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RESPONSE SURFACE MODELLING AND COST-EFFECTIVENESS EVALUATION OF RAW AND TREATED PALM KERNEL SHELL FOR UNBOUND PAVEMENT MATERIALS

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Abstract
Palm kernel shell (PKS), an abundant agricultural by-product, offers potential as a lightweight granular pavement material for construction. However, untreated PKS may exhibit variable strength, compaction, durability, and bearing characteristics, while chemical treatment increases production cost. This study applies response surface modelling and cost-effectiveness evaluation to raw and treated PKS mixtures to identify combinations best suited for unbound pavement material applications. PKS was collected, washed, dried, sieved, and prepared as raw, lime-coated, cement-coated, and cement–lime-coated material, with granite as control. Twenty-five mixtures were evaluated using compaction, unconfined compressive strength (UCS), triaxial shear strength, abrasion, unsoaked and soaked California Bearing Ratio (CBR) tests, and the results were modelled using response surface methodology (RSM) to identify favourable combinations. Processing costs were computed and compared with engineering performance to establish cost-effectiveness. Compaction produced maximum dry densities of 437.20–1800.20 kg/m³ and optimum moisture contents of 15.40–45.50%. UCS ranged from 362.79 to 615.60 kN/m², while cohesion and friction angle reached 38.00 kN/m² and 33°, respectively. Abrasion resistance ranged from 89.59% to 98.71%. Unsoaked and soaked CBR ranged from 38.46–76.20% and 42.83–82.47%, respectively. Response surfaces identified M2–M4 as favourable combinations, with unsoaked CBR above 70% and soaked CBR above 74%. Production cost ranged from N34,000 to N1,298,000 per tonne, demonstrating substantial variation between raw and treated mixtures. The study confirms that optimized treated PKS mixtures can provide suitable unbound pavement performance, with M2–M4 recommended for practical application, subject to field validation, lifecycle costing, and long-term durability assessment.

Keywords
Cost-effectiveness; Palm Kernel Shell; Pavement Engineering; Response Surface Modelling; Unbound Granular Materials

1. INTRODUCTION

The increasing demand for sustainable and cost-efficient materials in pavement engineering has intensified research into alternative aggregates derived from agricultural by-products [1]. Palm kernel shell (PKS), a residue from palm oil processing, has attracted attention for its lightweight nature, availability in tropical regions, and potential engineering applicability [2]. As conventional aggregates become increasingly scarce and environmentally taxing, the use of PKS as an unbound granular material offers a promising pathway toward resource conservation and waste valorization. Unbound pavement materials, which function without binding agents, rely heavily on mechanical interlock and strength characteristics, necessitating rigorous evaluation of alternative materials [3]. Unbound Granular Materials (UGMs) are non-cohesive materials widely used in pavement construction as sub-base and base layers to distribute traffic loads and protect the subgrade. Key characteristics such as particle size distribution, compaction, and drainage capacity determine their performance under repetitive loading [16].

Response surface modelling (RSM) has emerged as a robust statistical and optimization tool for analysing the interactive effects of multiple variables on engineering performance [4]. In pavement material studies, RSM facilitates the development of predictive models and optimization frameworks that improve the understanding of material behaviour under different treatment combinations [5]. Applying RSM to treated PKS enables identification of optimal conditions that improve strength, durability, and compaction characteristics, while also supporting efficient experimental design and reducing testing cost.

Treatment of PKS using stabilizing agents such as cement, lime, or other pozzolanic materials has been reported to improve its engineering properties by modifying microstructure and enhancing bonding, thereby increasing load-bearing capacity and resistance to deformation [6]. However, the economic implications of

such treatments remain a critical consideration, particularly in developing economies where cost constraints strongly influence material selection [7]. Cost-effectiveness analysis therefore becomes essential in determining the feasibility of adopting treated PKS as a substitute for conventional aggregate, requiring a comprehensive evaluation of material cost, processing requirements, and performance benefit relative to traditional options.

Despite the growing literature on alternative pavement materials, there remains limited integration of advanced modelling techniques such as RSM with economic evaluation frameworks in PKS research. Most existing studies [8], [9] have focused either on mechanical characterization or isolated cost assessment, with minimal attention to combined optimization of performance and cost, while variability in treatment methods and testing conditions has produced inconsistent findings [10]. This study addresses this gap by integrating response surface modelling with cost-effectiveness evaluation to comprehensively assess the suitability of raw and treated PKS as unbound pavement material, optimizing treatment parameters, quantifying engineering performance, and establishing economic viability within a unified analytical framework, thereby contributing to sustainable pavement engineering and circular-economy practice in infrastructure development.

2. MATERIALS AND METHOD

2.1 Preparation of Samples

Dangote Falcon Kwikset Portland limestone cement and Limbux hydrated lime were obtained in standard 50 kg bags and stored under dry conditions. Palm kernel shell (PKS), the primary aggregate, was collected from a palm oil processing site in Ido-Osun, Osun State, Nigeria. Raw PKS was washed to remove impurities, air-dried for 48 hours, and oven-dried at 105 ± 5 °C until constant weight was achieved, then sieved through a ½-inch sieve and stored in airtight containers. Lime-coated, cement-coated, and cement–lime-coated PKS were each produced by mixing 1 kg of dried shells with the respective slurry (lime, cement, or a combined cement–lime slurry) using a hand trowel until uniformly coated, followed by air- and oven-drying. Twenty-five mixture combinations of granite, raw PKS, and treated PKS (Table 1) were then formulated to evaluate the influence of treatment type and proportion on engineering performance.

Table 1: Experimental Mix Combinations of Aggregates (%)

Mix	Granite	Raw PKS	Lime-PKS	Cement-PKS	Cem-Lime-PKS
M1	30	0	0	0	0
M2	0	30	0	0	0
M3	0	0	30	0	0
M4	0	0	0	30	0
M5	0	0	0	0	30
M6	15	15	0	0	0
M7	15	0	15	0	0
M8	15	0	0	15	0
M9	15	0	0	0	15
M10	0	15	7.5	5	2.5
M11	0	7.5	15	2.5	5
M12	0	5	2.5	15	7.5
M13	0	2.5	5	7.5	15
M14	0	7.5	5	15	2.5
M15	0	5	7.5	2.5	15
M16	10	10	5	2.5	2.5
M17	10	5	10	2.5	2.5
M18	10	5	2.5	10	2.5
M19	10	5	2.5	2.5	10
M20	7.5	7.5	7.5	3.75	3.75
M21	5	10	7.5	5	2.5
M22	5	7.5	10	2.5	5
M23	5	7.5	2.5	10	5

Mix	Granite	Raw PKS	Lime-PKS	Cement-PKS	Cem-Lime-PKS
M24	2.5	5	7.5	7.5	7.5
M25	2.5	2.5	10	7.5	7.5

2.2 Mechanical Properties of Granite and PKS

The Aggregate Impact Value (AIV) test was carried out to determine the resistance of granite and PKS to sudden impact loading. For each material, 1 kg of aggregate passing the 14 mm and retained on the 10 mm sieve was compacted in a cylindrical mould and subjected to 15 blows using an Aggregate Impact Testing Machine (BS 812, Part 110) and (BS 812-112, 1990); AIV was calculated from the proportion passing the 2.36 mm sieve after impact, with lower values indicating greater toughness. The Aggregate Crushing Value (ACV) test assessed resistance to gradual compressive load: 3 kg of the same size fraction was loaded to 400 kN in an ACV apparatus, and the crushed fraction passing 2.36 mm was weighed and expressed as a percentage of the original mass, with lower ACV indicating higher load-bearing strength.

2.3 Engineering Performance of Raw and Treated PKS

2.3.1 Compaction Test

Compaction characteristics (maximum dry density, MDD, and optimum moisture content, OMC) were determined using the West African Standard (WAS) compactive effort. One kilogram of each oven-dried sample was compacted in a standard mould in five layers, each receiving 25 number of blows from a 4.5 kg rammer falling 450 mm, and dry density–moisture content relationships were used to generate compaction curves.

2.3.2 Unconfined compressive strength (UCS) test

Cylindrical specimens (150 mm diameter × 100 mm height) were prepared at OMC and tested in a Universal Testing Machine at 1 mm/min. UCS was computed from the applied load, calibration factor, and corrected cross-sectional area at failure.

2.3.3 Shear strength test

Shear strength parameters were determined by triaxial compression on 500 g specimens enclosed in a rubber membrane under a confining pressure of 100 kPa. Axial load was applied to failure, and cohesion (c) and angle of internal friction (φ) were derived using the Mohr–Coulomb failure criterion in accordance with ASTM D4767.

2.3.4 Abrasion resistance test

Abrasion resistance was assessed using the Los Angeles Abrasion Machine in accordance with ASTM C131: 1 kg of PKS and 12 steel balls were rotated for 500 revolutions at 30–33 rpm, and percentage loss was calculated from the initial and retained mass passing the 1.18 mm sieve.

2.3.5 California bearing ratio (CBR) test

The CBR test (AASHTO T193) was conducted under soaked and unsoaked conditions. Samples were compacted in a standard mould (150 mm diameter × 175 mm height) at OMC and MDD; soaked specimens were submerged for 96 hours, while unsoaked samples were tested immediately. Penetration was applied using a 50 mm plunger at 1.25 mm/min, and CBR was calculated from load at 2.5 mm and 5.0 mm penetration relative to standard values.

2.4 Statistical Evaluation Using Response Surface Modelling

Statistical evaluation is conducted to examine whether the differences observed in the engineering strength properties and asphalt performance of raw Palm Kernel Shell (PKS), lime-treated PKS, cement-treated PKS, and cement–lime-treated PKS are significant when compared with conventional aggregates. The analysis covers results obtained from compaction characteristics, unconfined compressive strength, shear strength, abrasion resistance, California Bearing Ratio (CBR), and selected asphalt performance indicators. Analysis of Variance (ANOVA) is adopted because it enables the comparison of multiple material groups tested under identical laboratory conditions using Design Expert Software.

Measured test results are first grouped according to material type and test category. For each group, the mean, variance, and standard deviation are computed. The total variation in the dataset is separated into variation due to material treatment and variation caused by experimental error. The ANOVA test statistics is calculated using Equation 2.1.

$$\text{CBR}\,(\%) = \frac{Ps}{Pr}\ x\ 100 \qquad (2.1)$$

Where; MSB represents the mean square between groups; and
MSW represents the mean square within groups.

These values are automatically generated using SPSS after entering the test data. The decision rule is based on the p-value. A p-value less than 0.05 indicates that treatment significantly influences the strength or durability property under consideration. Where significance is observed, post-hoc tests such as Tukey's Honest Significant Difference are applied to identify which treatment performs better.

2.5 Cost-Effectiveness Analysis

The cost-effectiveness of raw and treated PKS was evaluated by relating material cost to engineering performance for pavement applications. The assessment covered material acquisition, treatment, labour, and processing cost for raw PKS, lime-coated PKS, cement-coated PKS, and cement–lime-coated PKS, including washing, oven drying, coating, curing, crushing, and sieving, with all values standardized per tonne. Performance-to-cost ratios were determined by relating strength parameters to cost per tonne, allowing materials to be assessed on value rather than cost alone.

3. RESULTS AND DISCUSSION

3.1 Mechanical Properties of Granite and PKS

The results in Table 2 indicate that both PKS and granite exhibit satisfactory resistance to sudden impact loading, as reflected by their Aggregate Impact Values (AIV). The average AIV for PKS was 18.61%, while granite recorded a closely comparable 18.82%, both well below the 30% limit specified by BS 812-112. This suggests that PKS possesses impact resistance similar to conventional granite despite its organic origin, and the modest variation across the three samples for each material indicates acceptable consistency. These findings align with reports that properly processed PKS can demonstrate adequate toughness for pavement layers under low-to-medium traffic conditions [9].

Similarly, the Aggregate Crushing Value (ACV) results show that both materials resist gradual compressive load well. PKS recorded an average ACV of 19.67%, marginally lower than granite at 20.33%, indicating slightly better resistance to crushing under sustained loading. Both values remain well below the 30% threshold recommended by BS 812-110, confirming suitability for structural applications, with the close range across samples indicating uniform strength characteristics. This is consistent with recent improvements in PKS processing techniques that have been shown to enhance its mechanical properties [11]. The comparative analysis therefore indicates that PKS performs competitively with granite in both impact and crushing resistance, supporting its viability as an alternative aggregate without significant compromise in strength, in line with emerging research on the potential of agricultural waste materials in construction [12].

Table 2: Aggregate Impact and Crushing Values of PKS and Granite

Material	Property	S1 (%)	S2 (%)	S3 (%)	Avg (%)
PKS	AIV	21.26	18.25	16.33	18.61
Granite	AIV	22.45	16.77	17.25	18.82
PKS	ACV	18.24	21.43	19.35	19.67
Granite	ACV	19.50	20.30	21.20	20.33

3.2 Compaction Test

The response surface plots in Figures 1 and 2 show the effect of mixture composition on compaction characteristics. The maximum dry density (MDD) surface shows that increasing granite content generally improves particle packing and produces higher density, whereas increasing PKS content reduces density owing to its lightweight, porous structure. This trend matches the measured values, where the granite control recorded 1800.2 kg/m³ against 901.3 kg/m³ for untreated PKS, and 615.6, 437.2, and 526.3 kg/m³ for lime-coated, cement-coated, and cement–lime-coated PKS, respectively, confirming that granite enhances particle packing while PKS reduces overall compacted density.

The optimum moisture content (OMC) response surface (Figure 2) indicates variation in water demand with mixture composition. The granite control recorded the lowest OMC (15.4%), against 26.7% for untreated PKS, 27.3% for lime-coated PKS, 45.5% for cement-coated PKS, and 20.0% for cement–lime-coated PKS. Blended mixtures showed intermediate demand, including 20.65% for M6 and 21.38% for M7, with M16–M20 recording 21.74–26.44% and M21–M25 reaching up to 32.14%. These trends agree with reports of increased moisture demand for porous agricultural-based aggregates owing to their greater water absorption capacity [13], and the relatively high moisture requirement of cement-coated PKS further reflects the influence of the coating material on water demand.

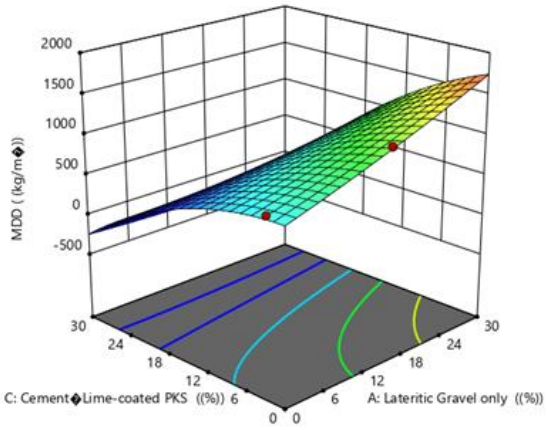


Figure 1. Response surface plot of maximum dry density (MDD).

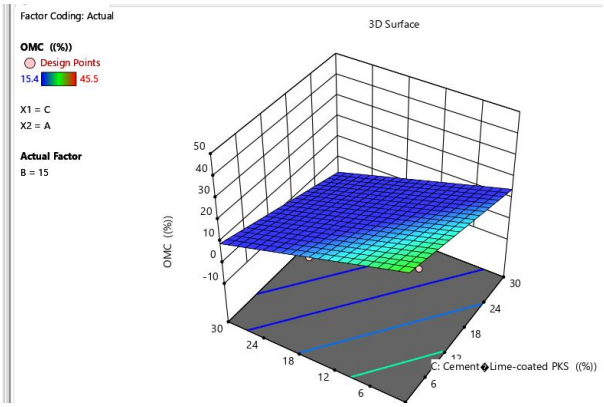


Figure 2. Response surface plot of optimum moisture content (OMC).

3.3 Unconfined Compressive Strength (UCS) Test

The UCS response surface (Figure 3) shows that increasing the proportion of treated PKS, particularly cement-lime-coated PKS, generally enhances compressive resistance, reflected in the transition from green to red regions of the surface. The highest measured values were 510.97 kN/m² for untreated PKS, 434.59 kN/m² for lime-coated PKS, 615.60 kN/m² for cement-coated PKS, and 603.38 kN/m² for cement–lime-coated PKS, against 362.79 kN/m² for the granite control, demonstrating that chemical treatment, particularly cement coating, improves particle bonding and load transfer within the compacted matrix.

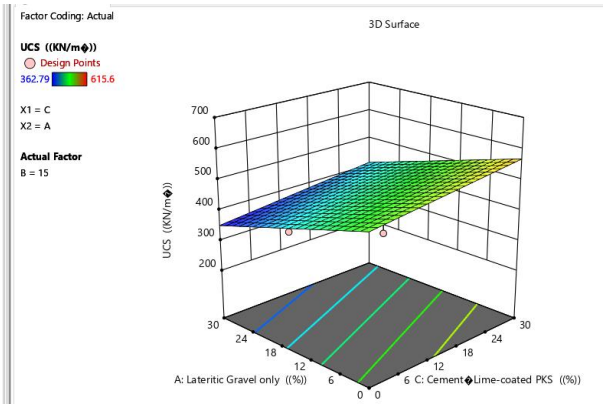


Figure 3. Response surface plot of unconfined compressive strength (UCS).

The higher-strength region of the response surface is associated with increased proportions of treated PKS while maintaining an appropriate mineral aggregate fraction. Blended mixtures also showed appreciable strength: granite blends with untreated, lime-coated, cement-coated, and cement–lime-coated PKS recorded 418.12, 399.46, 452.11, and 438.59 kN/m², respectively, while intermediate mixtures M10–M15 recorded 487.53–551.63 kN/m² and M16–M25 recorded 447.61–517.94 kN/m². This improvement with treated PKS is consistent with reports that chemical treatment enhances bonding and compressive resistance of bio-based granular materials [14], although excessive mineral aggregate content appears to reduce the contribution of

treated PKS to interparticle bonding, underscoring the importance of an optimum treated-PKS proportion for maximizing UCS [15].

3.4 Shear Strength Test

The response surface plots in Figure 4 illustrate the interaction between granite content and cement–lime-coated PKS on shear strength, with colour transitioning from blue through green to yellow representing increasing predicted response and red points marking experimental observations. Measured cohesion ranged from 10.00 kN/m² for untreated PKS to 38.00 kN/m² for the granite control, while the granite–PKS blend recorded 20.37 kN/m². Mixtures of granite with lime-coated, cement-coated, and cement–lime-coated PKS recorded 22.14, 21.05, and 23.92 kN/m², respectively, indicating improved bonding relative to untreated PKS.

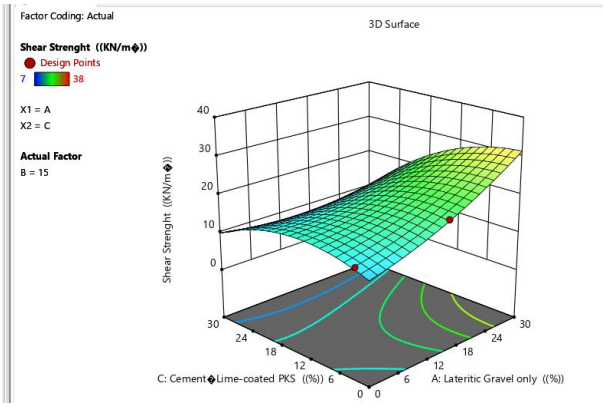


Figure 4. Response surface plot of shear strength.

The response surfaces further indicate that increasing granite content generally produces higher shear strength, reflected in the progressive shift toward higher-response regions. Intermediate mixtures recorded cohesion of 12.74–17.28 kN/m², while M16–M25 generally ranged from 15.74 to 20.11 kN/m², an improvement associated with greater particle interlocking from the granite fraction together with the additional bonding provided by the cement–lime coating. Friction angle across all tested mixtures reached up to 33°, a value typical of well-interlocked unbound granular systems.

3.5 Abrasion Resistance Test

The response surface plots in Figure 5 illustrate the interactive effects of granite content and cement–lime-coated PKS on abrasion resistance; the surfaces are generally elevated and gently inclined, with warm-colour regions indicating higher predicted resistance across the mixture domain. Measured abrasion resistance was 98.71% for the granite control and 97.04% for untreated PKS, while lime-coated, cement-coated, and cement–lime-coated PKS recorded 95.57%, 89.59%, and 96.20%, respectively, indicating that both raw and treated PKS retained appreciable resistance to mechanical wear, although cement coating produced the lowest response.

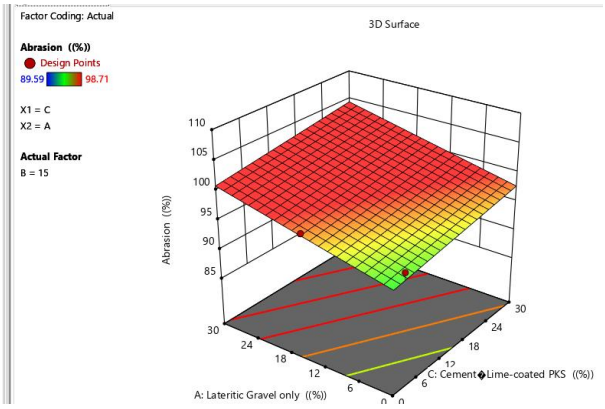


Figure 5. Response surface plot of abrasion resistance.

Blended mixtures showed improved abrasion resistance relative to some treated-PKS-only mixtures: the granite–untreated PKS mixture recorded 97.88%, while granite combined with lime-coated, cement-coated, and cement–lime-coated PKS recorded 96.92%, 94.87%, and 96.55%, respectively, and intermediate mixtures ranged from 91.78% to 96.14%. These results show that increasing granite fraction generally enhances abrasion resistance owing to its greater hardness and resistance to mechanical degradation,

consistent with reports that improved abrasion resistance in stabilized granular materials arises from the formation of rigid bonding structures [16].

3.6 California Bearing Ratio (CBR) Test

The response surface plots in Figures 6 and 7 illustrate the interactive effects of aggregate composition and cement–lime-coated PKS on unsoaked and soaked CBR, respectively. The curved response indicates that bearing capacity depends on the combined proportions of constituent materials rather than on any single component increasing in isolation. For the unsoaked condition, the granite control recorded 38.46%, while untreated PKS achieved 76.20%; lime-coated, cement-coated, and cement–lime-coated PKS recorded 70.46%, 63.34%, and 60.86%, respectively. The higher-response regions are concentrated around moderate proportions of treated PKS and aggregate, indicating that appropriate blending enhances particle interlock and load resistance.

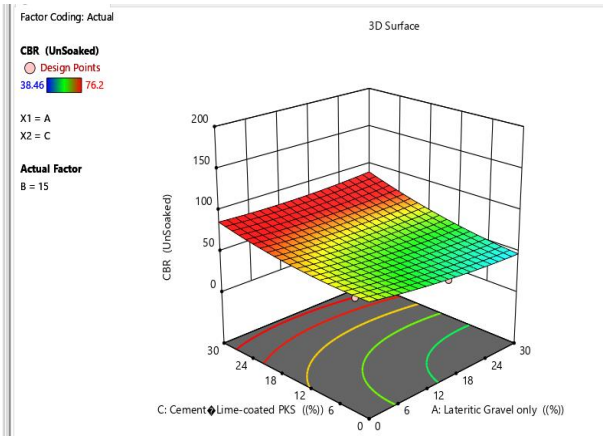


Figure 6. Response surface plot of unsoaked CBR.

The soaked CBR response surface (Figure 7) shows a comparable pattern, although generally lower owing to moisture exposure. The granite control recorded 42.83%, while untreated PKS recorded 82.47%; lime-coated, cement-coated, and cement–lime-coated PKS recorded 74.70%, 69.60%, and 66.99%, respectively. Blended granite–PKS mixtures recorded soaked CBR of 57.84%, 54.22%, 51.63%, and 49.88% for untreated, lime-coated, cement-coated, and cement–lime-coated PKS, respectively, while intermediate mixtures produced unsoaked CBR of 55.28–72.94% and soaked CBR of 50.76–67.52%. The reduction after soaking indicates some moisture sensitivity, but the relatively high retained CBR demonstrates satisfactory resistance to water-induced weakening, consistent with reports that chemically modified agricultural aggregates can maintain appreciable bearing capacity after moisture exposure.

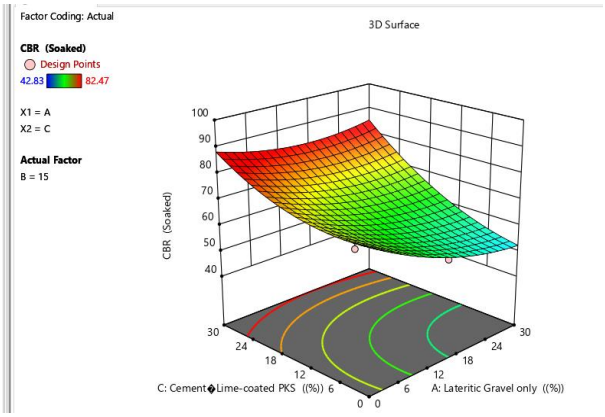


Figure 7. Response surface plot of soaked CBR.

3.7 Cost-Effectiveness Analysis of Raw and Treated PKS

3.7.1 Material and Production Cost Analysis

The cost-effectiveness analysis evaluates the economic viability of raw and treated PKS for unbound pavement applications by relating material and processing cost to engineering performance, considering material acquisition, treatment, labour, and processing cost alongside CBR, UCS, shear strength, compaction, abrasion resistance, loss on ignition, and moisture characteristics. This approach establishes whether the additional cost of treating PKS produces sufficient performance improvement to justify its use as an alternative pavement material.

Raw PKS has the lowest material cost at N3,100 per 50 kg (Table 3), whereas cost increased considerably for cement- and lime-based treatments owing to additional binder, labour, and processing requirements (Table 4). Engineering results show corresponding differences in performance, with CBR varying from 38.46% to 82.47%, UCS from 362.79 to 615.60 kN/m², and internal friction angle reaching 33°. Treated PKS generally exhibited improved strength and bearing characteristics relative to untreated material, though the associated increase in production cost must be weighed in selecting an appropriate treatment level. Notably, the most expensive treatment is not necessarily the most economically efficient option: the relatively low cost and acceptable engineering characteristics of untreated and moderately treated mixtures demonstrate the potential for economical pavement applications, indicating that cost-effectiveness depends on balancing treatment intensity, performance, durability, and expenditure rather than maximizing strength alone.

Table 3: Unit Material Cost Conversion

Material	Market + Transport Cost (N)	Mass Basis (kg)	Unit Cost (N/kg)	Cost per 50 kg (N)
PKS	3,100	50	62	3,100
Lime	25,000	25	1,000	50,000
Cement	10,200	50	204	10,200
Granite	1,200	50	24	1,200

Table 4: Processing Cost per 50 kg Bag

Material Type	Washing (N)	Drying (N)	Sieving (N)	Labour (N)	Total (N/50 kg)
Granite only	0	0	500	0	500
PKS only	300	0	500	0	800
Lime-coated PKS	300	0	500	800	1,600
Cement-coated PKS	300	0	500	800	1,600
Cement–Lime-coated PKS	300	0	500	800	1,600

3.7.2 Comparative cost evaluation

The comparative cost evaluation establishes the relationship between production expenditure and engineering performance across the investigated mixtures. M1 recorded the lowest total production cost of N1,700 per 50 kg (N34,000/tonne), whereas M5 recorded the highest at N64,900 per 50 kg (N1,298,000/tonne), reflecting variation in binder content, treatment requirements, and associated processing cost. When performance is considered alongside cost, M1 is relatively economical but exhibits a lower unsoaked CBR of 38.46% and shear strength of 362.79 kN/m². By contrast, M2 recorded a soaked CBR of 82.47% and shear strength of 510.97 kN/m² at a production cost of N3,900 per 50 kg (N78,000/tonne), a considerable improvement in bearing performance at substantially lower cost than the most heavily treated mixtures. M5, meanwhile, achieved a soaked CBR of 66.99% and shear strength of 603.38 kN/m² but required N64,900 per 50 kg, indicating that its higher strength did not correspond to proportional economic efficiency.

Intermediate-cost mixtures provide a more balanced relationship between expenditure and performance. Samples M10, M12, M16, and M21 recorded production cost between N12,125 and N18,875 per 50 kg while maintaining favourable characteristics, including soaked CBR above 60% and shear strength exceeding 480 kN/m², suggesting greater practical potential for large-scale application. The comparative analysis therefore indicates that optimum economic performance is achieved through a balanced treatment level that provides adequate engineering properties without incurring excessive production cost.

4. CONCLUSION

This study established that response surface modelling effectively identified suitable combinations of raw and treated palm kernel shell for unbound pavement applications. Treated mixtures demonstrated improved performance, with unsoaked and soaked CBR reaching 76.20% and 82.47%, respectively, and UCS attaining 615.60 kN/m². However, production cost increased substantially, from N34,000 to N1,298,000 per tonne, with treatment. Mixtures M2–M4 are therefore recommended as cost-effective options for unbound pavement applications, subject to field validation, while further studies should assess their long-term performance and lifecycle cost.

REFERENCES

[1] A. A. El-Sherbeni, A. M. Awed, A. R. Gabr, and S. M. El-Badawy, “Biomass-derived bio-oil for asphalt binder applications: production feasibility and performance enhancement,” Constr. Mater., vol. 5, no. 1, p. 11, 2025.

[2] E. Baffour-Awuah, S. A. Akinlabi, T. C. Jen, S. Hassan, I. P. Okokpujie, and D. F. Ishola, "Characteristics of palm kernel shell and palm kernel shell-polymer composites: a review," in IOP Conf. Ser.: Mater. Sci. Eng., vol. 1107, no. 1, 2021, p. 012090.

[3] W. Silva, L. Picado-Santos, S. Barroso, A. E. Cabral, and R. Stefanutti, "Assessment of interlocking concrete block pavement with by-products and comparison with an asphalt pavement: a review," Appl. Sci., vol. 13, no. 10, p. 5846, 2023.

[4] S. Elgharbi, I. Ounifi, A. Boubakri, and A. Abdedayem, "A review of the application of response surface methodology in nanofiltration: insights into process modeling, parametric analysis, and optimization," Sep. Sci. Technol., vol. 60, no. 12, pp. 1589–1603, 2025.

[5] H. I. A. A. Wahhab, W. Rafiq, and M. Khaliludin, "Modeling and design optimization of dense graded modified crumb rubber asphalt mixtures using response surface methodology," Constr. Build. Mater., vol. 435, p. 136895, 2024.

[6] L. H. Ali and Y. K. Atemimi, "Effective use of pozzolanic materials for stabilizing expansive soils: a review," IOP Conf. Ser.: Earth Environ. Sci., vol. 1374, no. 1, p. 012014, 2024.

[7] J. Styer, L. Tunstall, A. Landis, and J. Grenfell, "Innovations in pavement design and engineering: a 2023 sustainability review," Heliyon, vol. 10, no. 13, 2024.

[8] O. O. Adrian and P. N. Ogbeifun, "Investigation of the use of palm kernel shell as partial replacement of coarse aggregate in rigid pavement," NIPES J. Energy Technol. Environ., vol. 7, no. 3, pp. 116–126, 2025.

[9] C. Ezemenike, "Physical and mechanical properties of palm kernel shell as partial replacement for asphalt in flexible pavement construction," J. Appl. Sci. Environ. Manag., vol. 30, no. 6, p. 1811, 2026.

[10] C. Chen, J. Kang, Y. Liu, J. Yuan, L. Wang, and Z. Yu, "Effectiveness of surface treatment on rubber particles towards compressive strength of rubber concrete: a numerical study on rubber-cement interface," Constr. Build. Mater., vol. 350, p. 128820, 2022.

[11] O. C. Ukachukwu, D. I. Bertram, and E. B. Okpotolomo, "A comparative analysis between palm kernel shell and periwinkle shell as alternative aggregates to granite in concrete production," FUOYE J. Eng. Technol., vol. 10, no. 3, 2024.

[12] M. Duque-Acevedo, I. Lancellotti, F. Andreola, L. Barbieri, L. J. Belmonte-Ureña, and F. Camacho-Ferre, "Management of agricultural waste biomass as raw material for the construction sector: an analysis of sustainable and circular alternatives," Environ. Sci. Eur., vol. 34, no. 1, p. 70, 2022.

[13] M. Devaraj and P. S. K. Muthu, "Performance evaluation of self-compacting concrete incorporating sunflower husk ash as a sustainable cement substitute," Environ. Sci. Pollut. Res., vol. 33, no. 17, pp. 8123–8141, 2026.

[14] M. K. Yew, J. H. Beh, M. C. Yew, F. W. Lee, L. H. Saw, and S. K. Lim, "Performance of surface modification on bio-based aggregate for high strength lightweight concrete," Case Stud. Constr. Mater., vol. 16, p. e00910, 2022.

[15] P. K. Sah, B. K. Sah, and S. S. Kumar, "Sustainable utilization of sewage sludge ash in stabilizing subgrade soil: an appraisal," Environ. Dev. Sustain., vol. 27, no. 6, pp. 12477–12515, 2025.

[16] Rugabandana, G., Boateng, J. A., Maina, J., and Rimoy, S. (2026). A Critical Review of the Modelling and Factors Considered for Permanent Deformation of the Unbound Granular Materials. *International Journal of Pavement Research and Technology*, 1-20.

[17] Y. Li, L. Tian, L. Xu, M. Li, H. Bian, X. Wang, and S. Wang, "Glass-ceramic bonding agents for high-performance grinding: a material design framework based on multi-system comparisons," Inorganics, vol. 14, no. 4, p. 116, 2026.