

Assessment of the Performance Characteristics of Hot Mix Asphalt Incorporating Treated Palm Kernel Shell as a Partial Aggregate Substitute

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Abstract

The increasing demand for sustainable construction materials has necessitated the exploration of agricultural waste in pavement engineering. However, performance uncertainties limit their adoption. This study evaluates treated palm kernel shell in hot mix asphalt. Materials were collected and processed into raw and treated palm kernel shell using lime, cement, and combined coatings. Moisture content and loss on ignition tests were conducted to determine material properties. Hot mix asphalt samples were prepared using specified mix proportions incorporating granite and varying percentages of treated palm kernel shell. Laboratory batching, mixing, and compaction were carried out following standard procedures. Marshall Stability and Flow tests were performed, alongside bulk density, air voids, voids in mineral aggregate, and voids filled with bitumen evaluations. Moisture content ranged from 7.51 to 8.45, while loss on ignition varied between 8.74 and 10.81, indicating material consistency after treatment. Marshall Stability values decreased from 20.99 to 12.38, while flow ranged from 4.17 to 7.53, reflecting variations in deformation characteristics. Marshall Quotient ranged from 1.65 to 3.90, indicating stiffness differences. Air voids varied between 3.06 and 5.51, with corresponding bulk densities from 1.51 to 2.33. VMA ranged from 12.62 to 18.24, while VFB varied from 64.54 to 78.08, demonstrating binder distribution efficiency across mixes. Treated palm kernel shell improves asphalt performance within controlled limits. Optimal mixtures should balance stability, flow, and void properties. Further studies should focus on durability and field performance validation.

Keywords: Palm kernel shell, Hot mix asphalt, Marshall stability, Air voids, Sustainable materials, Asphalt performance.

Introduction

The performance of hot mix asphalt (HMA) is fundamentally governed by the characteristics of its constituent materials, particularly the mineral aggregates, which typically constitute more than 90% of the mixture by weight (Alemu *et al.*, 2023). Conventional aggregates such as granite, limestone, and basalt have been extensively studied and standardized due to their favorable mechanical strength, durability, and compatibility with bituminous binders (Kataware *et al.*, 2026). However, increasing demand for these natural resources, coupled with environmental concerns associated with quarrying activities, has stimulated the search for alternative materials that can partially substitute conventional aggregates without compromising performance (Silva *et al.*, 2023; Vijerathne *et al.*, 2024). Within this context, recent studies have focused on waste-derived and industrial by-products such as steel slag (Mashaan *et al.*, 2025) recycled concrete aggregate (Moura *et al.*, 2026), and waste glass Samantaray and Sehgal, (2025), demonstrating their potential to enhance sustainability while maintaining acceptable engineering performance in asphalt mixtures (Chathurika *et al.*, 2026).

In parallel with these developments, bio-based materials derived from agricultural residues have gained attention due to their renewability, low density, and potential environmental benefits (Sangmesh *et al.*, 2023). Palm Kernel Shell (PKS), a by-product of palm oil processing, is one such material characterized by a lignocellulosic structure composed primarily of cellulose, hemicellulose, and lignin, along with minor

inorganic constituents (Baffour-Awuah, *et al.*, 2021). Its intrinsic properties, including low specific gravity, high porosity, and relatively rough surface texture, suggest possible interactions with bituminous matrices that differ significantly from those of conventional mineral aggregates (Ulusoy, 2023). From a theoretical standpoint, these attributes may influence key asphalt mixture parameters such as stiffness, stability, and moisture susceptibility, thereby warranting systematic investigation within the framework of pavement engineering. Notwithstanding the growing interest in alternative materials, the majority of established research in asphalt technology continues to rely on well-characterized aggregate replacements such as reclaimed asphalt pavement (RAP), crumb rubber, and polymer-modified fillers. These materials have been rigorously evaluated using standardized laboratory and field procedures, with findings indicating improvements in rutting resistance, fatigue life, and overall durability when properly incorporated ((Makowska *et al.*, 2023). In contrast, the application of bio-based materials like PKS remains largely exploratory, with limited empirical data available to substantiate their performance under varying loading and environmental conditions. Consequently, their integration into HMA design requires careful consideration of both material variability and process optimization techniques.

Consequently, a critical problem emerges regarding the lack of comprehensive understanding of how bio-based materials like PKS influence the mechanical and durability characteristics of asphalt mixtures, particularly when compared to established aggregate substitutes. Existing studies have largely emphasized conventional materials with predictable performance, leaving a gap in knowledge concerning the behavior of agricultural residues under asphalt mixing and service conditions. Thus, the significance of this study lies in its contribution to sustainable infrastructure development through the exploration of PKS as a novel, bio-based aggregate replacement within HMA. By situating the investigation within the broader context of conventional aggregate replacement research. The findings are expected to contribute to the diversification of material options in asphalt technology, reduce reliance on non-renewable aggregates, and promote the valorization of agricultural waste in line with contemporary sustainability goals (Stefi and Vorgias, 2025). Finally, the scope of this study encompasses the characterization of treated PKS, its incorporation as a partial replacement for conventional aggregates in HMA, and the evaluation of key performance indicators such as stability, flow, density, and moisture susceptibility. Emphasis is placed on bridging the existing research gap by providing empirical insights into the behavior of PKS within asphalt systems, while maintaining alignment with established standards and methodologies commonly used in the assessment of conventional aggregate replacements.

Materials and Methods

This section presents a clear and systematic description of the procedures involved in preparing Hot Mix Asphalt (HMA) using raw palm kernel shell (PKS), lime-treated PKS, and cement–lime-treated PKS, as well as the evaluation of the effects of these treatments on asphalt performance. The discussion is structured in a logical sequence, beginning with material collection and preparation, followed by batching and mixing processes, and concluding with laboratory analysis.

Collection of Materials

All materials utilized in this study were carefully sourced from verified suppliers and production locations within the study area to ensure quality and consistency. The cement employed was Dangote Falcon Kwik Set Portland Limestone Cement, supplied in 50 kg bags and procured from a certified local distributor to ensure compliance with both Nigerian and international standards for general-purpose applications. Hydrated lime (Limbox brand), also supplied in 50 kg bags as illustrated in Plate 1, was obtained from Comixmen Nigeria, a recognized supplier of construction lime products. The lime was stored in a moisture-free environment and protected from contaminants to maintain its integrity during batching. The palm kernel shell (PKS) used in this study was sourced from a palm oil processing facility located in Ido-Osun, Osun State (7°46'60" N, 4°29'0" E), where it is generated as an agricultural by-product following kernel

extraction, as shown in Plate 2. The shells were manually sorted to eliminate soil particles, fibers, and other foreign materials. Thereafter, the PKS was thoroughly washed with clean water to remove residual oil and adhering impurities, and subsequently air-dried to a constant mass, as presented in Plates 3 and 4.

Crushed granite aggregate was obtained from a local distributor within the study area and was selected through visual inspection to ensure the absence of deleterious substances such as clay, organic matter, and excessive fines. Sharp sand, used as the fine aggregate, was similarly sourced from a local supplier. It was chosen based on its angular particle shape and cleanliness, which are essential for achieving adequate bonding and workability. Prior to use, the material was sieved where necessary to remove oversized particles and organic impurities, and it was stored on a clean, impermeable surface to prevent contamination before batching.



Plate 1: Cement and Lime Materials.



Plate 2: Palm Kernel Shell Collection.



Plate 3: Washing of Palm Kernel Shell.



Plate 4: Air-drying of Palm kernel shell.

Preparation of Raw and Treated Palm Kernel Shell (PKS)

The preparation of raw and treated palm kernel shell (PKS) was conducted to ensure uniformity and reliability in evaluating engineering performance. Raw PKS was obtained from a palm oil processing site and thoroughly washed to remove residual oil, dust, and impurities. The cleaned shells were air-dried for 48 hours and subsequently oven-dried at 105 ± 5 °C to constant mass. Thereafter, the dried shells were crushed using a laboratory jaw crusher and sieved through a $\frac{1}{2}$ -inch mesh to achieve uniform particle size suitable for pavement applications. Surface modification was carried out using lime, cement, and a combination of both materials. For lime treatment, hydrated lime slurry was prepared and mixed with PKS to ensure uniform coating, followed by air-drying and oven-drying to promote adhesion. Similarly, cement coating was achieved by preparing a cement paste and thoroughly mixing it with PKS before undergoing

the same drying procedure. For the combined cement–lime treatment, equal proportions of both materials were used to produce a homogeneous slurry, ensuring complete surface coverage.

Determination of Material Composition Parameters

The determination of material composition parameters, including moisture content and loss on ignition tests, was carried out at Landmark University, Omu-Aran, Kwara State.

Moisture content tests.

Moisture content is a fundamental property that influences compaction, density, and mechanical performance of PKS. Excess moisture reduces workability in concrete and affects the stability of pavement layers. For this test, approximately 50 g of representative PKS samples, both raw and treated, were collected. The samples were weighed using a digital weighing balance (OHAUS Pioneer PA214), then placed in a SEMCO Muffle Furnace as shown in Plate 5, and dried at 250 °C for 10 minutes as shown in Plate 5. Moisture content (%) was calculated using Equation 1.

$$\text{Moisture Content (\%)} = \frac{W_i - W_d}{W_i} \times 100 \quad (1)$$

Where; W_i is the initial mass of the sample, and W_d is the oven-dried mass.



Plate 5: Sample Placement in Furnace.

Loss on ignition tests.

The LOI test measures the amount of organic and volatile matter present in PKS, which affects thermal stability, durability, and reactivity in cementitious systems. A small, representative amount of PKS (approximately 5–10 g) was collected from both raw and treated samples. The PKS was ground to fine powder, placed in a ceramic crucible, and ignited in a Carbolite CWF 1300 muffle furnace at 550 °C for 2 hours as shown in Plate 6 and 7. LOI (%) was calculated using Equation 2.

$$\text{LOI (\%)} = \frac{W_i - W_f}{W_i} \times 100 \quad (2)$$

Where; W_i is the initial weight of the dried sample and W_f is the weight after ignition.



Plate 6: Sample Preparation for Loss on Ignition.



Plate 7: Samples Placed in Furnace.

This test indicated the reduction of organic content in treated PKS, as lime or cement coatings helped stabilize the material and reduce combustibles. The LOI test is also important for predicting the behavior of PKS when exposed to heat during concrete curing or environmental conditions in pavement applications.

Preparation of Materials for Hot Mix Asphalt

The materials used in the preparation of hot mix asphalt comprised coarse aggregate (granite), fine aggregate (sharp sand), palm kernel shell (raw, lime-treated, and cement–lime-treated), mineral filler, and bitumen. A 60/70 penetration grade bitumen was adopted due to its appropriate viscosity, adhesion, and resistance to deformation under tropical conditions. Prior to mixing, all aggregates and PKS samples were oven-dried at 105 ± 5 °C. The PKS served as a partial replacement for coarse aggregate, while the bitumen was heated to 150 – 160 °C to ensure adequate fluidity.

Laboratory batching and mix proportions

The asphalt mixtures were prepared using a controlled laboratory batch size of 1200 g per specimen, which is suitable for Marshall Specimen preparation. The batching was carried out using a digital weighing balance (OHAUS Pioneer PA214) to ensure accuracy. Table 1 and 2 presents the typical batching quantities used for each asphalt mixture. The PKS replacement level was kept constant to allow a fair comparison of the effect of treatment on asphalt performance.

Table 1: Experimental Mix Combinations for Raw and Treated PKS

Sample ID	Granite only (%)	PKS only (%)	Lime-coated PKS (%)	Cement-coated PKS (%)	Cement–Lime-coated PKS (%)
M1	30	0	0	0	0
M2	0	2.5	5	7.5	15
M3	0	7.5	5	15	2.5
M4	5	10	7.5	5	2.5
M5	5	7.5	2.5	10	5

Table 2: Laboratory Batch Quantities for Hot Mix Asphalt with PKS

Material	Control Mix (Granite only) (g)	Raw PKS Mix (g)	Lime-PKS Mix (g)	Cement–Lime-PKS Mix (g)
Granite (Coarse Aggregate)	600	510	510	510
PKS (Replacement)	0	90	90	90
Sharp Sand (Fine Aggregate)	450	450	450	450
Mineral Filler	90	90	90	90
Bitumen (60/70 Pen)	60 (5%)	60 (5%)	60 (5%)	60 (5%)

Total	1200	1200	1200	1200
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Mixing and compaction of hot mix asphalt

Mixing was carried out using a laboratory asphalt mixer. First, the heated aggregates and PKS were dry-mixed for about 1 minute to ensure uniform distribution. Heated bitumen was then added gradually, and mixing continued for 2–3 minutes until all particles were evenly coated as shown in Plate 5 and 6. The hot mixture was placed into a Marshall mold (101.6 mm diameter) and compacted using a Marshall Compaction hammer (4.5 kg). Each specimen received 75 blows on each face, following standard practice for heavy traffic conditions. Compacted specimens were allowed to cool at room temperature before testing.

Tests Conducted on Hot Mix Asphalt

The performance of the asphalt mixtures was assessed using standard laboratory testing procedures to evaluate the effect of treated palm kernel shell (PKS) on the properties of Hot Mix Asphalt (HMA). The tests were conducted on five PKS treatment combinations generated using Design-Expert software for optimized mix design.



Plate 5: Asphalt Binder Material.



Plate 6: Asphalt Extrusion Equipment.

Marshall Stability and Flow Test

The Marshall test was used to assess the strength and deformation characteristics of the asphalt mixes. The test was conducted using a Marshall Stability Testing Machine (ELE International). Specimens were conditioned in a water bath at 60 °C for 30 minutes before testing as shown in Plate 7 and 8.



Plate 7: Prepared Asphalt Mix Samples.



Plate 8: Marshall Stability Test of Samples.

The specimen was loaded at a constant rate of 50 mm/min until failure. The maximum load recorded as the Marshall Stability (kN), while the corresponding deformation was recorded as Flow (mm). Treated PKS mixes were expected to show improved stability due to better bonding between PKS and bitumen.

Bulk density and air voids

Bulk density was determined using a water displacement method with a digital balance. The air voids were calculated using measured bulk density and theoretical maximum density. These parameters helped assess compaction efficiency and durability of the asphalt mix.

Voids in mineral aggregate (VMA) and voids filled with bitumen (VFB)

VMA and VFB were calculated using standard Marshall Equations. These parameters indicate how well the bitumen fills the void spaces within the aggregate structure. Lime and cement–lime treatments were expected to improve VFB due to enhanced surface adhesion.

Results and Discussion

Material Composition

Moisture content

The moisture content results presented in Figure 1 indicate relatively low and closely distributed values for both raw and treated palm kernel shell samples, ranging from 7.51% to 8.62%. In general, M3 exhibited the highest moisture content, followed by M1 and M4, whereas M2 and M5 recorded comparatively lower values. This narrow variation suggests a fairly uniform moisture condition across the samples, which may be attributed to consistent processing and treatment procedures applied to the material. Such uniformity is desirable in pavement and construction applications, as it enhances predictability in compaction and bonding behavior.

Furthermore, the observed moisture contents are significantly lower than values reported for untreated PKS in other studies, where higher moisture levels and water absorption capacities have been documented due to the porous and fibrous structure of the material. For instance, recent findings have shown that PKS can exhibit high moisture-related properties, which often necessitate treatment to improve performance characteristics (Nafu *et al.*, 2025). In this context, the relatively reduced moisture values obtained in the present study may indicate the effectiveness of the treatment process in limiting water retention within the shell matrix.

Moreover, the gradual decrease observed from M3 to M5 could imply progressive improvement in the treatment efficiency or drying condition, thereby reducing the hygroscopic nature of the PKS. This trend aligns with the findings of Widodo *et al.*, (2026). who reported that appropriate treatment of PKS removes surface impurities and modifies its physical characteristics, including moisture-related behavior. Consequently, the results suggest that treated PKS possesses improved moisture stability, which is critical for its suitability as an alternative material in pavement construction, particularly in minimizing moisture-induced deterioration.

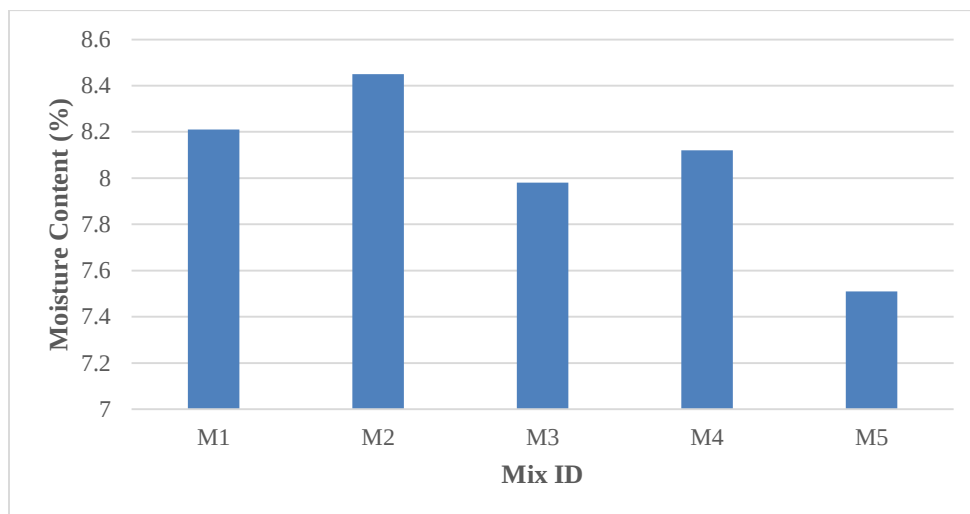


Table 2: Moisture content of Raw ant Treated PKS.

Loss of Ignition

The loss of ignition values presented in Figure 2 exhibit moderate variation among the raw and treated palm kernel shell samples, ranging from 8.74% to 10.81%. It is observed that M4 recorded the highest LOI value, followed by M2, while M5 showed the lowest value. The remaining samples, M1 and M3, fall within an intermediate range, indicating a relatively consistent thermal decomposition characteristic across the specimens. This distribution suggests that, although some variability exists, the organic and volatile content of the samples is fairly uniform, which is essential for ensuring predictable performance in engineering applications.

Furthermore, the LOI values reflect the extent of unburnt carbon and residual organic matter present in the material. Higher LOI values, such as those observed in M2 and M4, may indicate incomplete combustion or the presence of more volatile constituents, whereas lower values, particularly in M5, suggest improved thermal treatment and reduced organic residue. This observation is consistent with the findings of Okeke *et al.*, (2025), who reported that effective treatment processes significantly reduce LOI by enhancing the removal of carbonaceous materials, thereby improving the pozzolanic and filler characteristics of biomass-derived materials.

In addition, the relatively moderate LOI values obtained in this study align with recent research indicating that treated PKS and similar agro-waste materials can achieve acceptable LOI ranges suitable for construction applications when subjected to controlled processing conditions. For instance, Ismail et al. demonstrated that LOI values below approximately 12% are indicative of adequate material stabilization and improved compatibility in cementitious and pavement systems. Consequently, the results suggest that the treated PKS samples possess enhanced thermal stability and reduced organic content, which are critical factors in minimizing durability issues such as excessive shrinkage, weak bonding, and long-term degradation in pavement structures.

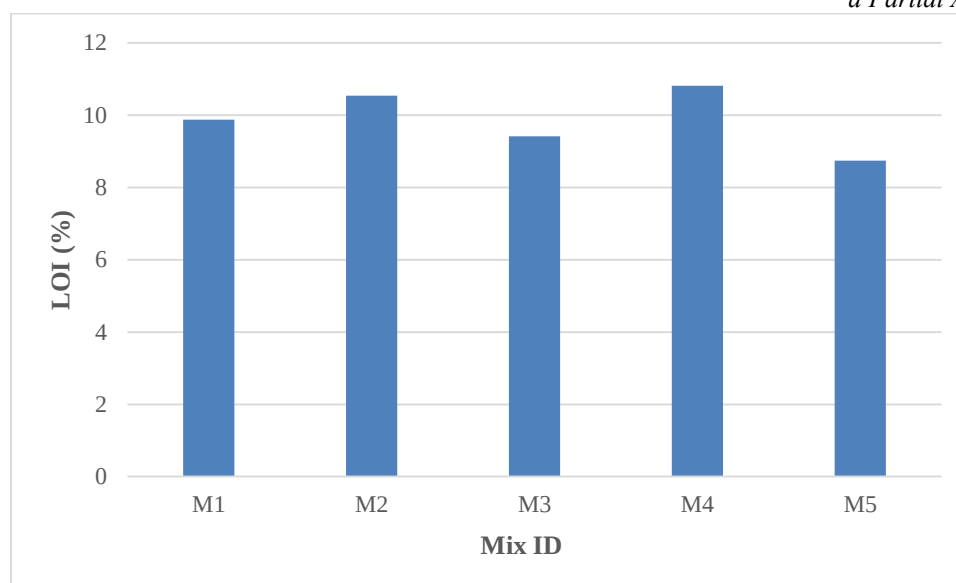


Table 2: Loss of Ignition of Raw ant Treated PKS.

Effects of Treatment on Hot Mix Asphalt Performance

This section evaluates the influence of treatment processes on the performance of hot mix asphalt incorporating palm kernel shell. The analysis includes Marshall stability and flow characteristics, bulk density and air voids, as well as volumetric properties such as voids in mineral aggregate and voids filled with bitumen, thereby determining the structural adequacy of the modified mixtures.

Marshall Stability and Flow Test

The assessment of Marshall stability and flow for hot mix asphalt (HMA) incorporating treated palm kernel shell (PKS) provides critical insights into the mechanical performance and deformation characteristics of the modified mixtures. Corrected stability and flow parameters serve as indicators of the load-bearing capacity and flexibility of the asphalt under applied traffic loads, reflecting the synergistic effect of aggregate treatment and bitumen distribution. The analysis of these properties enables the identification of mixtures that achieve an optimal balance between strength, stiffness, and deformability, which is essential for the design of durable and resilient pavement structures. The Marshall Stability and Flow results presented in Table 3 demonstrate the influence of treated palm kernel shell incorporation on the mechanical performance of hot mix asphalt. The stability values show a decreasing trend from M1 to M4, with M1 exhibiting the highest stability of 20.99 kN, while M4 recorded the lowest value of 12.38 kN. This reduction in stability across mixes suggests that increasing substitution levels or variations in treatment may reduce the load-bearing capacity of the asphalt matrix. However, the relatively high stability observed in M1 and M2 indicates that controlled incorporation of treated PKS can still maintain adequate structural integrity. Similar findings were reported by Mondal *et al.*, (2026), who observed that moderate inclusion of agricultural waste aggregates can enhance stability, while excessive replacement tends to weaken inter-particle bonding.

Furthermore, the flow values indicate variations in the deformation characteristics of the mixes under load. M4 exhibited the highest flow value of 7.53 mm, suggesting increased susceptibility to plastic deformation, whereas M5 recorded the lowest flow of 4.17 mm, indicating a stiffer mix. The relatively moderate flow values observed in M1, M2, and M3 imply a balanced resistance to deformation, which is desirable for flexible pavement performance. This trend aligns with the findings of Hassan and Siqueira *et al.*, (2026), who noted that treated bio-aggregates can improve flexibility but may lead to excessive deformation when not optimally proportioned. In addition, the Marshall Quotient, which represents the ratio of stability to

flow, provides further insight into mix stiffness. M3 recorded the highest quotient of 3.90 kN/mm, indicating superior stiffness and resistance to deformation, while M4 showed the lowest value of 1.65 kN/mm, reflecting poor load-deformation resistance. The relatively high Marshall Quotient values for M1, M2, and M3 suggest improved performance characteristics suitable for pavement applications. This observation is consistent with recent studies such as Kumar and Singh (2021), which highlighted that optimized treated waste materials in asphalt mixtures can enhance stiffness and durability when properly balanced.

Table 3: Marshall Stability and Flow of Treated PKS HMA

Mix ID	Mass in Air (g)	Mass in H ₂ O (g)	Corrected Stability (kN)	Corrected Flow (mm)	Marshall Quotient (kN/mm)
M1	1120	490	20.99	6.28	3.37
M2	1087	402	17.46	5.17	3.48
M3	1059	581	16.52	4.33	3.90
M4	1175	369	12.38	7.53	1.65
M5	1091	327	13.00	4.17	3.10

Bulk Density and Air Voids

The analysis of bulk density and air voids provides fundamental insights into the compaction efficiency and structural stability of hot mix asphalt (HMA) incorporating treated palm kernel shell (PKS). Bulk density, expressed through the specific gravity of total aggregate (GT) and mineral aggregate (GM), directly reflects the packing efficiency of aggregate particles and the ability of the mixture to resist permanent deformation. Air voids, quantified as the Volume of voids (V_v), indicate the space available within the mixture for binder accommodation and potential susceptibility to moisture infiltration or rutting. Together, these parameters influence the long-term performance and durability of pavements constructed with modified bio-aggregates.

The bulk density and air voids characteristics presented in Table 4 provide important insight into the internal structure and durability potential of the treated palm kernel shell hot mix asphalt. The specific gravity of the total aggregate and mineral aggregate shows noticeable variation across the mixes, with M3 exhibiting the highest values, while M4 and M5 recorded comparatively lower values. This variation suggests differences in aggregate packing efficiency and material composition, where higher specific gravity indicates denser and more compact mixtures. Such observations are consistent with the findings of Alaneme *et al.*, (2023) who reported that treated agricultural aggregates can enhance density when properly graded and proportioned. Furthermore, the volume of air voids across the mixes demonstrates a moderate range, indicating varying levels of compaction and permeability. M1 exhibited the lowest air void content, reflecting a well-compacted structure with minimal void spaces, whereas M5 recorded the highest value, suggesting increased porosity and potential susceptibility to moisture infiltration. The intermediate values observed in M2, M3, and M4 indicate relatively balanced compaction characteristics, which are desirable for achieving both durability and resistance to deformation. This trend aligns with the work of Qabur *et al.*, (2026), who emphasized that maintaining optimal air void levels is critical for preventing premature pavement distress.

In addition, the relationship between bulk density and air voids reveals an inverse trend, where mixes with higher density tend to exhibit lower air void content. This behavior underscores the importance of proper mix design and compaction control in optimizing pavement performance. While higher density improves load-bearing capacity, excessively low air voids may lead to bleeding, whereas higher void content may accelerate oxidation and moisture damage.

Table 4: Bulk Density and Air Voids of Treated PKS HMA

Mix ID	GT (Specific Gravity of Total Aggregate)	GM (Specific Gravity of Mineral Aggregate)	Volume of Voids (Vv, %)
M1	1.83	1.78	3.06
M2	1.66	1.59	4.12
M3	2.33	2.22	4.67
M4	1.51	1.46	3.70
M5	1.51	1.43	5.51

Voids in mineral aggregate and voids filled with bitumen

The evaluation of voids in mineral aggregate (VMA) and voids filled with bitumen (VFB) provides critical insight into the volumetric efficiency and binder adequacy of hot mix asphalt (HMA) incorporating treated palm kernel shell (PKS). VMA reflects the total interparticle void space within the aggregate skeleton, indicating the capacity of the mixture to accommodate bitumen, while VFB quantifies the proportion of these voids actually filled by binder, serving as a measure of the mixture's ability to resist deformation and moisture ingress. These parameters are essential in assessing both the structural performance and durability of HMA, particularly when unconventional aggregates such as PKS are incorporated.

The volumetric properties presented in Table 5, including volume of bitumen, voids in mineral aggregate, and voids filled with bitumen, provide critical insight into the durability and structural performance of the treated palm kernel shell hot mix asphalt. The volume of bitumen shows variation across the mixes, with M3 exhibiting the highest value, while M5 recorded the lowest. This suggests differences in binder demand and absorption characteristics, likely influenced by the surface texture and porosity of the treated palm kernel shell. Similar observations were reported by Pokorný *et al.*, (2022), who noted that bio-based aggregates tend to increase binder requirements due to their absorptive nature.

Furthermore, the VMA values demonstrate a moderate range across the mixes, with M3 showing the highest value and M4 the lowest. Higher VMA indicates greater space within the aggregate structure to accommodate bitumen, which can enhance durability and resistance to cracking. Conversely, lower VMA may result in insufficient binder content, potentially leading to reduced flexibility. The values observed suggest that most mixes maintain acceptable internal void structures, consistent with findings by Ahammed, *et al.*, (2024) who emphasized the importance of adequate VMA in ensuring long-term pavement performance. In addition, the VFB values reflect the proportion of voids effectively filled with bitumen, thereby indicating the efficiency of binder utilization within the mix. M1 recorded the highest VFB, suggesting a well-balanced mix with effective coating and reduced permeability, whereas M5 exhibited the lowest value, indicating a higher proportion of unfilled voids. The intermediate values observed in other mixes suggest varying degrees of binder distribution efficiency.

Table 5: VMA and VFB of Treated PKS HMA

Mix ID	% Volume of Bitumen (Vb)	VMA (Voids in Mineral Aggregate) (%)	VFB (Voids Filled with Bitumen) (%)
M1	10.88	13.94	78.08
M2	9.73	13.85	71.23
M3	13.57	18.24	74.82

M4	8.92	12.62	70.92
M5	8.75	14.26	64.54

Conclusion

The results indicate that treatment improved the physical and mechanical behavior of the material by reducing moisture affinity, moderating organic content, and enhancing aggregate–binder interaction. Based on the findings, it is concluded that:

- i. Treated palm kernel shell exhibited low and consistent moisture content ranging from 7.51% to 8.45%, indicating improved resistance to water-induced deterioration.
- ii. Loss of ignition values ranged from 8.74% to 10.81%, confirming reduction of volatile and organic constituents and improved thermal stability.
- iii. Marshall stability values varied from 12.38 kN to 20.99 kN, with corresponding flow values from 4.17 mm to 7.53 mm, indicating that optimal treatment enhances load-bearing capacity and deformation resistance.
- iv. The Marshall quotient ranged from 1.65 kN/mm to 3.90 kN/mm, demonstrating that mixtures with balanced stiffness and flexibility achieved superior performance.
- v. Volumetric properties showed air voids between 3.06% and 5.51%, VMA between 12.62% and 18.24%, and VFB between 64.54% and 78.08%, highlighting their influence on binder distribution and internal structure.
- vi. Mixtures with lower stability and higher flow, particularly 12.38 kN and 7.53 mm, exhibited reduced stiffness and higher susceptibility to deformation, indicating the effect of inadequate treatment or poor mix composition.

Recommendations

The use of treated palm kernel shell in asphalt mixtures is recommended at optimized conditions corresponding to higher stability up to 20.99 kN and balanced flow between 4.33 mm and 6.28 mm. Mix design should ensure controlled air voids from 3.06% to 4.67% and VFB above 70% for durability. Further research should focus on long-term performance and field validation to support large-scale sustainable pavement applications.

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