FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE
JOURNAL OF ENGINEERING AND ENGINEERING TECHNOLOGY

ENHANCING ASPHALT PAVEMENT PERFORMANCE THROUGH PALM KERNEL SHELLS INTEGRATION

Aderinola, O. S. and Ata G. O.*

Department of Civil Engineering, Federal University of Technology, Akure, Ondo State, Nigeria

**Correspondence: Email: atagraceoluremi@gmail.com*

Ajibade, F. O. (2025): Spatial Analysis of Urbanization Impacts on Water Resources Using Geographic Information System in Kano City. *FUTA Journal of Engineering and Engineering Technology /19(1),* 126-135

Received Date: 15.3.25 **Accepted Date: 28.5.25**

Abstract
Relying on natural aggregates for asphalt pavements causes harm to the environment by consuming a lot of energy and resources, while the lack of enough research on the use of palm kernel shells (PKS) slows down improvements in their performance. It seeks to assess the impact of adding PKS on asphalt roads in tropical regions experiencing high traffic. Various tests, like particle size distribution (ASTM C136/C136M-19), evaluating properties of bitumen (ASTM D5/D5M-20) and tests on strength (tensile, creep, deformation), as well as on flexibility (resilient modulus, Marshall stability and flow), along with SEM-EDX and XRD procedures, were carried out to check PKS's worth. Both PKS and conventional aggregates passed the gradation requirements. Analysis revealed that the bitumen has properties according to the set standards and its penetration is 66.5, softening point is 52.5 °C and flash or fire points are 330 °C and 360 °C respectively. The PKS sample had a specific gravity of 1.47 and contained 12 % water. These tests showed that PKS is a practical option as an aggregate. It had a tensile strength of 3.5 MPa (control: 3.1 MPa; 10 % PKS: 1.65 MPa) and a Marshall stability of 13 kN (control: 8 kN; 10 % PKS: 7 kN). At 4 % PKS, rutting resistance reached its highest point of 6.3 %. By using SEM-EDX and XRD, we found that 4 % PKS enhances the structure, with a higher amount of iron and aluminium present. When 4 % PKS is used, pavements are built to last and sustainably meet global goals for sustainability.

Keywords: *Palm kernel shell, asphalt concrete, marshall stability, waste integration, sustainability*

Introduction

The construction industry worldwide is being urged to build sustainable infrastructure due to a growing world population, increased urbanisation and the increase in people using transportation (Jaya et al., 2019; Ocholi and Samuel, 2020; Tagbor et al., 2022). Asphalt concrete, widely used for road surfaces, is valued for its durability, flexibility, and cost-effectiveness. Still, since the industry uses a lot of crushed stone and sand, mining these natural aggregates causes environmental problems due to their energy-intensive processes, disturbance of habitats and the resulting consumption of natural resources (Abdulwahab et al., 2019; Ekwulo and Etuk, 2021). Extracting aggregates from mines requires a lot of energy and adds to the amount of carbon in the atmosphere, plus the farther the quarries are from where the aggregates are used, the more it costs and negatively affects the environment (Al-Mansob et al., 2013; Susanta, 2014). Because resources are scarce, meeting the rising demand is difficult which results in the depletion of resources at the community level (Oyedepo et al., 2015).

Palm kernel shells (PKS), a by-product of palm oil processing, offer a sustainable alternative to reduce reliance on natural aggregates and manage waste (Ndoke, 2006; Ting et al., 2015). With plentiful resources in Nigeria, part of the tropics, PKS is seen as an opportunity to boost strength while helping to reduce construction expenses (Abdullah et al., 2017). Yet, there is limited information on how PKS performs when it rains a lot or when streets get crowded, as well as on how its structure impacts the durability of pavements. Specifically, Oyedepo et al. (2015) only examined basic mechanical properties and did not test samples in various conditions, unlike Susanta (2014), who investigated coconut shell charcoal but did not enhance its PKS content or use SEM-EDX or XRD. It aims to address the issues by examining the integration of PKS with rigorous testing and study of the structure and by testing durability and performance in South Asia's tropical weather, especially under heavy traffic.

Materials and Methods

Materials

Fine aggregate (passing 4.75 mm sieve, retained on 0.075 mm sieve), coarse aggregate (retained on 4.75 mm sieve), bitumen, and PKS were sourced locally in Ondo State, Nigeria. PKS was obtained from an Akure supplier as an alternative aggregate.

Experimental Design

Asphalt mixtures were prepared with 5 % bitumen (BT) and varying PKS percentages (0 %, 2 %, 4 %, 6 %, 8 %, 10 %) as partial fine aggregate replacements. The control mix contained 0 % PKS, 5 % stone dust (SD), 25 % fine aggregate (FA), and 70 % coarse aggregate (CA). Table 1 outlines the mix design.

Methods

Various tests were used for evaluating aggregate, bitumen, asphalt mixtures and their microstructure. Tests were performed on a sample through sieve analysis to cheque particle size, measuring water retention with moisture content, determining toughness and resistance to crushing with aggregate impact value (AIV) and aggregate crushing value (ACV) and using specific gravity to determine aggregate density. To evaluate bitumen, its hardness, thermal stability, fire and safety characteristics, flow, flexibility and purity were examined using penetration (ASTM D5/D5M-20), softening point (ASTM D36/D36M-14), flash and fire points (ASTM D92-18), viscosity (ASTM D4402/D4402M-15), ductility (ASTM D113-17) and water content (ASTM D95-13 tests, respectively. For the asphalt mixture, functionality was checked using Marshall stability and flow (ASTM D6927-15), indirect tensile strength (ASTM D6931-17), rutting resistance (AASHTO T 340-10), static creep (ASTM E139-06) and resilient modulus (ASTM D7369-20). To inspect the surface, the material's elements and its minerals, microstructural analysis was carried out using SEM-EDX (ASTM E986-04) and XRD (ASTM C1365-18). The experimental two

Table 1: Experimental Design

S/N	Sample	BT (%)	PKS (%)	SD (%)	FA (%)	CA (%)
1	Control	5	0	5	25	70
2	2% PKS	5	2	5	23	70
3	4% PKS	5	4	5	21	70
4	6% PKS	5	6	5	19	70
5	8% PKS	5	8	5	17	70
6	10% PKS	5	10	5	15	70

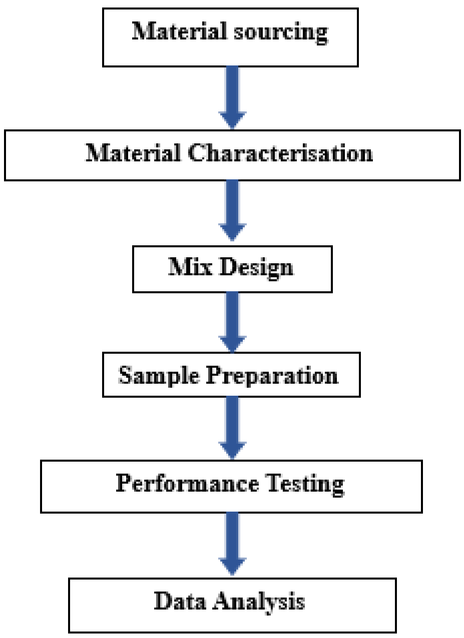

Figure 1: Flowchart of Experimental Process

Results and Discussion

Particle Size Distribution

The sieve analysis according to BS EN 933-1:2012 showed that both the coarse aggregates and the crushed coarse stone (PKS) pass as 'coarse aggregates' per ASTM C136/C136M-19. In PKS, the passing rates were 97.31 % at 25.26 mm and 93.52 % at 20.49 mm, while CA passed 95 % and 85 % of the particles (Fig. 2). The effect of the PKS was to give higher gradations (even 7%) than CA, as its passing percentages were 82.90 % at 16.72 mm and 72.34 % at 14.48 mm. Having a more detailed texture, allows the particles to be mixed better and to interact more closely, making compaction and distributing the load according to BS EN 12620:2002 possible. The results of this study indicate that the skeleton created by PKS is more regular and denser and so it holds together better as shown by Oyedepo et al. (2015). Thanks to such gradation, the pavement is less likely to scratch and wear when dealing with heavy traffic. As PKS is derived from living organisms, it may retain more moisture in areas with heavy rainfall, causing stripping or loosening of the protective layer. It is proposed by Abdullah et al. (2017) that including sealants or hydrated lime will reduce this issue. It is important to perform field studies under constant loading and wet weather to confirm that durability with PKS is good even in situations where exposure to wear and moisture is a major issue.

Bitumen Properties

All test results for bitumen (in Table 2) were satisfactory: hardness (66.5, required 60–70), resistance to heat (52.5 °C, range 30–80 °C), appropriate density (1.03, 1.01–1.06), safety (330 °C/360 °C, standard min. for flash/fire), chemical integrity (98.7 %, required min. 99 %) and flexibility (>100 cm, required 100 cm) during traffic As a result, the new materials work together and tolerate stress well (Jaya et al., 2019). Since the coating is not soft and is relatively flexible, it can manage roads in hot tropical climates (up to 40 °C). But if a road is in constant UV light, shows signs of oxidative ageing or is regularly near lots of traffic, the binder can wear out easily, causing the surface to crack or age. Since the solubility is just below 100 %, it might point to minor pollutants that could impair the mixture's strong bond while wet. According to Yusoff et al. (2014), testing in extreme weather (such as heavy rainfall and high humidity) and carrying heavy weights on the tyres can help assess how well the tyres withstand ageing. If bitumen is treated with polymers, it may become more stable in regions where seasonal temperatures vary.

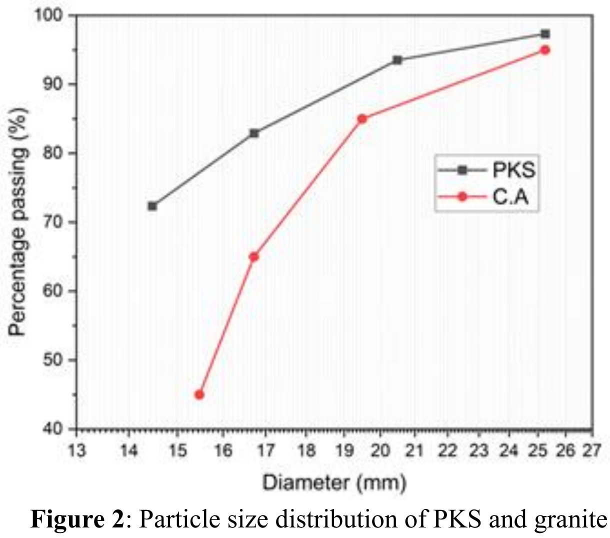

Figure 2: Particle size distribution of PKS and granite

Table 2: Bitumen Properties

Property	Test Method	Test Avg. Value	Standard Value
Penetration	ASTM D5/D5M-20	66.5	60–70
Softening Point	ASTM D36/D36M-14	52.5 °C	30–80 °C
Specific Gravity	ASTM D70-18	1.03	1.01–1.06
Flash and Fire Point	ASTM D92-18	330 °C, 360 °C	175 °C (min. flash)
Solubility	ASTM D2042-15	98.7 %	99 % (min)
Ductility	ASTM D113-17	>100 cm	100 cm (min)

Specific Gravity and Moisture Content

PKS exhibited lightweight features because it had a specific gravity of 1.47 and 12 % moisture, as compared to filler (2.76) and fine aggregate (2.74) at 12 % and 13 %. Pavements made from PKS are lighter, making them cheaper to build and more practical to construct. Still, having only 12 % moisture content can be challenging. When bitumen-aggregate adhesion is broken by moisture during mixing, the final compaction is poor and higher voids appear. As a result, the road is more likely to crack or strip off in humid areas. Interestingly, Abdullah et al. (2017) mention that rainy areas in the tropics experience even greater damage from moisture. If the PKS moisture content is below 5 % and you add anti-stripping agents (e.g., amines) to resin, you may avoid such challenges. If moisture is kept inside PKS, it may eventually harm the particles and require further investigations under changing wet-dry environments. Applying the right temperature settings and a smooth distribution of PKS enhances the mix's density and assists with grooves created by water and high humidity.

Aggregate Impact and Crushing Values

The AIV and ACV (Table 4) for PKS were 5.44 and 5.36, respectively, less than those for granite (AIV = 23.5, ACV = 27.3) because it is lightweight and has an organic structure. The value in both cases suggests that PKS is less resistant to damage and crushing since it has a lower density and is not as tough as stone aggregates. In areas with busy traffic or extreme weather (like freeze-thaw cycles), pavement using PKS easily breaks apart. Mixing PKS with granite allows PKS to take advantage of granite's support, as is clear when observing the results of the 4 % PKS mix. To improve their durability, mixes might boost the proportion of granite or insert silica fume, both according to Oyedepo et al. (2015). Trucks loaded with axle loads up to 80 kN are needed to assess the stability of PKS in areas with abrasive road surfaces and extreme temperatures. If the AIV/ACV is low, using lightweight pavements on rural roads may be preferred because their savings exceed the need for great durability.

Creep Rate and Deformation

Creep rate went down from 8.93×10^{-7} mm/s (at 0 % PKS) to 1.02×10^{-7} mm/s (at 10 % PKS), while sitting at 4 % PKS, creep rate was observed to be 8.26×10^{-7} mm/s (shown in Table 5). At 0.007 mm (2 % PKS) and 0.008 mm (4 % PKS), there was the lowest deformation; it then rose to 0.014 mm (10 % PKS). PKS might be making the cement more resistant to continuous deformation as it becomes harder to slip between the microscopic crystals. At higher contents, the fact that deformation is not linear also indicates that PKS particles get stuck together or have different shapes, so some PKS along the pathway may bear more stress than others, according to Muniandy and Abubakar (2013). When

Table 3: Specific Gravity and Moisture Content

Material	Specific Gravity	Moisture Content (%)
PKS	1.47	12
Filler	2.76	12
Fine Aggregate	2.74	13
Coarse Aggregate	2.73	-

Table 4: AIV and ACV

Material	AIV	ACV
PKS	5.44	5.36
Coarse Aggregate	23.5	27.3

Table 5: Creep Rate and Deformation

PKS Content (%)	Creep Rate ($\times 10^{-7}$ mm/s)	Deformation (mm)
0	8.93	0.010
2	9.81	0.007
4	8.26	0.008
6	7.33	0.010
8	6.25	0.012
10	1.02	0.014

the proportion of PKS is 4 %, the construction material reaches its optimal bonding, ensuring less deformation when faced with continued load. Ruts that form under heavy traffic can start if there are greater air voids or if the mix is less cohesive beyond the recommended PKS. Reducing the size of particles in PKS and mixing them evenly can help improve results, mainly when the mixture is placed in areas of high temperature and heavier creep occurs. Long periods of tests using repetitive loading are important to study creep, as the outcome under traffic changes could be different.

Tensile Strength

Results in Figure 3 demonstrate that strength was at a maximum of 3.5 MPa for 4 % PKS, but at 3.1 MPa for the control and at 1.65 MPa for 10 % PKS. The increase of 4 % PKS shows that binder is better separated by the coarse texture of PKS and thus led to improved interlocking between them, according to Abubakar and Baharudin (2012). If the cement content is above 4 %, it often leads to weakness because the mixture has decreased cohesion or contains spaces, causing it to bend easily under pressure. As a result of this lower content, the material risks cracking under significant traffic or as the temperature changes between day and night. Eventually, roads with a higher PKS concentration can develop loads and freeze-thaw cracking. Using more binder or including special additives (for instance, styrene-butadiene-styrene) might help eliminate or reduce risks, raising the strength of the pulp in various proportions of PKS. Trial periods of five to ten years are required in the field to cheque for cracking, as not all stresses from the environment can be fully copied in the laboratory.

Resilient Modulus

The resilient modulus lowered from 646 MPa at 0 % PKS to 580 MPa at 10 % PKS and it was 621 MPa at 4 % PKS (see Figure 4). Elastic recovery due to the constant modulus at 4% PKS supports use of this pavement material in moderate-traffic areas. Still, materials with high PKS contents become less stiff, apparently due to an increase in voids and weaker bonds between aggregates and cement, according to Muniandy and Abubakar (2013). Pavement in these areas might not last long, since it requires a stiff structure to resist being damaged by traffic. If the temperature is above 35 °C in a tropical region, roads made from low-strength asphalt can be more vulnerable to rutting under heavy loads. Increasing the binder's thickness or mixing granite and PKS in half and half will increase the ability to keep the geotextile's modulus. For areas with extreme temperatures or many heavy vehicles, it is important to use repeated loads to determine a better resilient modulus value during field tests (such as those listed in AASHTO T 342).

Rutting Resistance

Rutting resistance peaked at 6.3 % (4 % PKS) compared to 5.4 % (control) and 4.5 % (10 % PKS) (Figure 5). The improvement at 4 % PKS results from enhanced particle interlocking and uniform aggregate distribution, reducing permanent deformation under traffic, as supported by Tagbor et al. (2022). Beyond 4 %, decreased resistance likely stems from poor particle distribution or reduced binder adhesion, leading to mix instability. At 10 % PKS, increased voids exacerbate deformation, particularly under high temperatures or heavy axle loads. Optimizing PKS particle size (e.g., <4.75 mm) and improving mixing techniques (e.g., high-shear mixing) could enhance stability at higher PKS contents. Long-term, rutting resistance may degrade in tropical climates due to PKS's organic nature, necessitating field studies under simulated traffic (e.g., 1 million equivalent single axle loads). Additives like crumb rubber could further improve rutting resistance, particularly for high-traffic highways.

Marshall Stability and Flow

The stability attained 13 kN (4 % PKS), while it was 8 kN (control) and 7 kN (10 % PKS) (Figure 6). Ndoke (2006) reports that 4 % PKS allows the binder and aggregate to adhere optimally, increasing the strength of the mixture. Because PKS is lightweight, the walls do not adhere as strongly as before and become loose. This might occur due to an uneven PKS layout or if there is not enough binder coating at greater amounts. If pavements remain at 10 % PKS for too long, they are more likely to fail when supporting heavy traffic in hot conditions. By including ethylene-vinyl acetate or adding more granite, the stability of PKS could be better preserved. Confidence in stability over a decade or more can only be achieved when the field is validated in regular traffic.

Flow peaked at 4.8 mm (4 % PKS) compared to 3.2 mm (control) and 2.9 mm (10 % PKS) (Figure 6). The higher flow at 4 % PKS indicates enhanced flexibility, beneficial for absorbing traffic loads and reducing brittle cracking, as supported by Al-Mansob et al. (2013) (Figure 7). The decline at 10 % PKS suggests reduced ductility, possibly due to excessive voids or weaker binder-aggregate bonds. This could increase cracking risks under repeated loading, particularly in cold climates where thermal contraction is significant. Fatigue testing (ASTM D7313) could quantify cracking resistance under cyclic loads (e.g., 10,000 cycles), providing insights into PKS's impact on long-term ductility. Adjusting binder content or using finer PKS particles could optimize flow, ensuring flexibility across environmental conditions.

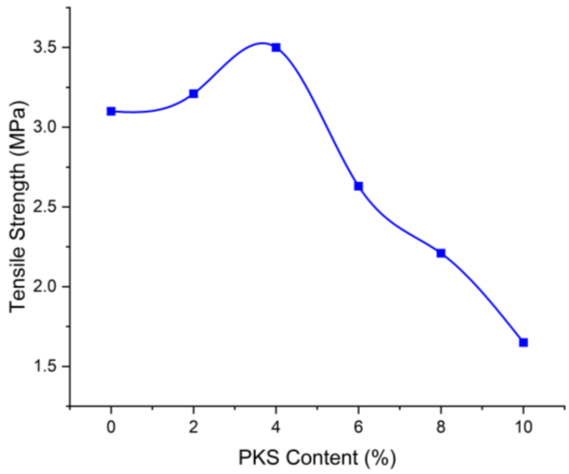

Figure 3: Indirect Tensile Strength

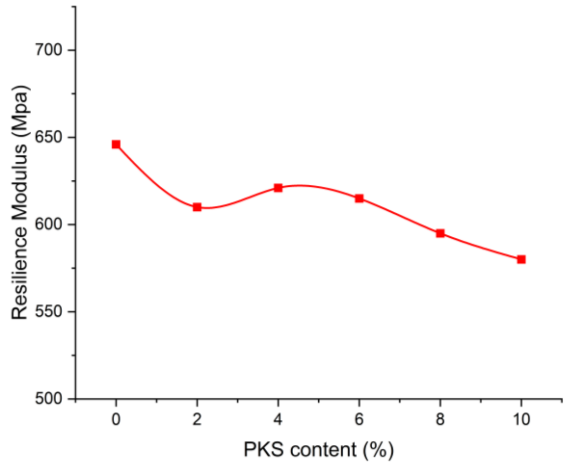

Figure 4: Resilient Modulus

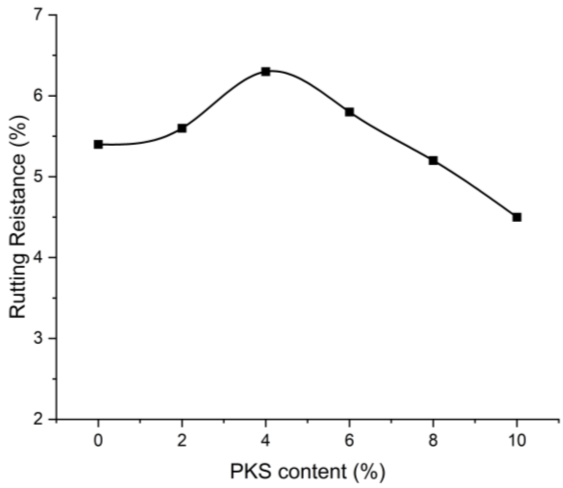

Figure 5: Rutting Resistance

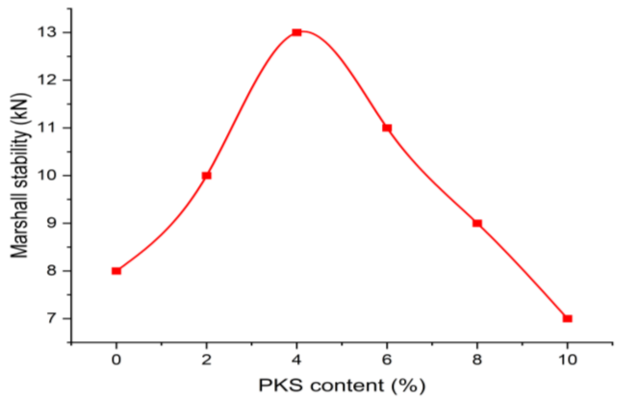

Figure 6: Marshall stability results

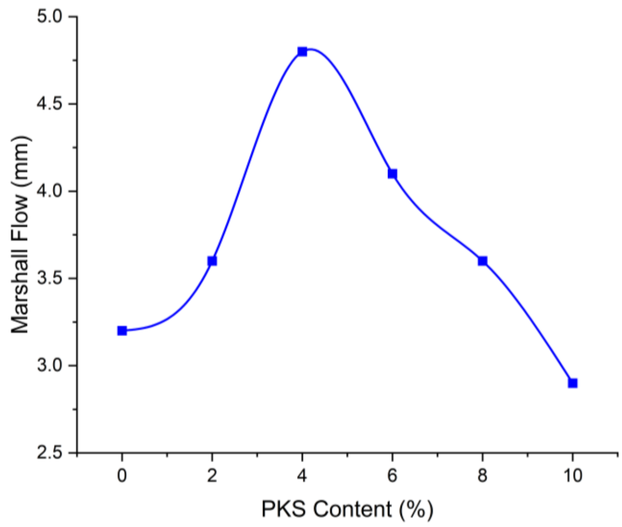

Figure 7: Marshall flow with varying PKS content.

Microstructural Analysis (SEM-EDX and XRD)

Control Sample: SEM showed that not all aggregates are regular and they contain small-scale cracks and openings (Figure 8). Si (55.22 %), Ca (21.14 %) and Al (8.90 %) are the main chemical compounds in EDX, suggesting that the crystals are stable thanks to silicate and carbonate minerals (Abubakar and Baharudin, 2012). Quartz, illite, albite and anorthite were identified in XRD, helping to increase strength and resistance against wearing (Figure 11). If there are micro-cracks, the structure becomes more susceptible to water entering and should be properly sealed in areas with lots of moisture.

4% PKS Sample: The presence of little to no voids and micro-cracks revealed in the SEM images points to the improved compaction of the soil (Figure 9). Silicon made up 35.81%, calcium 20.59%, iron 15.42% and aluminium 12.95%, while the higher percentage of iron in minerals makes the stone more durable (Muniandy and Abubakar, 2011). From the XRD results, illite, quartz, albite, anorthite and orthoclase were observed to have decreased quartz intensity by 5 %, making the bricks stronger and more durable in various conditions (Figure 12). While the mix of elements and minerals supports enduring stability, UV light or moisture in nature could impact the organic PKS parts.

10% PKS Sample: SEM revealed the formation of large areas, holes and small fractures, making the part more likely to get wet (Figure 10). According to Yusoff et al. (2014), the presence of calcium (26.31 %), silicon (36.11 %) and reduced iron (8.05 %) results in less reinforced concrete. According to XRD, the minerals found were illite, quartz, albite, anorthite and orthoclase, however, voids caused the reduction in cohesion (as seen in Figure 13). Impact on Chemistry: Lower iron and silicon in a 10 % PKS may make the product more prone to age because iron raises the durability of plastic. You can either use a lower percentage of pozzolan or fillers in the mixture or you can use fly ash as a filler to fix some voids. Extended investigations are necessary to review the impact of continual wetting and drying on the microstructure.

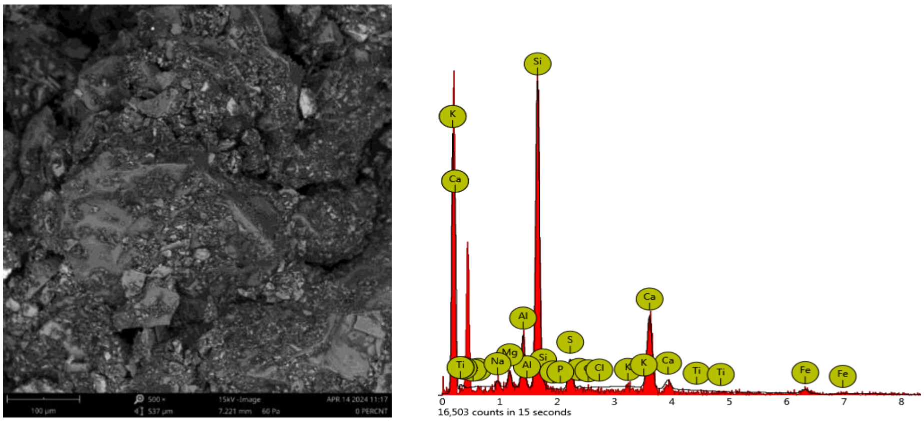

Figure 8: SEM-EDS results of control

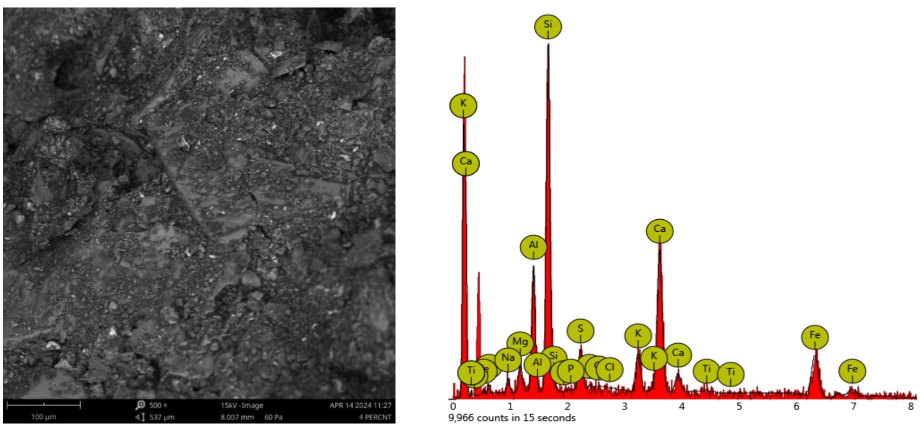

Figure 9: SEM-EDX results of 4% PKS sample

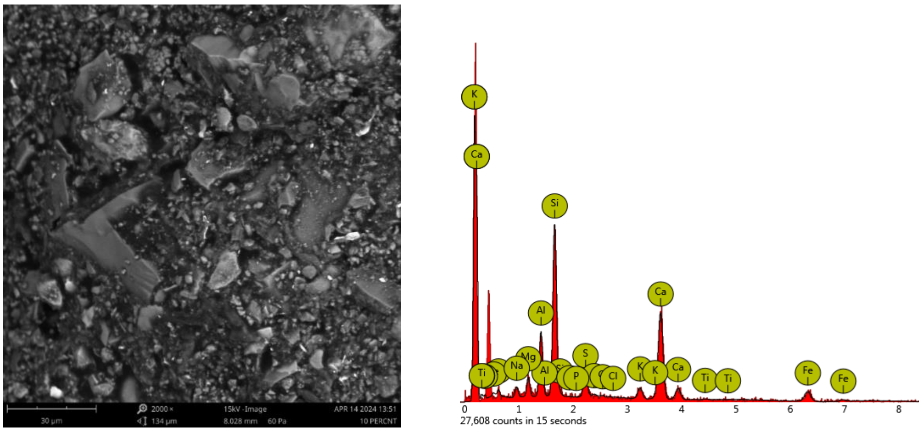

Figure 10: SEM-EDX results of 10% PKS sample

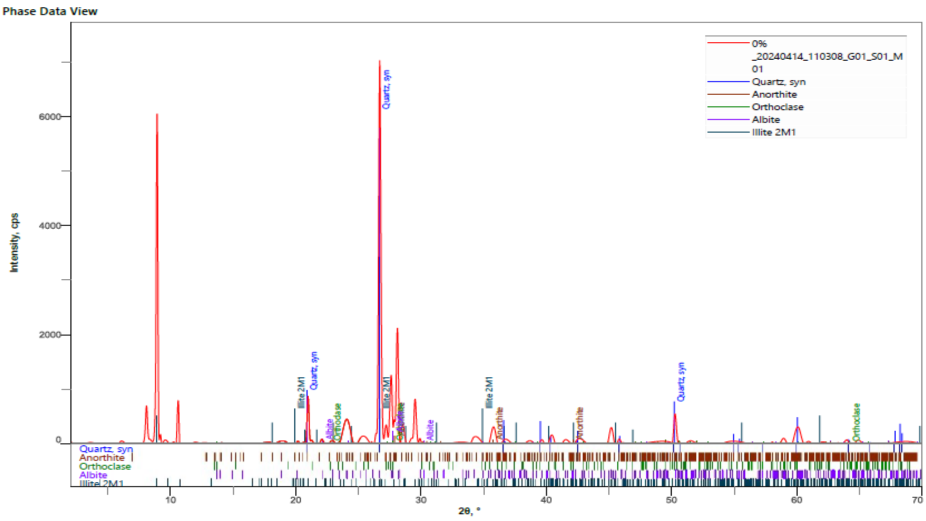

Figure 11: XRD results of the Control sample

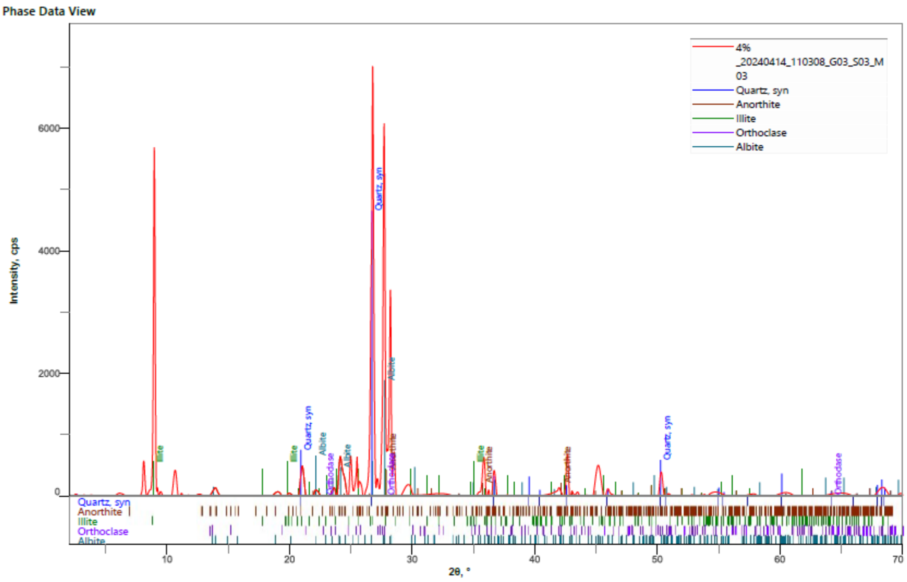

Figure 12: XRD results of the 4% PKS

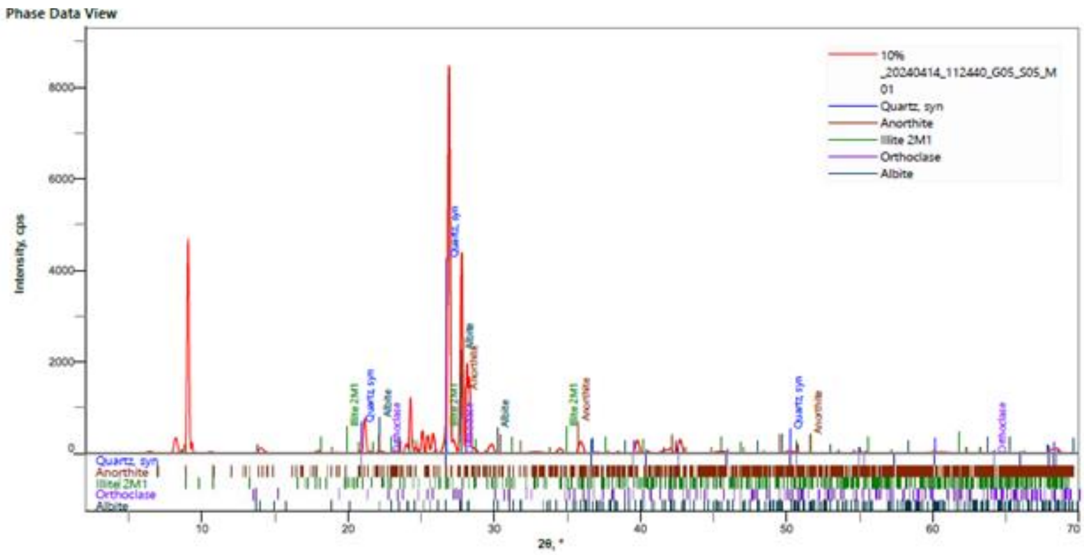

Figure 13: XRD results of the 10% PKS

Conclusion

The 4 % PKS mix optimizes asphalt pavement performance, achieving superior tensile strength (3.5 MPa), Marshall stability (13 kN), and rutting resistance (6.3 %). Microstructural analysis confirms enhanced structural integrity, supporting PKS as a sustainable aggregate alternative.

References

Abdullah M.E., Zamhari K.A., Buhari R., Abubakar S.K., Mohd Kamaruddin N.H., Nayan N., Hainin M.R., Hassan N.A., Hassan S.A. and Yusoff N.I.M. (2017). Voids characteristics of asphaltic concrete containing coconut shell, IOP Conference Series: Materials Science and Engineering, 222(1), 1–6.

Abdulwahab R., Alade A.O., Babalola O.A. and Olatunji O. (2019). Palm kernel shell as partial replacement for fine aggregate in asphalt, Annals of Faculty Engineering Hunedoara – International Journal of Engineering, 17(1), 201–204.

Abubakar I.U. and Baharudin K.S. (2012). Evaluation of the use of palm kernel shell as coarse aggregate in asphalt mixtures, Journal of Engineering Science and Technology, 7(6), 729–745.

Al-Mansob R.A., Ismail A., Yusoff N.I.M. and Azhari C.H. (2013). Comparison between mixtures of asphalt with palm oil shells and coconut shells as additives, Jurnal Kejuruteraan, 25(1), 25–31.

Ekwulo E.O. and Etuk E.U. (2021). Effect of coconut shell ash as void filler on durability and elastic modulus of asphalt concrete, IOSR Journal of Engineering, 11(5), 39–45.

Jaya R.P., Hainin M.R. and Masri K.A. (2019). Performance of charcoal coconut shell ash in the asphalt mixture under long term aging, International Journal of Recent Technology and Engineering, 8(3), 383–387.

Muniandy R. and Abubakar I.U. (2011). Laboratory evaluation of self-healing character of stone mastic asphalt incorporating palm kernel shell, Construction and Building Materials, 25(5), 2414–2421.

Muniandy R. and Abubakar I.U. (2013). Fatigue and rutting life prediction models for palm kernel shell-reinforced stone mastic asphalt, International Journal of Pavement Engineering, 14(3), 290–303.

Ndoke P.N. (2006). Performance of palm kernel shells as a partial replacement for coarse aggregate in asphalt concrete, Leonardo Electronic Journal of Practices and Technologies, 9(1), 145–152.

Ocholi A. and Samuel A. (2020). Assessment of palm kernel shells as partial replacement of coarse aggregates in highway pavements, International Journal of Engineering Management, 4(2), 25–29.

Oyedepo O.J., Olanitori L.M. and Olukanni E.O. (2015). Investigation of palm kernel shell as partial replacement for aggregate in asphaltic concrete, Malaysian Journal of Civil Engineering, 27(2), 223–234.

Susanta D.D. (2014). Assessment of the suitability of coconut shell charcoal as filler in stone matrix asphalt. National Institute of Technology, Rourkela.

Tagbor A., Adiko F.A., Anokye R. and Banahene J.O. (2022). The utilization of palm kernel shells and waste plastics in asphaltic mix for sustainable pavement construction, Scientific African, 16(1), 1–10.

Ting T., Jaya R.P., Hassan N.A., Yaacob H., Jayanti D.S. and Ariffin M.A.M. (2015). A review of utilization of coconut shell and coconut fibre in road construction, Jurnal Teknologi, 76(14), 121–125.

Widomski M.K., Stepniewski W. and Musz-Pomorska A. (2018). Clays of different plasticity as materials for landfill liners in rural systems of sustainable waste management, Sustainability, 10(7), 1–10.

Yusoff N.I.M., Breem A.A.S., Alattug H.N., Hamim A. and Ahmad J. (2014). The effects of moisture susceptibility and ageing conditions on nano-silica/polymer-modified asphalt mixtures, Construction and Building Materials, 72, 139–147.