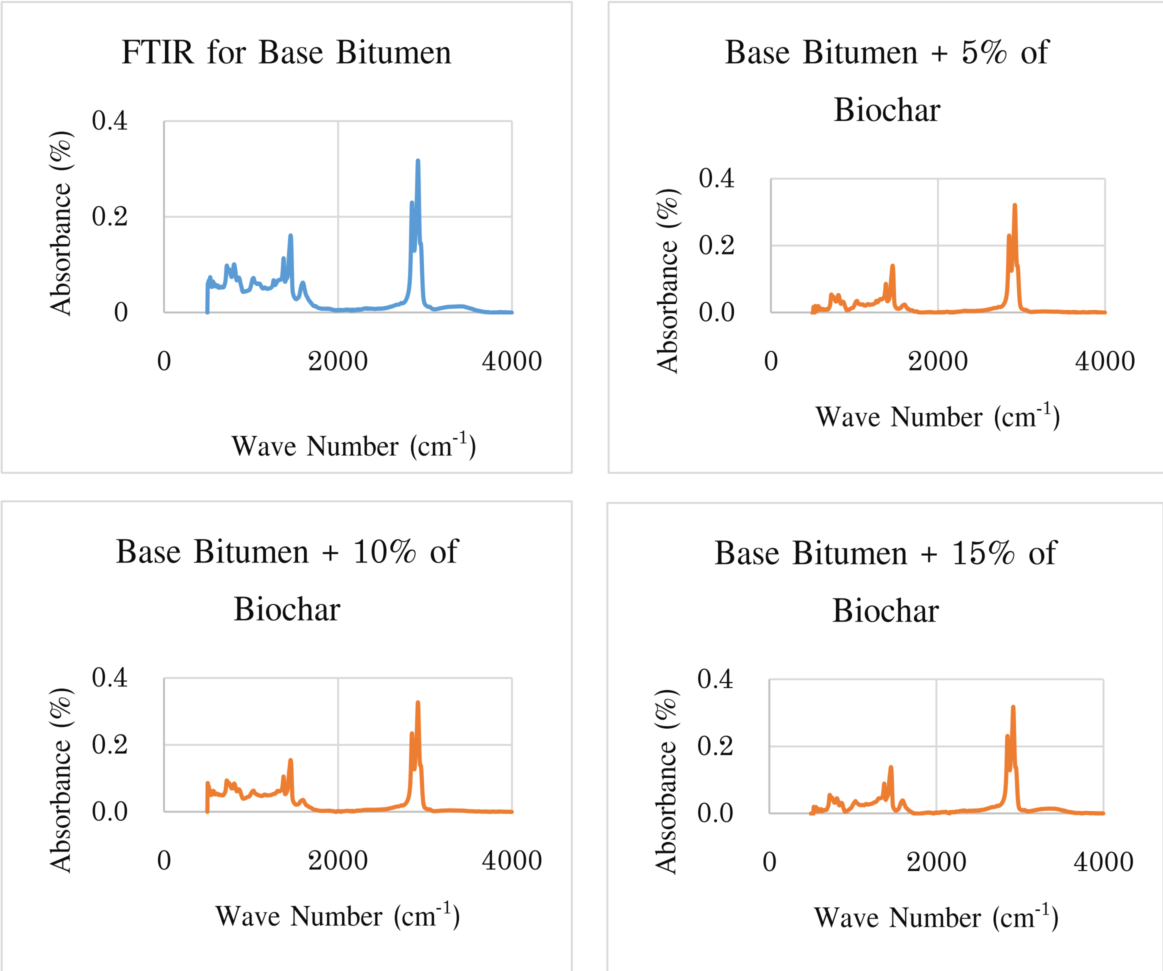

Figure 6 Spectral absorbance graphs of base and bio-bitumen binder.

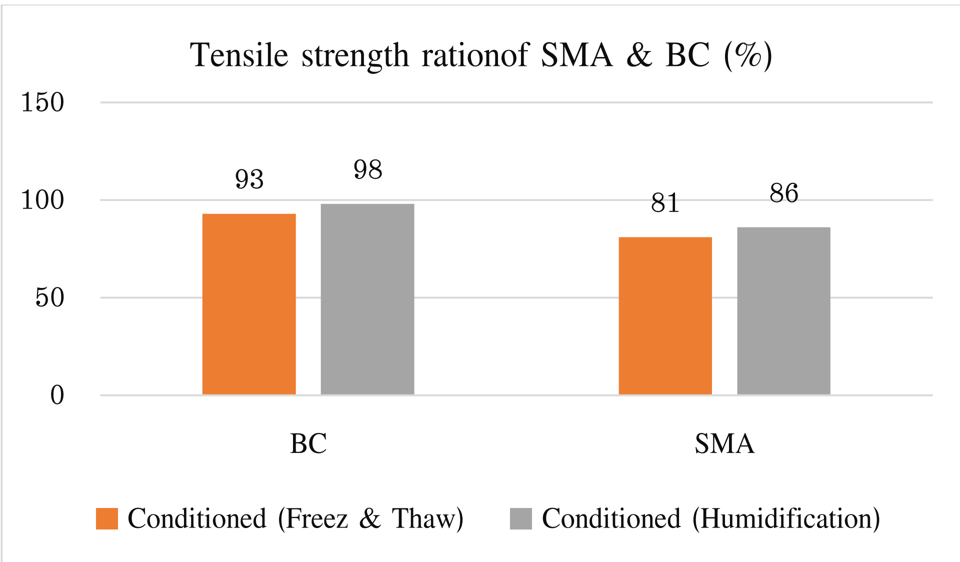

Figure 7 TSR comparison between SMA and BC.

Rutting resistance, evaluated via "proportional rut depth (PRD) and wheel tracking speed (WTS)", was higher for BC compared to SMA (Figure 8). PRD% values ranged from 1.21 to 1.33 for BC, whereas SMA ranged from 1.24 to 2.59. After 20,000 passes, rut depths were 11 mm for BC and 13 mm for SMA, both within the permissible IRC limit of <20 mm. ANOVA analysis confirmed that biochar significantly improved rutting resistance, especially in BC.

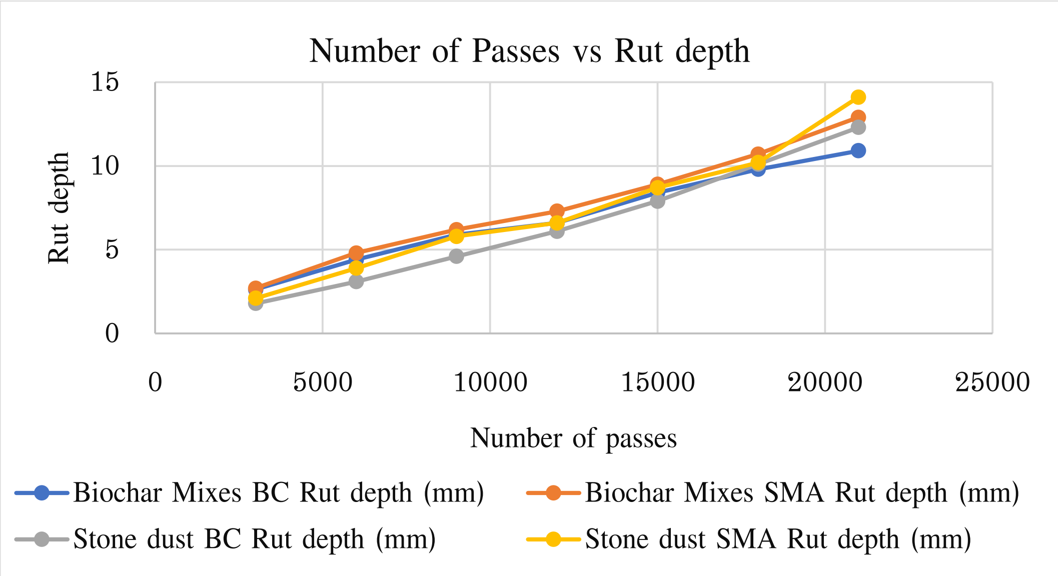

Figure 8 Rutting results comparison for modified and unmodified mixes.

Although stone dust filler yielded slightly higher mechanical performance, biochar-modified mixes satisfied all IRC specifications. The slight reduction is attributed to biochar acting partially as a binder modifier rather than solely a filler. In BC, biochar comprised approximately 43% of the binder mass, while SMA contained even higher proportions, potentially affecting the filler–binder balance. Nevertheless, biochar offers sustainability benefits through waste valorisation, VOC reduction during bitumen heating, and carbon sequestration potential, aligning with circular economy principles. On a relative basis, biochar at ₹10/kg is five times more expensive than conventional stone dust (₹2/kg). Nevertheless, the overall cost increase per ton of asphalt is moderate around 4-5% for BC and 8-10% for SMA while providing additional benefits such as carbon sequestration, waste valorization, and potential revenue through carbon credit trading.

This study, however, is limited to laboratory-scale evaluation. Future work should include long-term fatigue testing, field trials under varying environmental conditions, and integration of IoT-based bitumen fume monitoring. These data can be combined with life-cycle assessment (LCA) to completely measure biochar's environmental advantages in environmentally friendly pavement construction.

Conclusions

This study evaluated "Bituminous Concrete (BC) and Stone Matrix Asphalt (SMA)" modified with coconut shell biochar as a sustainable filler, following IRC: SP:79-2008 and MoRTH-2013 standards. SEM and FTIR analyses revealed that biochar additions in the range of 10–15% enhance microstructural integrity, improve homogeneity, and reduce carbonyl formation, thereby increasing rutting resistance and resistance to thermal and oxidative ageing. Excessive biochar addition (20%) led to particle agglomeration, increased stiffness, and potential brittleness, indicating an optimum dosage exists for peak performance. Marshall mixes design, supported by STAB-based aggregate blending, established optimum binder contents, with BC demonstrating superior performance in tensile strength, rutting, and resilient modulus across unconditioned, freeze–thaw, and humidified conditions. SMA, with a higher filler-to-binder ratio, exhibited slightly reduced flexibility and cohesion. Overall, biochar functions both as a filler and as a bitumen modifier, providing a sustainable alternative to conventional stone dust while contributing to carbon sequestration and eco-friendly pavement construction.

Future Scope

More investigation is required to validate and expand the application of biochar in asphalt mixtures. Fatigue testing should be conducted to assess long-term performance under repeated traffic loading. Field-scale trials are essential to confirm laboratory findings under varying climatic conditions and real traffic stresses. Comprehensive life cycle assessment (LCA) and economic analyses would quantify the environmental and cost benefits of biochar relative to conventional fillers. The integration of IoT-enabled sensors, digital twins, and AR/VR platforms could provide real-time monitoring of pavement health, bitumen emissions, rutting, and structural performance, supporting data-driven sustainable road construction. Additionally, exploring other biomass-derived fillers, such as rice husk ash, bagasse, and bamboo charcoal, could broaden material options and reduce reliance on a single feedstock. These directions will further enhance the durability, sustainability, and practical viability of biochar-modified pavements. Even though biochar is more expensive than stone dust, carbon credit incentives significantly reduce the net cost, making biochar a financially viable and environmentally beneficial alternative.

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