Nnamdi Azikiwe University Journal of Civil Engineering (NAUJCVE)

Volume-4, Issue-1, pp-105-114

www.naujcve.com

Research Paper Open Access

Mechanical Performance Enhancement Of Asphaltic Concrete Using Sorghum Husk Ash And Corn Cob Ash As Sustainable Fillers

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Abstract: *This study investigated the performance strength characteristics of asphaltic concrete modified with Sorghum Husk Ash (SHA) and Corn Cob Ash (CCA) as partial filler replacements. The primary aim is to enhance asphalt performance while promoting sustainable waste management through the utilization of agricultural by-products. A series of asphaltic concrete samples were prepared by replacing conventional mineral filler with varying proportions (10%, 20%, 30%, and 40%) of SHA–CCA blends at 10% intervals, ranging from 100% CCA to 100% SHA. The modified samples were evaluated based on Marshall Stability, flow, and Marshall Quotient in accordance with Federal Ministry of Works (FMW, 2016) and Asphalt Institute (AI, 1991) standards.Results revealed that ash incorporation improved asphaltic concrete properties at moderate replacement levels. The highest Marshall Stability of 21.8 kN was observed at 30% ash replacement with a 40:60 SHA–CCA ratio, while optimal flow values (2.5–3.6 mm) and Marshall Quotient values (up to 7.2 kN/mm) were recorded at 20% replacement with 60:40 SHA–CCA mix. Generally, performance improved with blended ash inclusion up to a peak point, beyond which further SHA increase led to a reduction in strength. All mixes met FMW standards for stability and flow, although AI standards for flow were not satisfied due to methodological differences.The study concludes that SHA and CCA are effective, environmentally friendly alternatives to conventional fillers, with 20–30% replacement levels offering the best balance of strength and durability. The findings support the adoption of agro-waste fillers in sustainable pavement construction.*

Keywords: *Asphaltic Concrete; Sorghum Husk Ash (SHA); Corn Cob Ash (CCA); Marshall Properties; Sustainable Pavement Materials*

Date of Submission:18-10-2025 Date of acceptance:27-10-2025

1. INTRODUCTION

The rapid urbanization and infrastructure expansion witnessed across developing countries have placed immense pressure on the demand for road construction materials, particularly bitumen and mineral fillers used in asphaltic concrete (Ajayi et al., 2025). Unfortunately, the continuous rise in the cost of conventional construction materials compounded by dwindling natural resources has significantly impeded the development of durable and economically viable road infrastructure, especially in rural and underdeveloped areas (Akinleye et al., 2021). Asphaltic concrete, a key component in flexible pavement systems, depends heavily on the quality and availability of its constituents, among which mineral fillers play a critical role in enhancing volumetric stability, improving adhesion between binder and aggregate, and optimizing mechanical performance under traffic loading conditions (Farahi et al., 2025). Traditionally, stone dust, cement, and lime have been widely used as fillers; however, their production and processing are energy-intensive and environmentally detrimental, contributing to carbon emissions and ecological degradation.

Furthermore, the scarcity and cost of these fillers have intensified the search for alternative, sustainable materials that can offer comparable or superior performance (Lu et al., 2025)

Concurrently, the challenge of agro-waste management in developing nations presents a dual environmental and public health dilemma (Fadele et al., 2021). Nigeria, for instance, is a major agricultural economy and one of the largest producers of maize and sorghum globally. The post-harvest processing of these crops generates large quantities of agricultural residues such as corn cobs and sorghum husks, which are often discarded through open burning or landfilling (Akinleye et al., 2023). These methods contribute significantly to air pollution, greenhouse gas emissions, and land degradation. However, recent studies have identified the potential of biomass-derived ashes, such as Corn Cob Ash (CCA) and Sorghum Husk Ash (SHA), as viable pozzolanic materials (Akinleye and Tijani, 2017). These ashes are rich in silica, alumina, and other oxides that enhance the physico-chemical interactions within asphalt mixes, offering opportunities for improving performance characteristics such as Marshall Stability, flow, durability, and resistance to rutting and moisture damage. Yet, despite these promising findings, there remains a substantial research gap regarding their combined utilization as mineral fillers in asphaltic concrete, particularly in optimized proportions that balance economic, mechanical, and environmental outcomes.

This study is motivated by the urgent need to identify sustainable, cost-effective, and high-performance alternatives to conventional asphalt fillers, in line with the global push towards greener construction technologies. The research investigates the synergistic effects of incorporating varying proportions of SHA and CCA as partial replacements for traditional fillers in asphaltic concrete. By systematically analyzing their influence on key mechanical properties such as stability, flow, and Marshall Quotient, this work aims to establish an optimal filler blend that meets engineering performance criteria and contributes to environmental sustainability through waste valorization. Therefore, the justification for this study is twofold: to reduce the dependency on expensive and environmentally unfriendly conventional materials and convert abundant agro-wastes into value-added construction resources. This dual approach supports sustainable infrastructure development and aligns with the United Nations Sustainable Development Goals (SDGs), particularly those related to sustainable cities, climate action, and responsible consumption and production.

II. MATERIALS AND METHODS

This study employed a systematic experimental approach to evaluate the suitability of Corn Cob Ash (CCA) and Sorghum Husk Ash (SHA) as sustainable mineral fillers in asphaltic concrete mixtures. The methodology integrated comprehensive material characterization, rigorous testing based on internationally recognized standards, and the Marshall Mix design procedure to assess performance outcomes of modified asphalt mixtures.

2.1 Materials and Characterization

All materials were locally sourced in Osun State, Nigeria, ensuring practical relevance and economic viability. Coarse aggregates (crushed granite), fine aggregates (sharp sand), and quarry dust were procured from quarries in Ede and evaluated for gradation, specific gravity, moisture content, water absorption, abrasion resistance, impact value, and crushing strength under BS 812, ASTM C136, and ASTM C127 standards. The particle size distributions were analyzed to determine the Coefficient of Uniformity (Cu) and Curvature (Cc), vital for aggregate classification and performance forecasting in asphalt matrices (Ajagbe et al., 2020).

CCA and SHA were obtained through controlled combustion of corn cobs and sorghum husks, respectively, followed by fine sieving using a 75 µm sieve to enhance particle compatibility with bituminous matrices. The ashes were characterized via X-ray Fluorescence (XRF) to determine their oxide compositions and assess their pozzolanic potential and filler behavior. A penetration-grade (60/70) bitumen was used as the binder, with its physical properties such as penetration, softening point, ductility, and flash point tested according to ASTM D5, D36, D113, and D92 to verify conformity with construction-grade standards.

This study utilized locally sourced materials to ensure sustainability and cost-effectiveness. The materials included coarse aggregate (crushed granite), fine aggregate (sharp river sand), quarry dust, corn cob ash (CCA), sorghum husk ash (SHA), and bitumen (60/70 grade). All materials were subjected to relevant physical, mechanical, and chemical tests to determine their suitability for asphalt concrete production.

Crushed granite was sourced from a quarry in Ede, Osun State. Physical tests conducted include sieve analysis, specific gravity, moisture content, water absorption, Los Angeles abrasion, aggregate impact, and crushing value, in accordance with BS and ASTM standards.Sharp river sand, also sourced from Ede, was subjected to sieve analysis, specific gravity, moisture content, and water absorption tests.Quarry Dust was obtained from the same quarry, quarry dust was evaluated for gradation, specific gravity, moisture content, and absorption capacity.Corn cobs were collected, washed, dried, and calcined in a furnace at a controlled temperature of 600°C for 4 hours. The resulting ash was sieved through a 75 µm sieve and analyzed via X-Ray Fluorescence (XRF) to determine its oxide composition.SHA was produced similarly to CCA and also analyzed using XRF to identify pozzolanic constituents.Penetration-grade bitumen (60/70) was procured from Ogun State and tested for penetration, flash point, ductility, and softening point according to ASTM and AASHTO specifications.

The experimental design employed a partial replacement approach, where quarry dust (QD) was incrementally replaced by a combined mixture of SHA and CCA at 10% intervals, ranging from 0% to 100%. Within each combined filler percentage, the proportions of SHA and CCA were also varied systematically from 0:100 to 100:0. This factorial design enabled the exploration of a wide composition spectrum, facilitating robust performance comparisons and statistical evaluations.

A comprehensive experimental mix design was developed to evaluate the performance of asphaltic concrete incorporating varying proportions of Quarry Dust (QD), Corn Cob Ash (CCA), and Sorghum Husk Ash (SHA) as mineral fillers. A total filler replacement of 100% (by weight of mineral filler) was adopted and QD was replaced in 10% intervals (0–100%), also, CCA and SHA were varied within the combined 100% of remaining filler, also in 10% intervals while the Control Mix was 100% Quarry Dust (no CCA or SHA). Table 1 shows the experimental design table. This design yielded a ternary blend matrix to assess the performance of different combinations.

2.2 Mix Design and Sample Preparation

Table 1: Experimental Design Mix Matrix

QD (%)	CCA (%)	SHA (%)	Combined Filler (%)
100	0	0	0
90	10	0	10
90	0	10	10
80	20	0	20
80	10	10	20
80	0	20	20
70	30	0	30
70	20	10	30
70	10	20	30
70	0	30	30
...	...	...	...
0	0	100	100

Note: Full design matrix spans from 0% to 100% QD and reverse for SHA+CCA in 10% intervals.

Bituminous concrete samples were produced using the **Marshall Mix Design** procedure (ASTM D6927). A fixed bitumen content of 4.5% by aggregate weight was maintained across all mixes. Aggregates and fillers were heated to 175–190°C and mixed with pre-heated bitumen at 120–125°C to achieve homogeneity. Approximately 1200g of mix was compacted in a pre-heated mold using 50 blows per side per standard procedure to fabricate cylindrical specimens with a target thickness of 63.5 ± 3 mm. Each specimen was demolded, cured, and conditioned before testing.

2.3 Laboratory Testing Procedures

The Aggregate Testing carried out include: Gradation (ASTM C136 / BS 812:103.1), Moisture Content (BS 812:109), Specific Gravity (ASTM C127 / BS 1377), Los Angeles Abrasion Value (ASTM C131, BS 812:113), Aggregate Impact Value (BS 812:112), and Aggregate Crushing Value (BS 812:110). The Bitumen Testing include: Penetration (ASTM D5), Flash and Fire Point (ASTM D92), Ductility (ASTM D113), Softening Point (ASTM D36).

To determine the mechanical and volumetric properties of the modified asphaltic concrete, a series of performance evaluations were conducted:

i. **Marshall Stability and Flow**: The specimens were tested at 60°C to determine the maximum load (kN) they could sustain before failure and the corresponding deformation (flow) in 0.25 mm increments. This provides insight into load-bearing capacity and plastic deformation tendencies.
ii. **Bulk Density and Voids Analysis**: Each specimen was analyzed for bulk density, air voids (Va), voids in mineral aggregate (VMA), and voids filled with bitumen (VFB), essential parameters in optimizing mix durability, stability, and workability.
iii. **Specific Gravity Tests**: Carried out on aggregates using the pycnometer method to inform the volumetric calculations and confirm compliance with mix design requirements.
iv. **Durability and Strength Tests on Aggregates**: Including Los Angeles Abrasion, Aggregate Crushing Value (ACV), and Aggregate Impact Value (AIV), these tests evaluated the resistance of aggregates to mechanical degradation under traffic loading.
v. **Bitumen Property Tests**: Penetration, ductility, softening point, and flash point were measured to validate the thermal and mechanical suitability of the binder for hot-mix asphalt production.

2.4 Data Analysis

Data obtained from laboratory tests were systematically analyzed using both descriptive and inferential statistical methods. The average values from triplicate tests were computed to ensure accuracy and minimize experimental error. Marshall properties such as stability, flow, bulk density, and air voids were compared across the various mix compositions to identify performance trends. Graphical representations (e.g., bar charts and line graphs) were used to visualize the effect of CCA and SHA on asphalt performance. The optimal mix was selected based on its compliance with standard specifications and its overall mechanical performance.

III. RESULTS AND DISCUSSION

3.1 Characterisation of Aggregate Materials Used for Asphalt Mix Production

The particle size distribution results for fine aggregate, mineral filler, and coarse aggregate indicate varying gradation characteristics. Fine aggregates were found to be poorly graded with Cu and Cc values of 2.7 and 1.06, respectively, as per ASTM D-2487. In contrast, the mineral filler and coarse aggregates were classified as well-graded materials, with Cu and Cc values of 1.6 & 1.19 and 1.7 & 0.98, respectively. The mineral filler also met the required 85% passing the 75-micron sieve, achieving 92%, which confirms its suitability. Overall, the coarse aggregates exhibited desirable physical and mechanical properties, making them suitable for use in both hot and warm asphalt mixtures used in this study.

3.2 Physical and Mechanical Properties of Coarse Aggregate for Asphalt Mixes

The physical and mechanical properties of the coarse aggregates used in the asphalt mixes were evaluated and presented in Table 2. The results showed that the aggregates met all the standard requirements for use in asphalt pavement construction. Key parameters such as specific gravity, water absorption, aggregate crushing value (ACV), and Los Angeles abrasion value (LAAV) were within acceptable limits, indicating good strength, durability, and resistance to wear and tear. These properties confirm the suitability of the selected coarse aggregates for producing high-quality hot and warm mix asphalt, contributing to the overall performance and longevity of the pavement structure.

Table 2: Engineering Properties of Coarse Aggregate for Asphalt Mixes

Test carried out	Obtained Test Results	Standard (Nigerian)	Remarks
Aggregate Impact value	19.2%	30% maximum	Adequate
Aggregate Crushing value	42.4%	45% maximum	Adequate
Los Angeles Abrasion	48.92	60% maximum	Adequate
Flakiness Index	28.62	30% maximum	Adequate
Elongation Index	29.53	30% maximum	Adequate
Density	1500.20 kg/m^3	-	-
Specific Gravity	3	3 Maximum	Adequate

3.3 Properties of Bitumen

Table 3 shows the properties of bitumen used for the study. From the table, the average penetration value for the bitumen used is 70 mm, this is in compliance with both FMW and ASTM standards for bitumen penetration which ranges from 60-70. Also, the softening point value of the bitumen complies with both the ASTM and FMW standards. Meanwhile, the ductility value of 90cm complies with the FMW and BIS standard. Furthermore, the specific gravity of 0.97 falls within the range of ASTM standard but deviate from FMW standard. Additionally, flash point value falls within the specifications of FMW and ASTM standards while the viscosity shows compliance with the BIS standard. The overall results gotten demonstrates the characteristics of the bitumen utilized for the study fall within the specification of the standards.

Table 3: Properties of the bitumen used for asphaltic production

		Penetration (mm)	Softening (°C)	Ductility (cm)	Viscosity (secs)	Flash Point (°C)	Fire Point (°C)	Specific Gravity
Test Results		70	48	90	76	255	308	0.97
Standard Range	FMW	60-70	48-56	≤100	-	Min.250	-	1.01-1.06
	ASTM	60-70	47-58	-	-	Min. 230	-	0.97-1.06
	BIS	-	-	≥75	≥70	-	-	-
	AI	-	>50	5-100	-	-	-	

N. B.: AI is Asphalt Institute (1991); BIS is Bureau of Indian Standards (1986); ASTM is American Society of Testing and Materials, D2041 for specific gravity; D36-95 for softening and D5-97 for penetration, and FMW is Federal Ministry of Works (2007).

3.4 Mix Proportion

The summary of Marshall Test results of the bitumen used to determined OBC for the asphalt mix is as presented in Table 4, from the table, the optimum bitumen content (OBC) gotten for the asphalt mix is 6.3. which falls within the range of FMW (2016) specification. Consequently, the Marshall mix design ratio will be 6.3:7:21: 65.7, which is interpreted as the proportions of filler, fine aggregate, coarse aggregate, and bitumen content.

Table 4 Mix design of Asphalt

BC	WT OF CA	WT OF FA	WT OF FILLER	WT OF BITUMEN	SG OF MATERIALS		PARAMETERS
8	816	72	216	96	CA	2.8	MAX STABILITY
7.5	810	72	252	90	FA	2.6	MAX GM
7	804	72	252	84	FILLER	1.9	Vv @4%
6.5	798	72	252	78	BITUMEN	0.98	AVERAGE
6	792	72	252	72	THEREFORE, OBC= 6.3		Therefore, the Marshall Mix Design ratio will be 65.7: 7: 21: 6.3 CA: FA: FILLER: BC
5.5	786	72	252	66			
5	780	72	252	60			

3.5 Marshall Properties for Modified Asphaltic Concrete

The Marshall tests were conducted to evaluate the performance of asphalt mixtures modified with different proportions of Sorghum Husk Ash (SHA) and Corn Cob Ash (CCA) at 10%, 20%, 30%, and 40% total ash content. For each level of replacement, the SHA:CCA ratio varied from 0:100 to 100:0 in 10% increments (e.g., 10A = 0% SHA, 100% CCA; 10K = 100% SHA, 0% CCA). The properties measured include weight in air, weight in water, stability, flow, and Marshall Quotientas presented in Table 5.

Overall, the results showed that stability generally increased with ash content up to 30% replacement, with peak stability values around samples with balanced SHA-CCA mixes. For instance, the highest stability was observed in sample 30E (21.8 kN) and 30F (21.5 kN). The Marshall Quotient, which indicates the mixture's strength and stiffness, also peaked around these compositions, confirming optimal performance at 30% ash replacement. However, at 40% replacement, both stability and Marshall Quotient values began to decline, with the lowest observed in sample 40K (13.8 kN, MQ = 4.6), indicating possible over-replacement and weaker mechanical performance.

All samples mostly met or exceeded the Federal Ministry of Works (FMW) and Asphalt Institute (AI) standards for flow (2–6 mm) and minimum Marshall Stability (8–16 kN), though a few values at 40% replacement slightly underperformed.

Table 5: Marshall Properties of Modified Asphalt Mixtures

Ash Replacement (%)	Sample	SHA:CCA (%)	Stability (kN)	Flow (mm)	MQ (kN/mm)
10%	10A	0:100	17.0	3.5	4.9
	10E	40:60	19.6	3.2	6.2
	10K	100:0	16.2	2.3	7.0
20%	20A	0:100	17.1	3.6	4.8
	20F	50:50	20.8	3.1	6.7
	20K	100:0	15.8	2.5	6.4
30%	30A	0:100	18.4	3.8	4.8
	30E	40:60	21.8	3.6	6.1
	30K	100:0	16.1	3.0	5.4
40%	40A	0:100	14.3	4.0	3.6
	40F	50:50	18.6	3.5	5.3
	40K	100:0	13.8	3.0	4.6

3.6 Marshall Stability and Flow (10–40% Ash Replacement)

The Marshall Stability and Flow tests for asphaltic concrete modified with varying ratios of Sorghum Husk Ash (SHA) and Corn Cob Ash (CCA) at 10%, 20%, 30%, and 40% replacement levels reveal a consistent trend across all mixtures. Stability generally increased with the inclusion of SHA up to a certain ratio before declining, indicating an optimal SHA:CCA blend that enhances performance. For each ash content level, the highest Stability was observed at mid-range SHA:CCA ratios specifically, 50:50 at 10% and 40%, 60:40 at 20%, and 40:60 at 30% replacement with maximum values of 19.8 kN, 21.5 kN, 21.8 kN, and 18.6 kN respectively as shown in Table 6. Conversely, Flow values steadily decreased as SHA content increased, showing that SHA stiffens the mix, while CCA improves workability. All results for both Stability and Flow fell within FMW (2016) specifications (≥8 kN and 2–6 mm respectively), though none met the Asphalt Institute's broader flow standard (8–16 mm) due to methodological differences.

Table 6: Peak Stability and Flow at Various Ash Replacement Levels

Ash Replacement (%)	Peak Stability (kN)	SHA:CCA Ratio at Peak	Flow at Peak (mm)	SHA:CCA Ratio at Max Flow	Flow (Max) (mm)
10%	19.8	50:50 (10F)	3.5	0:100 (10A)	3.5
20%	21.5	60:40 (20G)	3.6	0:100 (20A)	3.6
30%	21.8	40:60 (30E)	3.8	0:100 (30A)	3.8
40%	18.6	50:50 (40F)	4.0	0:100 (40A)	4.0

3.7 Stability

An asphalt concrete Stability refers to its capacity to withstand deformation under pressure. The Stability values for 10%, 20%, 30% and 40% Ash replacement are shown in Table 5. From the table, the Stability values increased from 0% SHA and 100% CCA mix proportion till it got to 50:50%, 60:40%, 40%:60% and 50%:50% for 10%, 20%, 30% and 40% ash replacements respectfully where decrease in the Stability value was recorded. Furthermore, the table show that the Stability value at 0% SHA and 100% CCA is high compared to 100% SHA and 0% CCA. The result also showed that addition of SHA increased the Stability value of the sample to a point where it started decreasing.

Additionally, the result showed that 30% ash replacement shows maximum Stability value of 21.8kN at 30E which is 40% SHA and 60% CCA mix proportion compared to other percentage ash replacements this shows that 30% ash replacement with 40% SHA and 60% CCA displays the best Stability value and strength and can be adopted in asphaltic concrete production these deviates from the result gotten by Akinleye *et al,* (2020).

Meanwhile, the results gotten revealed that all the values obtained for Stability satisfy the required FMW (2016) specification. Consequently SHA-CCA combination could be adopted in asphaltic concrete production as partial replacement for filler materials.

3.8 Marshall Flow

The flow values for 10%, 20%, 30% and 40% ash replacements are also presented in Table 5. From the table, it can be observed that the flow decreased with increasing SHA content. Like Stability, SHA significantly affects flow of asphaltic concrete which is shown in the result as percentage SHA increased from 10% (i.e 10B, 20B, 30B and 40B) the flow value decreased and this follows the same trend till when CCA is totally replaced by SHA i.e 100% SHA. This reduction in flow values as SHA is introduced shows the impact of SHA not only in flow but also in Stability of asphaltic concrete. Also, CCA improves the properties of asphaltic concrete compared to how SHA does. Furthermore, 4.0mm flow values are recorded as the samples with highest Stability value for 40% ash replacement which doesn't follow the trend of Akinleye (2020). Meanwhile All values obtained satisfy the requirement specified by FMW (2016) specification, but none of the values meet up with the requirement of AI (1991) due to the different test procedures adopted by FMW (2016) for Marshall Stability.

3.9 Marshall Quotient

The Marshall Quotient (MQ), defined as the ratio of Marshall Stability to Flow, is a vital parameter for evaluating the rutting resistance and stiffness of asphaltic concrete. Analysis across all replacement levels (10%, 20%, 30%, 40%) revealed that MQ values generally increased with rising SHA content, reaching a peak before declining at higher SHA proportions—though the decrease was not always uniform. The 20% ash replacement showed the highest MQ value of 7.2 kN/mm at a 60:40 SHA:CCA ratio, indicating optimal performance in terms of stiffness and resistance to permanent deformation. Conversely, the lowest MQ value of 3.6 kN/mm was recorded at 40% ash replacement with 0% SHA as shown in Table 7, highlighting that excessive ash content, especially with high CCA dominance, may weaken structural performance. These findings are consistent with the conclusions of Mistry et al. (2018) and Choudhary et al. (2020), confirming that higher MQ values enhance rutting resistance and load-bearing capacity. Ultimately, moderate ash replacement with balanced SHA and CCA ratios offers the most favourable mechanical properties.

Table 7: Marshall Quotient for All Ash Replacement Levels

Ash Replacement (%)	Sample with Peak MQ	SHA:CCA (%)	MQ Value (kN/mm)	Sample with Lowest MQ	SHA:CCA (%)	MQ Value (kN/mm)
10%	10K	100:0	7.0	10A	0:100	4.9
20%	20G	60:40	**7.2**	20A	0:100	4.8
30%	30E	40:60	6.1	30A	0:100	4.8
40%	40F	50:50	5.3	40A	0:100	**3.6**

IV. CONCLUSION

This study evaluated the performance strength characteristics of asphaltic concrete modified with Sorghum Husk Ash (SHA) and Corn Cob Ash (CCA) as partial filler replacements. A comprehensive investigation into the physical, mechanical, and Marshall properties of the modified asphalt mixes was carried out across varying ash replacement levels (10%, 20%, 30%, and 40%) and SHA–CCA blend ratios.

From the results, it was observed that the incorporation of SHA and CCA significantly influenced the strength behavior of asphaltic concrete. The Marshall Stability values increased with the inclusion of both ashes, reaching optimal performance at 50:50 and 60:40 SHA–CCA proportions depending on the total replacement level. Specifically, the highest stability of 21.8 kN was recorded at 30% ash replacement with 40:60 SHA–CCA mix, while 20% replacement also showed excellent results with 21.5 kN at 60:40 SHA–CCA ratio. Marshall Flow values decreased with increasing SHA content, indicating increased stiffness, with all values falling within the FMW (2016) specification of 2–6 mm, although deviating from AI (1991) due to procedural differences.

Furthermore, the Marshall Quotient, a measure of rutting resistance, peaked at 7.2 kN/mm for the 20% ash replacement at 60:40 SHA–CCA, indicating enhanced deformation resistance and load distribution capacity at moderate ash levels. In contrast, the 40% ash replacement consistently showed lower strength and stiffness values, suggesting it may be less suitable for heavy-duty pavement applications.

Overall, the study confirms that SHA and CCA are viable, eco-friendly filler alternatives for asphalt modification, especially at 20–30% replacement levels with balanced SHA–CCA ratios. The study recommends an optimal replacement levels of 20–30% total ash content are recommended for practical use in flexible pavement layers to balance strength, workability, and durability. Also, a 50:50 or 60:40 SHA–CCA mix ratio is ideal for achieving the best mechanical properties, particularly in terms of Marshall Stability and resistance to rutting.Further research should explore the long-term durability, moisture susceptibility, and field performance of SHA-CCA modified asphalt under varying climatic and traffic conditions.

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