

OPTIMIZATION OF COCONUT SHELL ASH AS A BITUMEN MODIFIER USING MARSHALL STABILITY PROPERTIES

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ABSTRACT

The quest for sustainable pavement materials has led to the exploration of agricultural waste products like coconut shell ash (CSA) as potential modifiers for asphalt. This study evaluates the efficacy of CSA as a bitumen modifier in flexible pavements. Specifically, the research investigates the influence of varying CSA percentages on the Marshall Properties of asphalt concrete mixtures to determine an optimal incorporation level. Conventional 60/70 penetration grade bitumen was modified with CSA at percentages of 5%, 10%, 15%, 20%, and 25% by weight. The fundamental properties of the base materials were characterized, and the Marshall properties of the resulting asphalt mixtures were assessed. Results indicated a non-linear relationship between CSA content and performance. Marshall Stability increased to a maximum of 4.1 kN at 10% CSA content, with a value of 3.8 kN at 5% CSA; both values meet the specification requirements (≥ 3.5 kN) of the Federal Ministry

Introduction:

Flexible pavements are critical infrastructure components, providing durable and safe surfaces for transportation networks. The performance and longevity of these pavements are largely dependent on the quality of the asphalt binder used (Venkatesh & Prakash, 2010). Conventional bitumen, such as the widely used 60/70 penetration grade, is effective but has inherent limitations, including susceptibility to temperature variations, aging, and rutting under heavy traffic loads (Ahmed & Sandeep, 2023; Kumar & Dixit, 2014). These challenges have spurred extensive research into modifying bitumen with various additives to enhance its engineering properties and durability (Huang,

of Works and Housing. However, stability significantly declined to 3.1 kN at higher CSA percentages (15-25%). Flow values remained within acceptable limits (2-4 mm) for mixes containing 5% and 10% CSA. The study concludes that CSA can effectively enhance the performance of asphalt concrete when used as a modifier at an optimal content of 5% to 10%, offering a promising solution for sustainable waste valorization in pavement construction.

Keywords: Coconut shell ash, Flexible pavement, Bitumen modifier, Marshall stability, Sustainable construction, Waste valorization.

2008). Concurrently, the management of agricultural waste presents a significant global environmental concern. The coconut industry, in particular, generates substantial waste in the form of shells, which are often discarded or burned openly, contributing to pollution (Agyeman et al., 2022). Finding sustainable, value-added applications for such waste is a priority aligned with circular economy principles. Coconut Shell Ash (CSA), a byproduct of controlled combustion, is rich in carbon and silica, possessing properties that make it a potential modifier for construction materials (Abdullah et al., 2019). Its utilization offers a dual benefit of waste valorization and material enhancement, a concept explored in various geotechnical and construction applications (Behera & Sahu, 2016; Nair & Madhusoodanan, 2015).

Previous studies have explored the use of various waste materials, including fly ash, plastic, and crumb rubber, as bitumen modifiers with promising results. Specifically for CSA, research indicates that its incorporation can alter the physical properties of bitumen, such as increasing the softening point and reducing penetration, thereby improving resistance to temperature susceptibility (Mohd et al., 2017; Ramadhansyah et al., 2019). Furthermore, CSA has been investigated as a filler in asphalt concrete, with some studies reporting improvements in Marshall stability and durability at optimal replacement percentages (Emmanuel et al., 2021; Suchithra, 2021).

However, the existing body of literature reveals inconsistencies regarding the optimal percentage of CSA and its comprehensive effects on the performance of asphalt mixtures. Many studies focus on CSA as a filler or aggregate replacement, but a clear systematic investigation into its effects as a bitumen modifier across a range of percentages is needed. The impact of CSA on key Marshall mix design parameters; stability and flow; requires further elucidation to establish standardized guidelines for its application.

Therefore, this study aims to systematically evaluate the effects of Coconut Shell Ash powder on the performance of asphalt in flexible pavements. Specifically, the research

investigates the influence of varying CSA percentages (5%, 10%, 15%, 20%, and 25%) on the Marshall Stability and flow values of asphalt concrete mixtures to determine an optimal incorporation level.

Literature review

The pursuit of enhanced asphalt performance and sustainable construction practices has driven research into various bitumen modifiers. Conventional bitumen, while effective, is prone to issues such as thermal cracking, rutting, and aging (Huang, 2008). To address these limitations, researchers have explored a wide range of modifiers, including industrial and agricultural wastes, offering the dual benefits of improved pavement properties and waste management (Behera & Sahu, 2016).

Among agricultural wastes, coconut shell (CS) and its byproducts have garnered significant attention. The global coconut industry generates substantial waste, with shells often being disposed of through open burning, leading to environmental pollution (Agyeman et al., 2022). Coconut Shell Ash (CSA) is rich in carbon and silica, and its properties—such as low specific gravity, high porosity, and resistance to crushing—make it a promising candidate for construction applications (Abdullah et al., 2019). Research has explored its use both as an aggregate replacement and as a filler or modifier in bituminous mixes.

Studies focusing on CSA as a filler material have reported positive outcomes. Ahmed & Sandeep (2023) compared CSA with fly ash as a filler in bituminous concrete. They found that a 3% CSA content yielded a maximum Marshall stability of 22.6 kN, significantly higher than the 17.3 kN achieved with fly ash at 2.5%. The study concluded that CSA meets all filler specifications, enhancing stability and reducing air voids, thus proving to be a durable and cost-effective alternative. Similarly, Suchithra (2021) investigated CSA as a filler at percentages ranging from 4.5% to 6%, noting that the modified bitumen showed improved properties in all aspects, including workability and strength, compared to pure bitumen.

When used as a bitumen modifier, CSA has been shown to significantly alter the rheological properties of the binder. Mohd et al. (2017) investigated the effect of CSA fineness on 60/70 penetration grade bitumen. Their results indicated that the incorporation of CSA increased the softening point and viscosity while decreasing the penetration value, thereby improving the bitumen's resistance to temperature susceptibility. The study highlighted that the finest particle size ($<75\mu\text{m}$) yielded the best results and that modification helped mitigate the effects of aging. Ramadhansyah et al. (2019) supported these findings, reporting that the addition of 2% to 4% CSA by weight of bitumen improved the stability and permanent deformation characteristics of

asphalt mixtures, as evidenced by enhanced resilient modulus and dynamic creep performance.

Beyond its direct effects on bitumen, research has also examined the performance of asphalt concrete incorporating CSA as a partial aggregate replacement. Yaacob et al. (2017) evaluated the stiffness modulus and dynamic creep properties of asphaltic concrete with CSA replacing conventional aggregates at 0% to 40% by volume. The study found that a 15% replacement level optimally increased the resilient modulus and creep stiffness, demonstrating the potential of CSA as a sustainable road construction material. The effectiveness of CSA is often attributed to its inherent material properties. It has a high lignin content, similar to hardwoods, which contributes to durability and abrasion resistance (Nagarajan et al., 2014). Furthermore, its microporous structure, characteristic of activated carbon, provides excellent absorption qualities (Olowoyo & Orere, 2012). These properties promote better cohesion within the asphalt matrix. Emmanuel et al. (2021) provided evidence for this, demonstrating that a 3% optimum CSA content as a void filler increased the durability and elastic modulus of asphalt concrete, attributing the improvement to reduced air voids and increased mixture density.

The broader context of waste utilization in asphalt modification reinforces the validity of exploring CSA. Studies on other materials, such as Palm Oil Fuel Ash (POFA) and crumb rubber, have shown similar trends of increased hardness, higher softening points, and improved aging resistance upon their incorporation into bitumen (Hainin et al., 2014; Norhidayah et al., 2015). This consistency in findings across different waste materials underscores the potential of agricultural byproducts as viable modifiers.

Despite the promising results, the existing literature reveals inconsistencies, particularly regarding the optimal percentage of CSA incorporation. While some studies recommend levels as low as 2-4% (Ramadhansyah et al., 2019) or 3% (Emmanuel et al., 2021), others have tested higher percentages with varying outcomes. This discrepancy highlights a critical research gap: the need for a systematic investigation into the effects of a wider range of CSA percentages (e.g., 5% to 25%) on the key Marshall properties of asphalt mixtures. Therefore, this study aims to fill this gap by comprehensively evaluating the impact of varying CSA percentages (5%, 10%, 15%, 20%, and 25%) on the Marshall Stability and flow of 60/70 grade bitumen, thereby determining an optimal incorporation level for flexible pavement applications.

Methodology

This study adopted an experimental research design to investigate the effect of Coconut Shell Ash (CSA) powder as a modifier on the properties of 60/70 penetration grade bitumen and the performance of the resulting asphalt concrete mixtures. The research

methodology followed a systematic approach beginning with material preparation and characterization, followed by the preparation and testing of modified asphalt mixtures. The binder used was 60/70 penetration grade bitumen, sourced from Abubakar Tafawa Balewa University, Bauchi's transport laboratory. Coarse and fine aggregates, including crushed granite (12.5mm and 10mm nominal sizes), stone dust, and river sand, were obtained from local quarries. Coconut shells were sourced from a local market, cleaned, sun-dried, and subjected to controlled combustion to produce ash. The resulting ash was ground and sieved to obtain a fine powder with particles passing the 75 μ m sieve, consistent with conventional filler size.

The experimental program commenced with the characterization of all constituent materials. The bitumen was tested for penetration (ASTM D5), softening point (Ring and Ball Method), and specific gravity (ASTM D70). The aggregates were evaluated through sieve analysis (ASTM C136), specific gravity (ASTM C127 & C128), and mechanical properties including Aggregate Crushing Value (BS 812-110), Aggregate Impact Value (BS 812-112), Los Angeles Abrasion (ASTM C131), and Flakiness Index (BS 812-105.1). While standard characterization of the base 60/70 bitumen was conducted (penetration = 65.01), this study focuses on evaluating CSA's effects through the performance of the final asphalt mixture using Marshall Stability tests. The modification's effectiveness is therefore assessed through composite material performance.

The core of the investigation involved the Marshall Mix design method (ASTM D6927). The optimum binder content (OBC) for the control mix—containing 0% CSA—was first determined to be 6.1% by weight of the total mix. Using this OBC as a baseline, asphalt mixtures were then prepared by replacing a portion of the bitumen with CSA powder at five distinct percentages: 5%, 10%, 15%, 20%, and 25% by weight of the bitumen. For each CSA percentage, three cylindrical specimens (63.5 mm height and 101.6 mm diameter) were fabricated and compacted with 75 blows per face using a Marshall compactor to simulate medium traffic conditions.

The key performance indicator for the asphalt mixtures was the Marshall Stability and Flow test (ASTM D6927). This test measures the resistance to plastic flow under a gradually applied load, providing stability (in kN) and flow (in mm) values. The results for the CSA-modified mixtures were critically compared against the control mix and relevant standard specifications to evaluate the efficacy of CSA as a bitumen modifier.

Results and Discussions

The experimental results are presented and discussed in two main parts: first, the characterization of the constituent materials (aggregates and bitumen), and second, the performance of the asphalt mixtures modified with Coconut Shell Ash (CSA).

Material Characterization:

The properties of the aggregates and base bitumen were established to ensure they met standard specifications for asphalt production. The specific gravity of the coarse and fine aggregates was found to be 2.65 and 2.60, respectively, falling within acceptable ranges. The Aggregate Crushing Value (ACV) of 28.95% indicated an aggregate with satisfactory resistance to crushing under load. The 60/70 penetration grade bitumen had a penetration value of 65.01 mm at 25°C and a specific gravity of 1.01, confirming its standard properties before modification. The results are summarized in Table 1.

Table 1: Properties of Base Materials

Material	Test	Standard	Result	Specification Limit
Coarse Aggregate	Specific Gravity	ASTM C127	2.65	-
	Aggregate Crushing Value (%)	BS 812	28.95	Max 30%
Fine Aggregate	Specific Gravity	ASTM C128	2.60	-
Bitumen (60/70)	Penetration at 25°C (0.1 mm)	ASTM D5	65.01	60 - 70
	Specific Gravity	ASTM D70	1.01	-

The results confirm that the aggregates and the 60/70 penetration grade bitumen conform to the required standards for asphalt concrete production, providing a reliable baseline for the study.

Determination of Optimum Bitumen Content (OBC)

The Marshall Mix design was conducted on the control mix (0% CSA) at different bitumen contents (5%, 10%, 15%, 20%, 25%). The average Marshall Stability and Flow values are presented in Table 2.

Table 2. Marshall Test Results for Control Mix

Bitumen Content (%)	Stability (KN)	Flow (0.25 mm)
5%	4.50	3.48
10%	7.20	4.26
15%	4.20	4.56
20%	3.60	4.56
25%	4.40	4.70

The OBC was determined by analyzing the relationship between bitumen content and Stability, Bulk Density, and Air Voids. The optimum was found to be **6.1%**, which was

subsequently used for preparing all CSA-modified specimens to ensure a consistent comparison.

Effects of CSA on Marshall Properties of Asphalt Mixture

The key objective of this study was to evaluate the effect of CSA on asphalt performance. Marshall specimens were prepared at the OBC of 6.1% with CSA incorporation levels of 5%, 10%, 15%, 20%, and 25% by weight of bitumen. The results are presented in Table 3.

Table 3. Marshall Test Results for CSA-Modified Mixes

CSA content (%)	Stability (kN)	Flow (0.25mm)	Air Voids (%)
5	3.8	3.70	3.49
10	4.1	3.53	3.06
15	3.1	3.39	4.04
20	3.1	2.56	1.56
25	3.1	2.72	5.35

The data reveals a clear trend. The incorporation of CSA initially enhanced the mechanical properties of the asphalt mixture. The Marshall Stability increased from the control value to a peak of 4.1 kN at 10% CSA replacement, while the Flow value decreased to 3.53 mm, indicating a stiffer and more resistant mixture. This improvement can be attributed to the fine, particulate nature of CSA, which may act as a filler, improving the packing density and inter-particle friction within the asphalt matrix at lower percentages.

However, beyond the 10% threshold, the stability significantly declined to 3.1 kN for the 15%, 20%, and 25% CSA mixtures. This decline suggests that excessive CSA content disrupts the bitumen's binding ability, likely due to an imbalance in the binder-to-filler ratio. The mixture becomes overly filled, leading to a deficiency in the effective bitumen film thickness coating the aggregates, which is crucial for cohesion and durability.

Comparison with Specifications and Practical Implications

The stability values for the 5% and 10% CSA mixtures (3.8 kN and 4.1 kN, respectively) meet the common specification requirement of a minimum 3.5 kN stipulated by the Federal Ministry of Works and Housing. In contrast, the mixtures with 15% CSA and higher failed to meet this benchmark. This finding is critical as it identifies a practical upper limit for CSA incorporation. The results suggest that CSA can be effectively used as a bitumen modifier at low to moderate percentages (5-10%), enhancing stiffness without compromising stability, making it suitable for sustainable pavement

construction. This aligns with the findings of Emmanuel et al. (2021), who also reported optimal performance at lower CSA percentages.

The Flow value, which measures the mixture's plasticity, decreased gradually from 3.70 mm to 2.56 mm as CSA content increased from 5% to 20%, before a slight increase at 25%. The initial decrease indicates that the addition of CSA made the mixture stiffer and less susceptible to deformation, which is desirable for resisting rutting. This stiffening effect is consistent with the increase in binder viscosity observed in other studies when CSA is added (Mohd et al., 2017). The flow values for 5% and 10% CSA fell within the typical specification range of 2-4 mm, indicating a balanced mix of stability and flexibility.

The air voids (VIM) showed a non-linear trend, decreasing to a minimum at 20% CSA before increasing sharply at 25%. The initial decrease is due to the void-filling action of the fine CSA particles. The subsequent increase at 25% CSA is likely due to the mixture becoming too dry and harsh (as excess filler absorbs bitumen), making it difficult to compact effectively, thus trapping more air voids.

Comparison with Specifications and Optimal CSA Content

The specifications of the Federal Ministry of Works and Housing (FMWH) typically require a minimum Marshall Stability of 3.5 kN and a Flow value between 2-4 mm. Based on the results:

- Mixes with 5% and 10% CSA successfully met both the stability and flow requirements.
- Mixes with 15%, 20%, and 25% CSA failed to meet the minimum stability requirement, rendering them unsuitable.

Therefore, the optimal CSA content for maximizing Marshall Stability while maintaining acceptable flow properties is between 5% and 10% by weight of bitumen. This range is consistent with the findings of Ramadhansyah et al. (2019), who recommended 2-4% CSA, and supports the concept that low to moderate doses of CSA can effectively enhance asphalt performance without detrimental effects.

Conclusion

This study systematically investigated the feasibility of utilizing Coconut Shell Ash (CSA) as a sustainable modifier for 60/70 grade bitumen in flexible pavement applications. The experimental investigation led to the following key conclusions:

The base materials; aggregates and 60/70 penetration grade bitumen; were confirmed to meet standard specifications, providing a reliable baseline for evaluating the effects of CSA.

The Marshall test results clearly demonstrate that CSA modification significantly affects asphalt mixture performance. The observed stiffening effect, evidenced by increased stability and reduced flow at optimal percentages—aligns with literature reports of CSA improving bitumen properties such as viscosity and temperature susceptibility. The maximum stability of 4.1 kN was achieved at 10% CSA content, with a value of 3.8 kN at 5% CSA. Both values meet the minimum stability requirement (≥ 3.5 kN) specified by the Federal Ministry of Works and Housing.

Conversely, CSA percentages exceeding 10% (i.e., 15%, 20%, and 25%) resulted in a significant decline in Marshall Stability to 3.1 kN, which fails to meet the required specification. This suggests that while CSA acts as an effective performance enhancer at lower volumes, it disrupts the asphalt matrix at higher concentrations, likely due to excessive absorption of the binder leading to a lean mix.

In summary, this research demonstrates that Coconut Shell Ash, an agricultural waste product, can be successfully valorized as a bitumen modifier. The findings confirm that its use at optimal percentages of **5% to 10%** by weight of bitumen enhances the Marshall properties of asphalt concrete, contributing to improved pavement performance. This application not only offers a technical benefit but also presents an environmentally friendly and economically viable solution for waste management.

Based on the findings of this study, the following recommendations are made:

1. It is recommended that Coconut Shell Ash be adopted as a bitumen modifier and filler in asphaltic concrete for flexible pavement construction, with an optimal incorporation level of 5% to 10% by weight of bitumen to achieve maximum stability.
2. Further investigations are encouraged to systematically study the effect of CSA on the fundamental rheological properties of bitumen (penetration, softening point, viscosity) across the same percentage range. Also, the long-term durability of CSA-modified asphalt should be evaluated, including its resistance to moisture damage, aging, and fatigue cracking.

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