

Suitability of Palm Kernel Shell as Unbound Granular and Bituminous Pavement Aggregate: Effects of Chemical Treatment on Engineering Performance

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Abstract: Rising demand for conventional aggregates and the growing volume of agro-industrial waste have renewed interest in palm kernel shell (PKS) as an unbound granular and bitumen-bound pavement material. This study characterizes raw and lime-, cement-, and cement-lime-coated PKS and evaluates their engineering performance relative to granite and stone dust. Microstructural and chemical properties of PKS ash were probed via electron microscopy, energy-dispersive spectroscopy, and X-ray fluorescence, while the conventional aggregates were characterized through particle size distribution together with impact and crushing value testing. Engineering performance of raw and treated PKS was assessed through moisture content, loss on ignition, compaction, unconfined compressive strength (UCS), shear strength, abrasion resistance, and bearing-capacity (CBR) testing, complemented by Marshall stability testing of hot mix asphalt (HMA) incorporating treated PKS. XRF analysis showed the PKS ash to be silica-dominant ($\text{SiO}_2 = 46.85\%$, $\text{CaO} = 12.34\%$, $\text{Al}_2\text{O}_3 = 8.27\%$), confirming pozzolanic potential. AIV and ACV of PKS (18.61% and 19.67%) were comparable with granite (18.82% and 20.33%) and within BS 812 limits. Maximum dry density fell from 1800.2 kg/m³ for granite to as low as 437.2 kg/m³ for cement-coated PKS, while UCS rose from 362.79 kN/m² (granite) to 615.60 kN/m² (cement-coated PKS). Unsoaked CBR ranged from 38.46% to 76.20% and soaked CBR from 42.83% to 82.47%, with raw PKS outperforming granite and most treated variants. Marshall stability of PKS-modified HMA ranged from 12.38 to 20.99 kN, with the best-performing mix (M14) recording a Marshall quotient of 3.90 kN/mm and voids-filled-with-bitumen of 74.82%. Analysis of variance confirmed that all measured responses were statistically significant ($p < 0.05$). Cost-performance analysis showed that raw PKS delivered the highest bearing capacity per unit cost, while chemically coated variants, though mechanically superior in specific properties, carried substantially higher production costs. The results establish raw and treated PKS as technically viable, and in several respects economically favourable, alternatives to conventional aggregate for unbound granular pavement layers and modified hot mix asphalt.

Keywords: Palm Kernel Shell, Unbound Granular Material, Aggregate Stabilization, Hot Mix Asphalt, California Bearing Ratio, Sustainable Pavement Materials.

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I. INTRODUCTION

Unbound granular materials (UGMs) make up the sub-base and base courses beneath the majority of flexible road pavements, transferring wheel loads down to the subgrade and allowing water to drain away from the pavement structure. Their performance is governed principally by particle size distribution, compaction characteristics, and shear resistance

(Kafle et al., 2024). Conventional sources of UGM, chiefly crushed stone and gravel, are becoming scarcer and costlier in many developing regions owing to intensive extraction and rising haulage distances (Lyapin et al., 2020; Yankai and Deechongkit, 2025).

Palm kernel shell (PKS) is a fibrous, cellulose-rich residue left over from processing oil palm fruit, generated in

large volumes wherever palm oil is milled throughout the tropics. Its light weight and naturally porous texture have made it an appealing candidate material for concrete, asphalt mixtures, and unbound pavement courses (Baffour-Awuah et al., 2021; Adrian and Ogbeifun, 2025). Its low density and high void ratio offer potential weight and cost savings, but the raw material's low intrinsic stiffness and moisture sensitivity restrict its direct use without surface modification (Dadzie et al., 2020). Previous studies on lime-, cement-, and bitumen-stabilized agro-wastes, including rice husk ash and coconut shell, report measurable gains in strength and durability following chemical treatment (Marzouk et al., 2023), yet a systematic, side-by-side evaluation of raw against chemically coated PKS across the full suite of pavement-relevant tests, and its extension into hot mix asphalt, remains limited in the literature.

This paper reports the physical and chemical characterization of raw PKS and conventional aggregates (granite and stone dust), and quantifies the engineering performance of raw, lime-coated, cement-coated, and cement-lime-coated PKS as an unbound granular material and as a partial coarse-aggregate substitute in hot mix asphalt. Statistical validation via analysis of variance (ANOVA) and a cost-performance comparison are used to establish the practical suitability of each treatment option for pavement construction.

II. MATERIALS AND METHODS

➤ Materials

Palm kernel shell was sourced from a palm oil processing facility in Ido-Osun, Osun State, Nigeria (7°46'60"N, 4°29'0"E). The shells were hand-picked to remove soil and fibrous debris, washed to remove residual oil, air-dried, crushed, and sieved to the required particle size. Crushed granite (nominal 1/2-inch) and stone dust were obtained from local aggregate suppliers and air-dried prior to testing. Ordinary Portland cement (Dangote Falcon Kwikset) and hydrated lime (Limbox) were used as the coating agents, and 60/70 penetration-grade bitumen was used as the asphalt binder.

➤ Characterization of Raw PKS and Conventional Aggregates

Surface morphology and elemental composition of calcined PKS ash (800 °C) were examined using a JEOL JSM-6510LV scanning electron microscope fitted with an Oxford Instruments EDX detector. Bulk oxide composition was determined by wavelength-dispersive X-ray fluorescence (PANalytical Axios) on pressed pellets of pulverized PKS ash (< 75 µm). Particle size distributions of granite, PKS, and stone dust were obtained by mechanical sieve analysis (Testmak TMS 204) in accordance with BS 812. For both granite and PKS, resistance to sudden impact and to gradual crushing was quantified as AIV and ACV following BS 812-112 and BS 812-110, respectively; each test was run in triplicate on the size fraction that passed a 14 mm screen but was held back by a 10 mm screen.

➤ Preparation of Raw and Treated PKS

Raw shells were dried in an oven held at 105 ± 5 °C and then crushed down to a maximum particle size of ½ inch. Lime-coated PKS was produced by immersing dried shells in a hydrated-lime slurry until uniformly coated, followed by air- and oven-drying. Cement-coated PKS followed an identical procedure using a Portland cement slurry, while cement-lime-coated PKS used half the cement and half the lime dosage of the single-agent coatings, combined in one slurry. All treated samples were oven-dried at 105 °C and stored in airtight containers prior to testing.

➤ Experimental Mix Design

A four-factor mixture design (Design-Expert 13.0) was used to generate 25 experimental blends (M1–M25) of granite/lateritic gravel, raw PKS, lime-coated PKS, cement-coated PKS, and cement-lime-coated PKS at the factor levels summarized in Table 1. Single-material mixes (M1–M5) established baseline performance, while binary, ternary, and quaternary blends (M6–M25) captured interaction effects between constituents. Results reported here focus on the single-material baselines (M1: granite; M2: raw PKS; M3: lime-coated PKS; M4: cement-coated PKS; M5: cement-lime-coated PKS) and on selected blends, which most clearly isolate the effect of chemical treatment; the complete 25-mix dataset was used for the regression and ANOVA analysis in Section 3.8.

Table 1 Factor Levels for the PKS-Based Mixture Design

Factor	Description	Low (%)	Mid (%)	High (%)
A	PKS only	0	15	30
B	Lime-coated PKS	0	15	30
C	Cement-coated PKS	0	15	30
D	Cement-lime-coated PKS	0	15	30

➤ Engineering Performance Tests

Moisture content and loss on ignition (LOI) were determined on ~50 g and ~5–10 g samples respectively, using a muffle furnace (250 °C for moisture; 550 °C for 2 h for LOI). Compaction behaviour was captured by determining maximum dry density (MDD) and optimum moisture content (OMC) via the standard Proctor procedure set out in ASTM D698. Unconfined compressive strength (UCS) was measured on 50 mm × 100 mm cylindrical specimens at optimum

moisture content using a universal testing machine (Instron 5980) at 1 mm/min. Cohesion (c) and the angle of internal friction (φ) were back-calculated from a 100 × 100 mm direct shear box (ELE International) run at normal stresses of 50, 100, and 150 kPa, applying the Mohr–Coulomb failure envelope to the resulting data. Abrasion resistance was evaluated in a Los Angeles abrasion drum, subjecting each sample to 500 drum revolutions alongside a charge of 12 steel spheres. Bearing capacity was expressed as CBR, measured

for each mixture both immediately after compaction and after 96 hours of soaking, using a 150 mm diameter, 175 mm high mould prepared at the moisture content and density established from the compaction tests.

➤ Hot Mix Asphalt Preparation and Testing

HMA specimens (1200 g batch) were prepared with granite, sharp sand, mineral filler, 60/70 penetration bitumen (5% by mass), and PKS (raw, lime-coated, or cement-lime-coated) as a partial coarse-aggregate substitute, following the batching schedule in Table 2. Aggregates and PKS were oven-

dried and dry-mixed for 1 minute before heated bitumen (150–160 °C) was added and mixed for 2–3 minutes. Each specimen was compacted into a 101.6 mm diameter Marshall mould using 75 blows on each face, then conditioned for 30 minutes in a 60 °C water bath before stability and flow were read, in line with ASTM D6927. The associated volumetric parameters — bulk specific gravity, air-void content (V_v), voids in the mineral aggregate skeleton (VMA), and the proportion of those voids filled with binder (VFB) — were then back-calculated using the usual Marshall mix-design relationships.

Table 2 Laboratory Batch Quantities for Hot Mix Asphalt with PKS

Material	Control (g)	PKS Mix (g)
Granite (coarse)	600	510
PKS (replacement)	0	90
Sharp sand (fine)	450	450
Mineral filler	90	90
Bitumen (60/70)	60 (5%)	60 (5%)
Total	1200	1200

➤ Statistical Analysis and Cost Evaluation

Analysis of variance (ANOVA) was performed in Design-Expert 13.0 on the full 25-mix dataset to assess the statistical significance of mixture composition on each measured response, with linear or quadratic models selected on the basis of the highest adjusted R² and an insignificant lack-of-fit term ($p > 0.05$). A response was accepted as significant where the model p-value was below 0.05. Material and processing costs (washing, drying, coating, and labour) were tabulated per 50 kg and per tonne for each mixture, and a cost-performance index, defined as soaked CBR per N1,000 of material cost per tonne, was computed to benchmark the economic efficiency of raw against treated PKS.

III. RESULTS AND DISCUSSIONS

➤ Chemical and Physical Characterization of PKS

SEM examination of calcined PKS ash revealed an irregular, angular morphology with interconnected pores and

a high specific surface area, features associated by Ahmed et al. (2024) with improved interfacial bonding in cementitious matrices. EDX spectra were dominated by oxygen, with substantial carbon, silicon, calcium, and potassium peaks, consistent with an oxide-rich biomass ash. XRF confirmed this picture quantitatively (Table 3; Figure 1): silica is the dominant oxide at 46.85%, followed by CaO (12.34%), K₂O (9.62%), Al₂O₃ (8.27%), and Fe₂O₃ (6.41%). The combined SiO₂ + Al₂O₃ + Fe₂O₃ fraction of 61.53% satisfies the general threshold for Class F pozzolans, indicating that PKS ash carries genuine supplementary cementitious potential in addition to its role as a granular aggregate. The remaining oxides — TiO₂, MnO, ZnO, CuO, Cr₂O₃, and SnO₂ — each appeared only at trace level, most plausibly introduced through soil adhering to the shells at harvest rather than forming part of the shell's inherent mineral makeup.

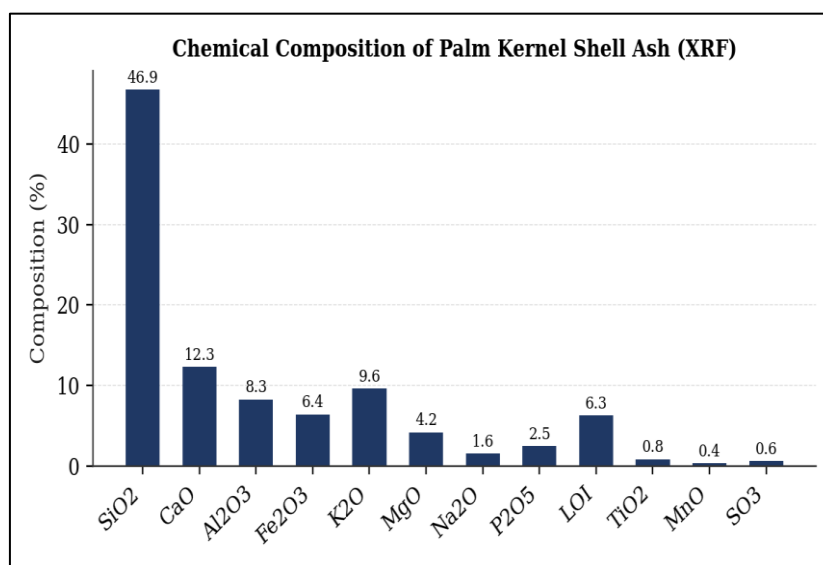


Fig 1 Chemical Composition of Palm Kernel Shell Ash (XRF).

➤ Mechanical Properties of Aggregates

Sieve analysis showed granite to be more coarsely graded than PKS: 94.23% passed the 37.5 mm sieve and only 9.78% passed 5 mm, against 97.90% and 24.95% for PKS, respectively. The coefficient of uniformity was 3.0 for granite and 4.41 for PKS, the latter exceeding the well-graded threshold of 4 under the Unified Soil Classification System. Stone dust, used as fine aggregate, was well within the fine-aggregate envelope (100% passing 8 mm; 5.24% passing 0.075 mm).

AIV and ACV, summarized in Table 3 and Figure 2, showed PKS (18.61% and 19.67%) to be closely comparable with granite (18.82% and 20.33%), both comfortably below the 30% ceiling specified in BS 812-110/112 for base-course aggregates. This is a notable finding: despite its markedly lower density, PKS's cellular structure distributes impact and crushing loads with an efficiency similar to crystalline granite, supporting its candidacy as a structural aggregate rather than merely a lightweight filler.

Table 3 Impact and Crushing Resistance (AIV/ACV) Recorded for PKS and Granite

Material	AIV (%)	ACV (%)	BS 812 limit
PKS	18.61	19.67	≤ 30%
Granite	18.82	20.33	≤ 30%

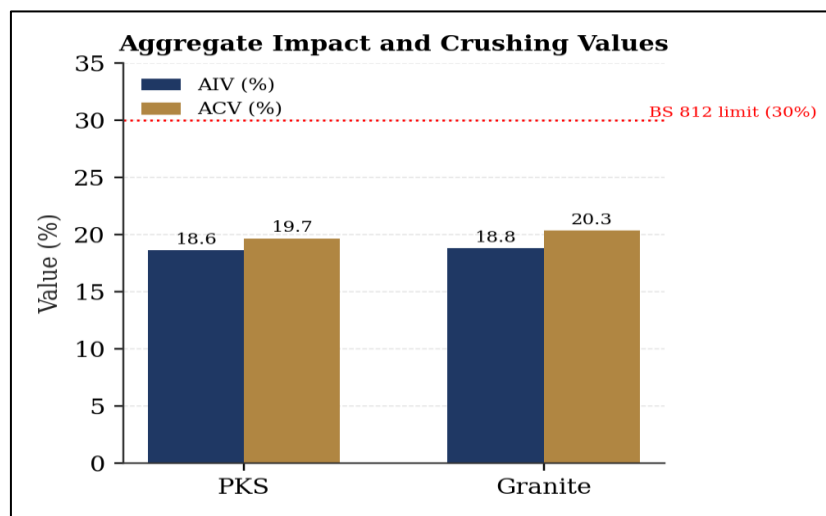


Fig 2 Aggregate Impact and Crushing Values of PKS and Granite.

➤ Influence of Chemical Coating on Moisture Content and Loss on Ignition

Moisture content and LOI of the five baseline mixtures (M1–M5) are shown in Figure 3. Granite (M1) recorded the lowest moisture content (4.24%) and LOI (2.80%), consistent with its dense, crystalline, and chemically inert structure. Raw PKS (M2) absorbed substantially more moisture (11.67%) and lost far more mass on ignition (18.53%), reflecting its porous, lignocellulosic composition. Chemical coating reduced both

parameters relative to raw PKS: cement coating (M4) produced the largest reductions (7.82% moisture; 8.61% LOI), attributable to a dense hydration-product layer that partially seals surface pores, while lime coating (M3) achieved intermediate reductions through pozzolanic pore-blocking. The cement-lime blend (M5) fell between the single-agent treatments, suggesting an interaction effect between the two binders on coating density.

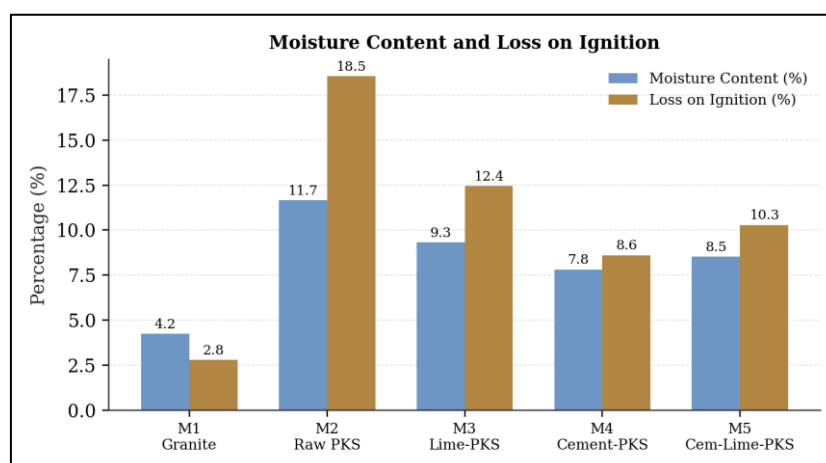


Fig 3 Moisture Content and Loss on Ignition of Raw and Treated PKS.

➤ Compaction Characteristics

Figure 4 traces maximum dry density and optimum moisture content across the mixtures, and the pattern points clearly to particle density as the property driving compaction behaviour. Granite achieved the highest MDD (1800.2 kg/m³) at the lowest OMC (15.4%), while raw PKS achieved less than half this density (901.3 kg/m³) at a much higher OMC (26.7%), reflecting its low specific gravity (1.1–1.4, against ~2.6 for granite) and irregular, void-rich packing. Cement

coating produced the lowest MDD of all single materials (437.2 kg/m³) alongside the highest OMC (45.5%), an outcome consistent with the additional water demand of the cement coating itself rather than with a further loss of aggregate density. Blends of granite with PKS (e.g., 1:1 mixes) recovered substantial density (up to ~1254 kg/m³), confirming that granite content, not treatment type, is the dominant lever for compaction performance in mixed layers.

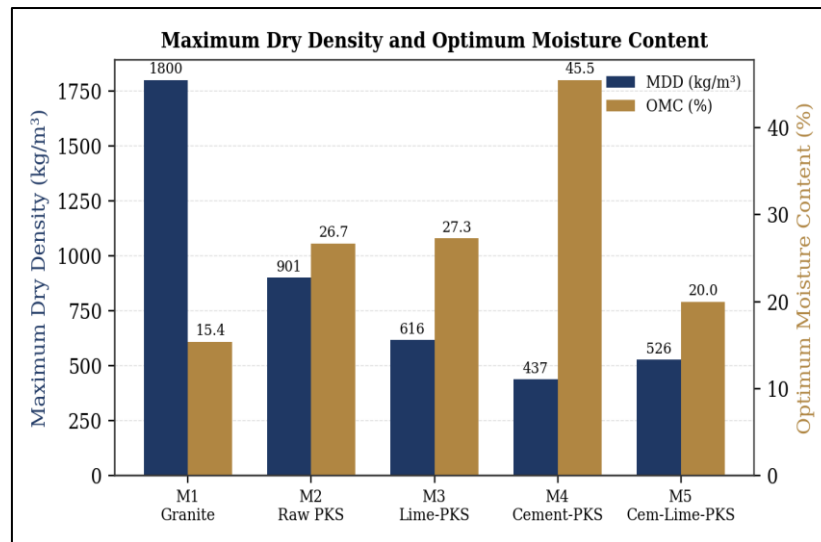


Fig 4 MDD–OMC Relationship Established for the Raw and Treated PKS Blends.

Table 4 Summary of Engineering Properties of Raw and Treated Palm Kernel Shell Compared with Granite (Baseline Mixtures M1–M5)

Mix	Material	Moisture (%)	LOI (%)	MDD (kg/m ³)	OMC (%)	UCS (kN/m ²)	Cohesion (kN/m ²)	Abrasion (%)	CBR-U (%)	CBR-S (%)
M1	Granite (control)	4.24	2.80	1800.2	15.4	362.79	38.00	98.71	38.46	42.83
M2	Raw PKS	11.67	18.53	901.3	26.7	510.97	10.00	97.04	76.20	82.47
M3	Lime-coated PKS	9.31	12.45	615.6	27.3	434.59	–	95.57	70.46	74.70
M4	Cement-coated PKS	7.82	8.61	437.2	45.5	615.60	–	89.59	63.34	69.60
M5	Cement-lime PKS	8.54	10.29	526.3	20.0	603.38	–	96.20	60.86	66.99

Note: CBR-U = unsoaked CBR; CBR-S = soaked CBR. Cohesion values for single treated PKS (M3–M5) were not isolated in the shear box tests; cohesion of 1:1 granite–PKS blends is reported in Section 3.5. Friction angle across all mixtures ranged from 24.61° to 28.93°.

➤ Strength Properties: UCS and Shear Strength

Unconfined compressive strength (Figure 5; Table 4) increased markedly on chemical treatment. Cement coating raised UCS from the granite baseline of 362.79 kN/m² to

615.60 kN/m², the highest value recorded among the single materials, while cement-lime coating achieved a comparable 603.38 kN/m². Even raw PKS (510.97 kN/m²) outperformed granite, suggesting that the angular, rough-textured shell particles interlock effectively under axial load despite their lower stiffness. The strength gain in cement- and lime-treated variants is attributable to calcium silicate and calcium aluminate hydration products bridging adjacent particles, consistent with stabilization mechanisms reported for other bio-aggregates (Loganina et al., 2021).

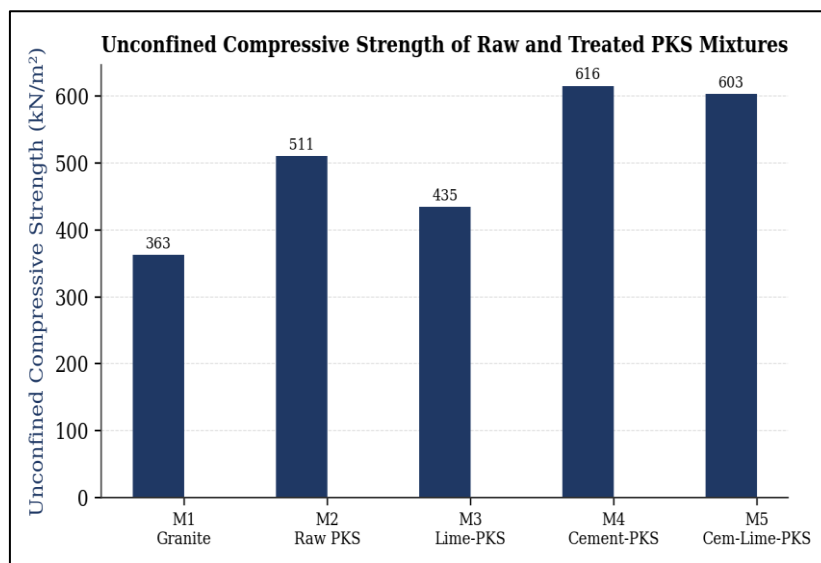


Fig 5 UCS Values Recorded for the Raw and Treated PKS Mixtures.

Cohesion followed a different pattern: granite alone recorded the highest cohesion (38.0 kN/m²), driven by strong mechanical interlock between angular crystalline particles, while raw PKS alone recorded only 10.0 kN/m². When blended with granite in equal proportion (Figure 5b), cohesion of PKS-bearing mixtures rose substantially, and chemical treatment further improved bonding within these blends, from

20.37 kN/m² (raw PKS blend) to 23.92 kN/m² (cement-lime blend). This indicates that PKS performs best in shear when combined with, rather than substituted entirely for, a rigid mineral aggregate. Friction angle across all tested mixtures ranged from 24.61° to 28.93°, a range typical of well-interlocked unbound granular systems (BS 8004).

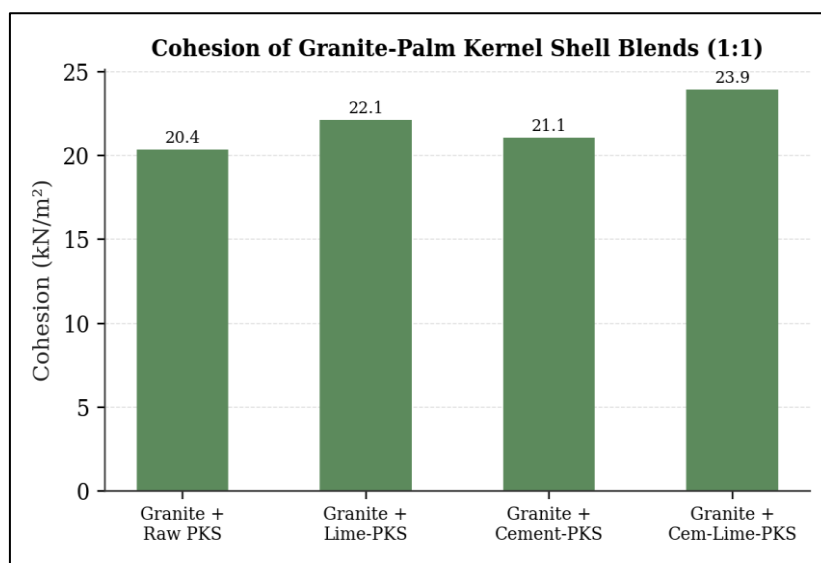


Fig 5b Cohesion of 1:1 Granite–Palm Kernel Shell Blends.

➤ Durability: Abrasion Resistance and CBR

Abrasion resistance (Figure 6) remained high across all mixtures, ranging from 89.59% (cement-coated PKS) to 98.71% (granite), comfortably within the 30–50% maximum loss typically specified for base/sub-base aggregates. The comparatively lower resistance of cement-coated PKS is attributed to the brittle nature of the cement shell, which can

crack and expose the softer organic core under repeated mechanical action; the cement-lime blend (96.20%) avoided this weakness through a more distributed bonding matrix. Granite–PKS blends consistently exceeded 94%, confirming that granite content stabilizes abrasion performance in mixed layers.

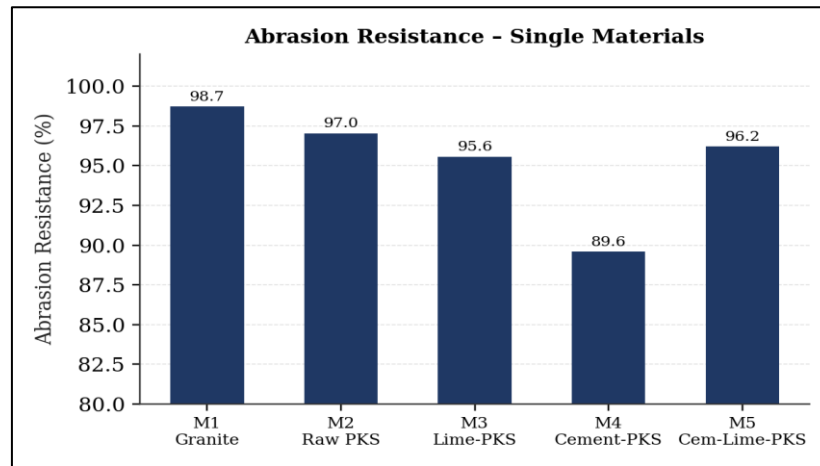


Fig 6a Abrasion Resistance of Single Materials (M1–M5).

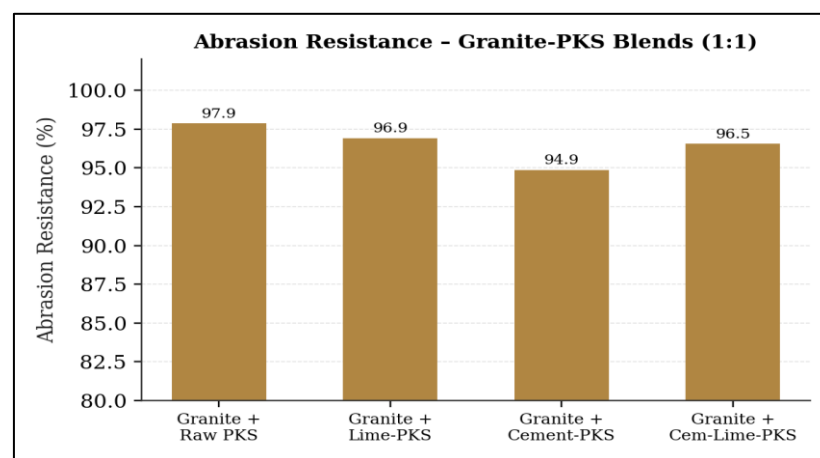


Fig 6b Abrasion Resistance of 1:1 Granite–PKS Blends.

The California Bearing Ratio (Figure 7) provided the clearest evidence of PKS's suitability as a bearing layer. Raw PKS recorded the highest CBR of any single material (76.20% unsoaked; 82.47% soaked), exceeding granite (38.46%/42.83%) by more than a factor of two. This is attributed to the angular, fibrous shell surface, which mobilizes strong interparticle friction during compaction. Chemical treatment reduced CBR relative to raw PKS (lime: 70.46/74.70%; cement: 63.34/69.60%; cement-lime:

60.86/66.99%), likely because the smoother coated surface lowers frictional resistance even as it improves cohesion and compressive strength. Critically, soaked CBR exceeded unsoaked CBR in every mixture, indicating that moisture exposure did not compromise, and in some cases marginally improved, the bearing capacity of both raw and treated PKS — a favourable characteristic for pavement layers subject to seasonal saturation.

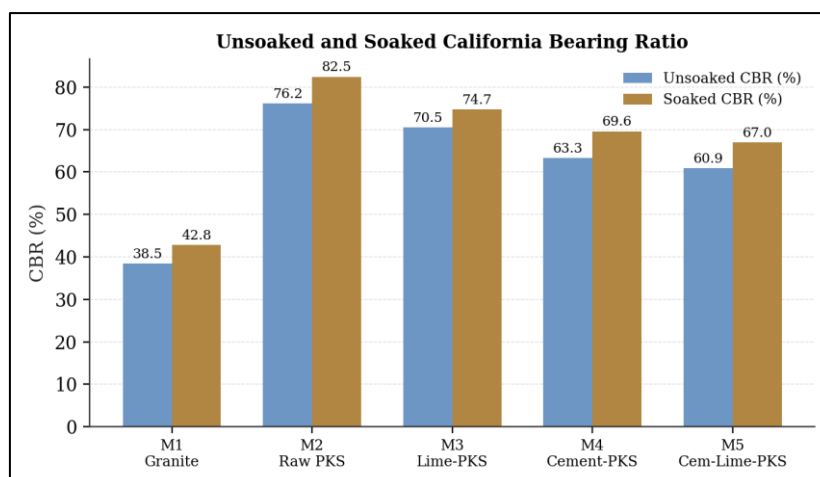


Fig 7 Unsoaked and Soaked CBR of Raw and Treated PKS Mixtures.

➤ Hot Mix Asphalt Performance

Marshall stability and flow results for five representative treated-PKS asphalt mixes are given in Table 5 and Figure 8. Mix M12 achieved the highest corrected stability (20.99 kN) with a flow of 6.28 mm, reflecting strong aggregate interlock and binder adhesion at its treatment level. Mix M14, though lower in peak stability (16.52 kN), returned the highest Marshall quotient (3.90 kN/mm) of all five mixes, the most favourable stiffness-to-deformation balance, aided by its higher bitumen content (13.57%). By contrast, M21 (lightly

treated PKS) recorded the lowest stability (12.38 kN) and the highest flow (7.53 mm), reflecting weaker aggregate–binder bonding at low treatment levels. Corresponding volumetric analysis showed M14 with the highest VMA (18.24%) and a VFB of 74.82%, indicating adequate binder saturation without excessive void space, while M23 exhibited the lowest VFB (64.54%), signalling under-filled voids and a higher susceptibility to moisture damage. All five mixes satisfied the stability and flow criteria of ASTM D6927 for medium-to-heavy traffic asphalt layers.

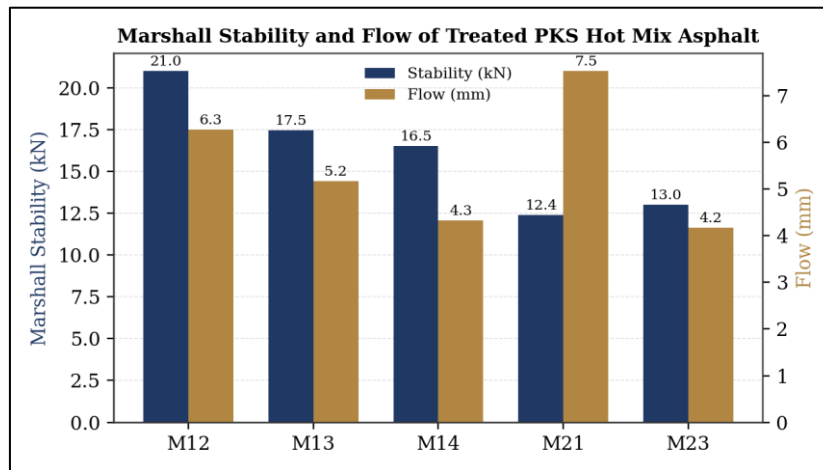


Fig 8 Marshall Stability and Flow of Treated PKS Hot Mix Asphalt.

Table 5 Marshall Stability, Flow, and Mix Volumetrics for the Treated PKS Asphalt Blends

Mix	Stability (kN)	Flow (mm)	MQ (kN/mm)	G _T	G _M	V _v (%)	V _b (%)	VMA (%)	VFB (%)
M12	20.99	6.28	3.37	1.83	1.78	3.06	10.88	13.94	78.08
M13	17.46	5.17	3.48	1.66	1.59	4.12	9.73	13.85	71.23
M14	16.52	4.33	3.90	2.33	2.22	4.67	13.57	18.24	74.82
M21	12.38	7.53	1.65	1.51	1.46	3.70	8.92	12.62	70.92
M23	13.00	4.17	3.10	1.51	1.43	5.51	8.75	14.26	64.54

Note: MQ = Marshall quotient (stability/flow ratio); G_T = specific gravity of the total aggregate blend; G_M = specific gravity of the mineral aggregate fraction; V_v = percentage air-void content; V_b = bitumen volume fraction; VMA = void space within the mineral aggregate skeleton; VFB = share of that void space occupied by bitumen.

➤ Statistical Validation

ANOVA performed on the complete 25-mix dataset (Table 6) confirmed that mixture composition exerted a statistically significant influence ($p < 0.05$) on every measured

response. Quadratic models best described CBR (unsoaked and soaked), shear strength, and maximum dry density, indicating that these responses are governed by non-linear interactions between granite and the three PKS treatment types rather than by their individual proportions alone. Linear models were adequate for UCS, OMC, abrasion, LOI, and moisture content, implying a more proportional dependence on constituent fractions. Lack-of-fit tests were insignificant in all cases ($p > 0.05$ relative to pure error), confirming that the fitted models adequately represent the experimental data and supporting their use for mixture optimization.

Table 6 ANOVA Summary for All Measured Responses

Response	Model	F-value	p-value
CBR (unsoaked)	Quadratic	36.92	<0.0001
CBR (soaked)	Quadratic	53.64	<0.0001
UCS	Linear	11.05	0.0001
Shear strength	Quadratic	71.20	<0.0001
MDD	Quadratic	75.94	<0.0001
OMC	Linear	17.38	<0.0001
Abrasion	Linear	10.30	0.0002
LOI	Linear	32.27	<0.0001
Moisture content	Linear	33.04	<0.0001

➤ Cost-Performance Analysis

Raw material cost varied widely: PKS was the cheapest input at N62/kg (N3,100/50 kg), against N24/kg for granite, N204/kg for cement, and N1,000/kg for hydrated lime. Processing (washing, drying, coating, labour) added N500/50 kg for granite alone and N1,600/50 kg for any chemically coated PKS. Combining these figures, total production cost ranged from N34,000/tonne (M1, granite) to N1,298,000/tonne (M5, cement-lime PKS) — a 38-fold spread that is not matched by an equivalent spread in engineering performance.

To reconcile cost against performance, a cost-performance index (soaked CBR per N1,000/tonne) was

computed for the five baseline mixtures (Figure 9). Raw PKS (M2) returned the second-highest index (1.06), only marginally below granite (1.26), while chemically treated variants scored an order of magnitude lower (0.05–0.23) because their processing and lime/cement input costs rose far faster than their corresponding gains in bearing capacity. This indicates that, on a pure cost-per-unit-strength basis, raw PKS is the most economically efficient treatment option among the PKS variants tested, and that chemical coating is best reserved for applications where the additional compressive strength, cohesion, or asphalt-binder compatibility it provides is specifically required, rather than applied as a default treatment.

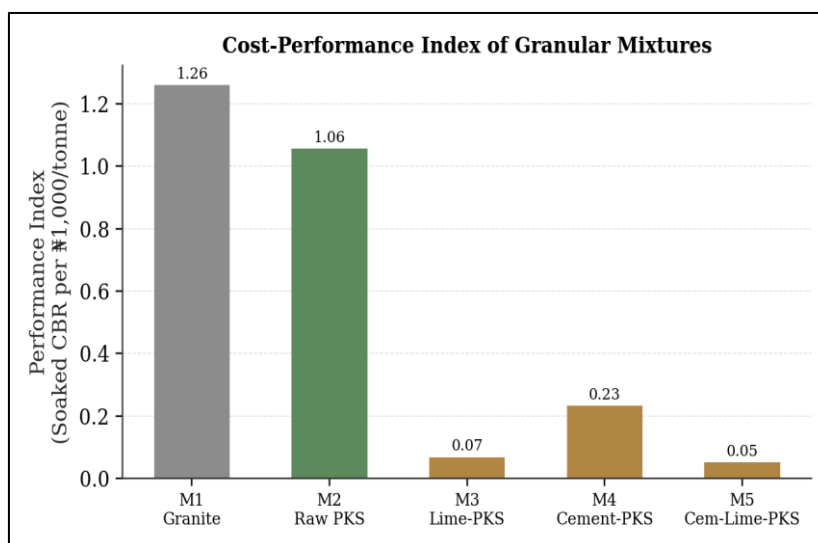


Fig 9 Cost-Performance Index of Granular Mixtures (Soaked CBR per N1,000/tonne).

Table 7 Production Cost and Cost-Performance Index of Baseline Mixtures (M1–M5)

Mix	Material	Material Cost (N/50 kg)	Processing Cost (N/50 kg)	Total Cost (N/tonne)	Soaked CBR (%)	Performance Index*
M1	Granite (control)	1,200	500	34,000	42.83	1.26
M2	Raw PKS	3,100	800	78,000	82.47	1.06
M3	Lime-coated PKS	53,100	1,600	1,094,000	74.70	0.07
M4	Cement-coated PKS	13,300	1,600	298,000	69.60	0.23
M5	Cement-lime PKS	63,300	1,600	1,298,000	66.99	0.05

*Performance Index = Soaked CBR (%) per N1,000 of total cost per tonne. Higher values indicate greater bearing capacity delivered per unit of production cost.

IV. CONCLUSIONS

Raw and chemically treated palm kernel shell were characterized and evaluated as unbound granular and bitumen-bound pavement materials. XRF confirmed PKS ash to be silica-dominant ($\text{SiO}_2 = 46.85\%$) with pozzolanic potential, and AIV/ACV values (18.61%/19.67%) placed PKS on par with granite and within BS 812 limits. Chemical coating consistently reduced moisture content and organic volatility relative to raw PKS, with cement coating the most effective (7.82% moisture; 8.61% LOI), and raised UCS to a maximum of 615.60 kN/m², a 70% improvement over the granite control. However, raw PKS delivered the highest CBR of any single

material tested (76.20% unsoaked; 82.47% soaked), outperforming both granite and all chemically treated variants, indicating that its natural angularity and surface texture are, on their own, highly effective at mobilizing bearing capacity. Marshall testing of PKS-modified hot mix asphalt showed that treated PKS mixes can meet ASTM D6927 stability and flow criteria, with the best-performing mix achieving a Marshall quotient of 3.90 kN/mm. ANOVA confirmed that all measured responses depended significantly ($p < 0.05$) on mixture composition, validating the reliability of the trends reported. Cost-performance analysis showed raw PKS to be the most economically efficient PKS-based option, with a performance index within 20% of granite and an order of magnitude better than any chemically coated variant. Overall, the results support raw PKS as a cost-effective substitute for conventional aggregate in unbound granular pavement layers, and chemically treated PKS as a targeted option where its specific

gains in compressive strength or asphalt-binder compatibility justify the additional processing cost.

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