

Valorizing Palm Kernel Shell and Oyster Shell Wastes as Asphalt Mineral Fillers: A Waste-Management and Resource-Efficiency Assessment of Moisture-Resistant Pavements in the Niger Delta

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Abstract

Palm-oil processing and artisanal shellfish harvesting generate large, geographically concentrated residue streams in the Niger Delta that are presently managed by open dumping, uncontrolled burning and shoreline accumulation. In the same region, flexible pavements fail prematurely under prolonged inundation, consuming primary aggregate and quarried mineral filler in repeated reconstruction cycles. This paper evaluates whether these two problems can be made to solve one another, by assessing palm kernel shell ash (PKSA) and oyster shell ash (OSA) as blended mineral fillers in hot-mix asphalt concrete from a waste-management and resource-efficiency perspective rather than a purely mechanical one. Laboratory results from a 6×6 factorial in PKSA and OSA, together with a 14-day full-submergence series, were used to define the specification-compliant envelope within which waste can be absorbed, and that envelope was then converted into a material-flow assessment. Eleven of thirty-six blends satisfied all Asphalt Institute volumetric and stability criteria simultaneously, and the maximum compliant waste-ash uptake was 12 % by mass of the mixture. At that loading a single lane-kilometre of 50 mm wearing course absorbs approximately 51 tonnes of waste ash and displaces an equivalent tonnage of quarried mineral filler; a 10 km dual two-lane carriageway absorbs approximately 2 040 tonnes. Because ash yields differ greatly between the two feedstocks, the corresponding raw-waste diversion is dominated by palm kernel shell and is strongly sensitive to calcination yield, for which a parametric treatment is given. Durability gains translated into an equivalent-damage service-life extension factor of 1.24 to 2.03 relative to the unmodified control, implying a proportionate reduction in the frequency of resurfacing and in the primary materials consumed over a pavement life cycle. The assessment also identifies the conditions under which the environmental case fails: uncontrolled open burning of shells, unverified leaching behaviour, and transport distances that erode the avoided-burden credit. A staged implementation and quality-control framework is proposed.

Keywords: Waste valorisation; Circular economy; Palm kernel shell ash; Oyster shell ash; Asphalt pavement; Material flow analysis; Niger Delta

1. Introduction

The Niger Delta presents an unusual convergence of two apparently unrelated problems. The first is the disposal of bulky organic residues. Palm-oil processing, much of it at small and medium mills distributed through the rural interior, generates palm kernel shell as a hard,

lignocellulosic residue in quantities that greatly exceed local demand for fuel or aggregate. Oyster shell is created when people harvest shellfish and sell them at the waterside market or board and disembark from the boats, and these shells pile up in oyster landing areas, drainage channels and shoreline areas. There are no systems for the systematic collection of either stream. Both are dealt with in the same manner, with the palm kernel shell waste burned uncontrolled and the rest of the waste simply dumped. Pavement failure (Igwe & Ottos 2017; Ottos & Nyebuchi 2018) is the second problem. The annual rainfall in the area regularly surpasses 2,500 mm with pipes and drains often becoming full for days and carriageways becoming completely flooded. That's the time when moisture can affect the bond between the binder and the aggregate, reduce the bond between the mastic and increase the rate of ravelling and structural disintegration (Igwe et al., 2016; Omar et al., 2020; Wang et al., 2019). The result is a short resurfacing cycle - every cycle requires primary crushed rock, mineral filler (quarried) and hot mix bitumen, as well as the energy used in the quarrying, haulage and hot mix production. The environmental costs of road maintenance in the region are thus not a fundamental cost of road ownership, but a variable cost which is proportional to the rate of failure of the pavements. The use of waste materials is cost effective in moisture related environment such as Niger delta has been proven (Otto & Amadi-Oparaeli, 2020; Otto & Awarri 2021). From a materials point of view, both residues can be considered as plausible mineral fillers. The amount of filler is very small, but it has a great influence on the properties of the mixing, such as stiffness, cohesion, permeability and resistance to moisture (Wu et al., 2021; Xu et al., 2021). The chemical composition of oyster shell is mostly composed of calcium carbonate and after calcination it is calcium oxide, which is similar to the two most commonly used anti-stripping fillers around the world: limestone filler and hydrated lime (Silva et al., 2019; Kim et al., 2020). Compared to the other raw materials, Palm kernel shell ash is finer, porous, siliceous, and has been proven to enhance the durability properties when added to the concrete mixture at moderate proportion, but it reduces the strength at high proportion (Oktavia et al., 2024; Inyang et al., 2024; Pratiwi et al., 2024). Waste fillers in asphalt have been reviewed repeatedly, and although it is often claimed that they are environmentally responsible, they are rarely quantified (Otto, et al., 2020; Yan et al., 2022; Jwaida et al., 2024). It is this gap that is the focus of this paper. The mechanical results are the overwhelming part of the technical literature on waste fillers, and a paragraph of environmental advocacy is tacked on at the end. What is seldom provided is the amount of waste that is needed per km of road, plus the specification that the mixture must still meet the specification – this is the amount that is important to a waste manager or a highway agency. The constraint is binding, it's what makes an open-ended sustainability claim a bounded engineering quantity. If the mixture absorbs a lot of waste and does not meet the volumetric requirement, then it will not be constructed; if it meets the volumetric requirement but absorbs almost nothing, then it will not be considered a waste-management intervention. In this study, therefore, the waste management aspects of PKSA and OSA are assessed. The aims are: (i) to characterise the two waste streams and the processing chain needed to obtain specification compliant waste ash; (ii) to define from a complete factorial laboratory programme the specification compliant envelope (and therefore the maximum waste ash is possible to be used in a wearing course); (iii) to transform that envelope into a quantity of material-flow per lane kilometre and per project; (iv) to quantify how much of the quarried mineral filler is avoided, as a result of the processing chain and the use of the waste-ash in the wearing course; (v) to show when the environmental case does not work; and (vi) to propose an implementation and quality-control framework suitable for the local context.

2. Materials and methods

2.1 Waste streams and the processing chain

Palm kernel shells were collected from an oil palm processing plant along Elele – Owerri expressway while the shells of oysters were collected from waterside markets in the Port Harcourt area of the country. Both were washed to remove adhering organic matter and salt and then sun-dried, broke down, made of a controlled temperature fire, ground and sieved so that the fraction that came out through the 0.075 mm sieve was used as a filler. The chain is summarised in Figure 1 and the burdens that are displaced by it.

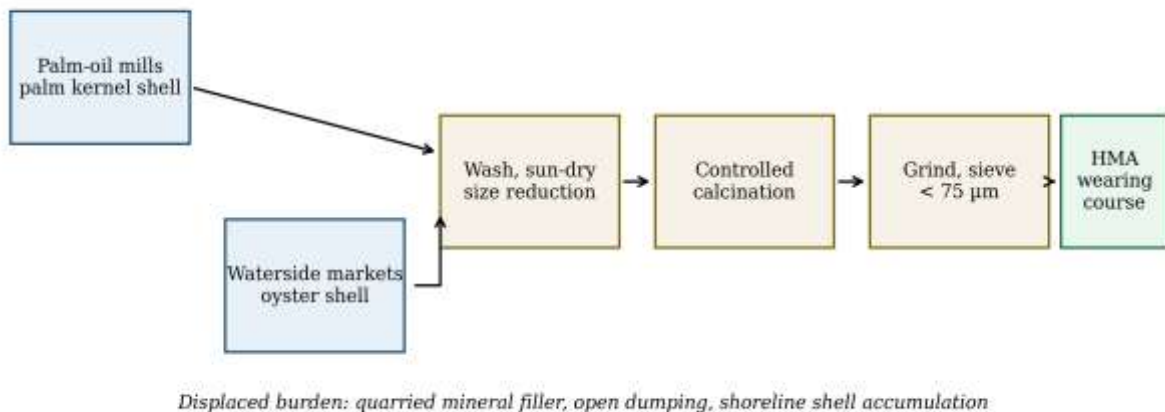


Figure 1. Processing chain converting palm kernel shell and oyster shell waste into specification-grade mineral filler, and the burdens displaced at each end. This chain has two characteristics that are important for the environmental balance, and are assessed explicitly. The first is the calcination. Calcareous shell material is converted to calcium oxide and calcium carbonate to calcium oxide starts at around 640-710 °C and it is this conversion that is responsible for the alkaline surface that causes anti-stripping behaviour. The degree of calcination is thus very critical for the adhesion to be achieved and should not be overlooked, but the calcination temperature should still be controlled so as not to over- or under-calcine the particles. The same applies to palm kernel shell, where residual unburnt carbon and a high loss on ignition impair adhesion, so that pre-treatment is a determinant of performance rather than a refinement of it (Pratiwi et al., 2024; Yan et al., 2022). The second feature is that both feedstocks are processed in the same facility and with the same unit operations, which is what makes a blended two-waste filler operationally realistic rather than merely conceptually attractive.

2.2 Mixture design and laboratory programme

A 60/70 penetration-grade bitumen, crushed gravel and river sand were used throughout. Aggregate proportions were selected so that the combined gradation fell within the ASTM C136 envelope. The optimum binder content was established by the Marshall procedure for heavy traffic (75 blows per face) as the mean of the binder contents at maximum stability, maximum bulk density and the median air-void limit, giving 4.9 %.

A complete 6 × 6 factorial was executed in which PKSA and OSA were each set at 0, 2, 4, 6, 8 and 10 % by mass of the total mixture, giving 36 combinations and a maximum combined waste loading of 20 %. Marshall stability and flow, bulk density, air voids (VTM), voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), indirect tensile strength and the tensile and compressive elastic moduli were determined for each combination in the unconditioned state. A parallel immersion series, in which OSA content was varied from 0 to

10 % at constant PKSA content, was fully submerged for 0, 1, 2, 4, 7 and 14 days before testing, and yielded the indirect tensile strength ratio (ITSR), the swelling index and the first and second durability indices in addition to the mechanical and volumetric responses.

2.3 Definition of the waste-absorption envelope

The maximum uptake of waste is not a materials property; it is the largest combined filler loading for which the mixture still satisfies every applicable acceptance criterion at once. Each of the 36 blends was accordingly screened against the full Asphalt Institute criteria set: air voids 3–5 %, Marshall flow 2–4 mm, VFA not less than 65 %, VMA within 9–21 %, and Marshall stability not less than 8 kN. A blend was counted as available for waste absorption only if it passed all five simultaneously. This is a deliberately conservative basis: single-criterion screening, which is what most waste-filler studies apply implicitly, admits mixtures that a highway agency would reject.

2.4 Material-flow assessment

The compliant envelope was converted into physical tonnage on the basis of a 50 mm wearing course laid over a standard 3.65 m lane width. Taking the measured bulk density of the modified mixtures as 2 326 kg/m³, the mass of mixture per lane-kilometre is

$$m = w \cdot t \cdot L \cdot \rho = 3.65 \times 0.05 \times 1\,000 \times 2\,326 = 424.5 \text{ tonnes per lane-kilometre} \quad (1)$$

with the mass of ash incorporated following directly from the filler percentage. The corresponding quantity of raw waste diverted depends on the ash yield of each feedstock, which differs by roughly an order of magnitude between a lignocellulosic residue and a calcareous shell and which is in any case sensitive to calcination conditions. Rather than adopt single point values, the raw-waste diversion is presented parametrically as a function of ash yield, with an indicative calculation at representative values clearly identified as such. Displacement of conventional quarried mineral filler is taken as one-to-one by mass, which is exact by definition since the ash occupies the filler position in the gradation.

2.5 Service-life extension

Moisture-induced loss of Marshall stability followed first-order kinetics, $\ln P(t) = \ln P_0 - kt$, and this was used to derive an equivalent-damage service-life extension factor. For each blend the fitted model was solved for the immersion time at which stability falls to a common terminal value, taken as the day-14 stability of the unmodified control (17.58 kN). The ratio of that time to the corresponding time for the control gives a dimensionless factor expressing how much longer the modified mixture sustains an equivalent level of moisture damage. This is a laboratory-scale proxy, not a field service-life prediction, and it is interpreted as such throughout.

3. Results and discussion

3.1 The compliance envelope determines how much waste can be used

Of the 36 blends investigated, only 11 satisfied all five acceptance criteria simultaneously (Figure 2, Table 1). The 25 exclusions are not random. The entire zero-OSA row and most of the zero-PKSA column fail on VFA, which falls below 65 % because insufficient void space is filled with binder. The high-PKSA region fails on air voids, which drop below the 3 % minimum — at 10 % PKSA with 10 % OSA the air-void content is only 1.55 % — and such mixtures would be at risk of bleeding and plastic deformation in service. The envelope is therefore a diagonal band running from moderate PKSA with low OSA to low PKSA with high OSA.

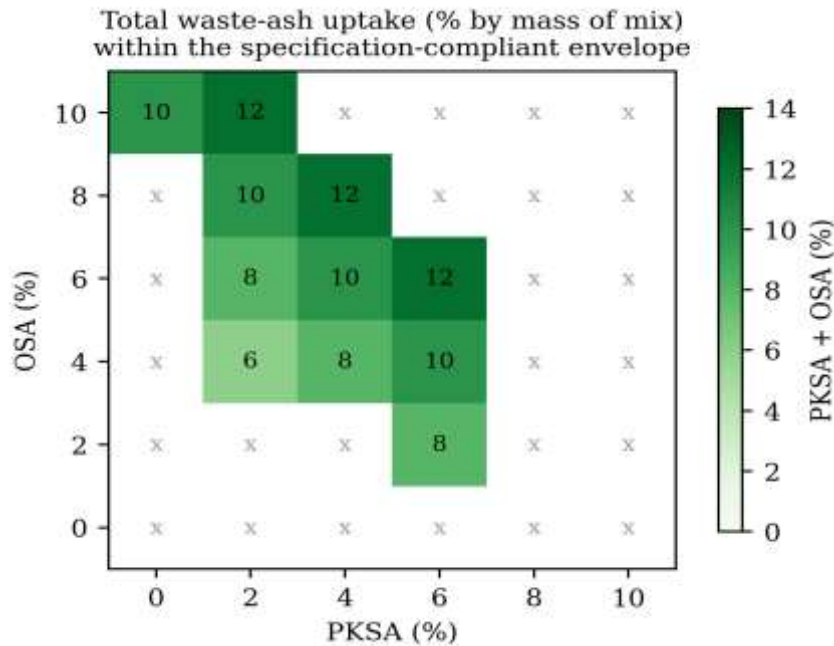


Figure 2. Total waste-ash uptake (PKSA + OSA, per cent by mass of mixture) for blends satisfying all Asphalt Institute criteria. Cells marked "x" fail at least one criterion and are unavailable for waste absorption.

The practical significance of the envelope is that it caps waste uptake at 12 % by mass of the mixture. Four compliant blends reach that ceiling: 2 % PKSA with 10 % OSA, 4 % PKSA with 8 % OSA, 6 % PKSA with 6 % OSA, and, at 10 %, 6 % PKSA with 4 % OSA. Of these, the 2 % PKSA and 10 % OSA combination gives the highest stability (27.2 kN) and stiffness (0.925 MPa), while the 6 % PKSA and 6 % OSA combination gives the highest VFA (77.1 %) and the largest share of the agro-waste stream. The choice between them is a waste-management decision as much as an engineering one, and depends on which residue is locally the more burdensome.

Table 1. Specification-compliant blends and their waste-absorption capacity.

PKSA (%)	OSA (%)	Total waste (%)	Stability (kN)	VTM (%)	Flow (mm)	VFA (%)	Ash absorbed (t / lane-km)
2	10	12	27.2	3.58	3.27	70.9	50.9
4	8	12	25.9	3.35	3.62	73.9	50.9
6	6	12	22.6	3.02	3.63	77.1	50.9
0	10	10	32.3	4.14	2.90	65.8	42.5
2	8	10	26.9	3.86	3.32	69.2	42.5
6	4	10	22.9	3.30	3.90	75.4	42.5
4	6	10	24.1	3.59	3.79	72.4	42.5
2	6	8	26.7	4.12	3.53	67.7	34.0
4	4	8	23.6	3.83	3.95	70.9	34.0
6	2	8	20.4	3.54	3.98	74.0	34.0
2	4	6	25.1	4.39	3.45	66.2	25.5

3.2 Material flow: how much waste a road can absorb

Applying equation (1), one lane-kilometre of 50 mm wearing course contains approximately 424.5 tonnes of mixture. Table 2 converts the compliant filler loadings into absorbed tonnage at three scales: the lane-kilometre, a 10 km dual two-lane carriageway (40 lane-kilometres) and a 25 km dual two-lane corridor (100 lane-kilometres).

Table 2. Waste-ash absorption and displaced quarried filler at three project scales, for a 50 mm wearing course on a 3.65 m lane at a bulk density of 2 326 kg/m³.

Waste loading (% by mass)	Ash absorbed and quarried filler displaced (tonnes)		
	1 lane-km	10 km dual 2-lane (40 lane-km)	25 km dual 2-lane (100 lane-km)
4 % (2 % PKSA + 2 % OSA)	17.0	679	1 698
6 %	25.5	1 019	2 547
8 % (2 % PKSA + 6 % OSA)	34.0	1 358	3 396
10 % (2 % PKSA + 8 % OSA)	42.5	1 698	4 245
12 % (2 % PKSA + 10 % OSA) — envelope maximum	50.9	2 038	5 094
Total mixture placed	424.5	16 980	42 450

These are substantial quantities. At the envelope maximum, a single 10 km dual two-lane resurfacing project would consume roughly two thousand tonnes of processed waste ash and displace an identical tonnage of quarried mineral filler. Expressed differently, the wearing course of such a project could accommodate the entire ash output of a considerable regional collection programme. The scale is worth stating because it counters an intuition, common in discussions of waste valorisation in construction, that filler applications are too small to matter. Filler is a small fraction of a very large mass flow, and road construction is one of the few activities in the regional economy that operates at a tonnage comparable to the waste streams themselves. Converting absorbed ash into raw waste diverted requires the ash yield of each feedstock, and here the two streams behave very differently. Calcareous shell loses only its carbonate carbon dioxide and adsorbed organics on calcination and retains most of its mass; lignocellulosic shell loses the great majority of its mass as combustion products and retains only a small mineral residue. The consequence is that the raw-waste diversion is dominated by palm kernel shell even when the two ashes are used in equal proportion. Table 3 presents the relationship parametrically.

Table 3. Raw waste diverted per lane-kilometre as a function of ash yield, for a mixture containing 6 % PKSA and 6 % OSA (25.5 tonnes of each ash per lane-kilometre). Ash yield is treated parametrically because it is strongly dependent on calcination conditions and feedstock moisture.

Ash yield (%)	Raw feedstock required per tonne of ash (t)	Raw waste diverted per lane-km at 6 % filler loading (t)
5	20.0	509
8	12.5	318
10	10.0	255
15	6.7	170

Ash yield (%)	Raw feedstock required per tonne of ash (t)	Raw waste diverted per lane-km at 6 % filler loading (t)
30	3.3	85
50	2.0	51
60	1.7	42

Read across a plausible operating range — a low single-figure to low double-figure yield for palm kernel shell and a high yield for oyster shell — a mixture at 2 % PKSA and 2 % OSA diverts of the order of 85 to 170 tonnes of raw palm kernel shell and 14 to 17 tonnes of raw oyster shell per lane-kilometre. The asymmetry is important for programme design: the palm-oil residue is the volumetrically dominant diversion, whereas the shell residue is the technically dominant contributor to performance. A collection programme that treats them as interchangeable will misallocate its logistics.

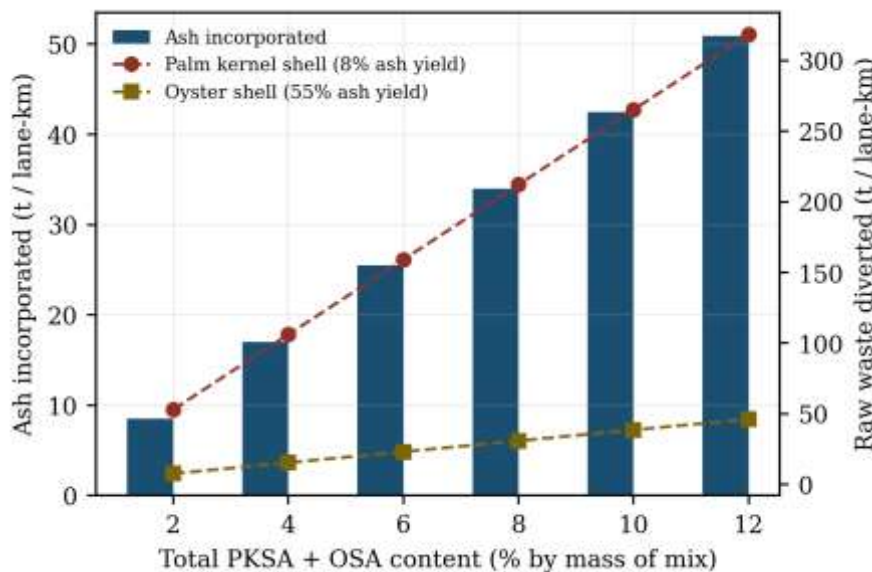


Figure 3. Ash incorporated and raw waste diverted per lane-kilometre as a function of total filler loading, at indicative ash yields of 8 % for palm kernel shell and 55 % for oyster shell.

3.3 Avoided primary material and the limits of the credit

Every tonne of waste ash placed in the filler position displaces a tonne of quarried mineral filler, ordinarily crushed limestone or granite dust produced as a by-product of aggregate crushing. The avoided burden comprises the extraction, crushing, screening and haulage associated with that tonne, together with the land-use and dust impacts of quarrying. The distance of transport of the filler to and from the quarry (a large proportion of cost and burden of filling) and the distance of transport from scattered mills and waterside markets to collect shells make the credit very sensitive to transport distances in both directions.

It is therefore not defensible to claim a net environmental benefit without a site-specific accounting, and this paper does not do so. What can be stated is the physical quantity displaced, which is exact, and the conditions under which the credit is likely to survive. Those conditions are: that collection radii for both feedstocks are comparable to or shorter than the haul distance from the nearest quarry; that calcination is carried out in a controlled kiln with heat recovery rather than by open burning; and that processing is co-located with either the waste source or the asphalt plant so that only one of the two haulage legs is added. Where shells are open-

burned in the field which is the prevailing practice the resulting emissions and the uncontrolled combustion products may well exceed the burden avoided, and the intervention would then be a net environmental loss dressed as a gain. When assessing the balance of life-cycle costs of similar biochar-waste-filler systems, reducing material use has consistently been found to be a small fraction compared to processing energy costs (Chen et al., 2020; Quintana et al., 2022; Yan et al., 2022).

3.4 Service-life extension and second-order material savings

The larger impact a durable pavement has on the environment is the man hours and resources saved from being replaced over and over. The loss of Marshall stability due to moisture showed first order reaction with R2 between 0.92-0.97. The equivalent-damage extension factors are obtained from the models when the time is determined at which each mixture falls to the terminal stability at day 14 as the control mixture. Equivalent-damage extension factors can be calculated from the models at the time when each mixture reaches the terminal stability of the control mixture at day 14.

Table 4. Equivalent-damage service-life extension derived from first-order stability decay. The terminal condition is the day-14 stability of the unmodified control (17.58 kN).

Blend level (% OSA at constant PKSA)	Decay constant k (d^{-1})	Fitted initial stability (kN)	Time to terminal condition (d)	Extension factor	Retained stability at day 14 (%)
0 (control)	0.02792	25.18	12.9	1.00	65.6
2	0.02845	27.68	16.0	1.24	65.4
4	0.02758	30.01	19.4	1.51	66.4
6	0.02691	31.79	22.0	1.71	67.3
8	0.02612	32.97	24.1	1.87	67.9
10	0.02431	33.20	26.2	2.03	69.7

The extension factor increases steadily with the highest blend level being 2.03. Two mechanisms contribute. The former, namely the higher initial stability due to the calcium in the mastic, is the primary one, and the latter is real, decreasing the rate constant by 12.9% from 0.02792 to 0.02431 d^{-1} , which is a statistically significant trend. The story with the durability indices is the other way: The first durability index, which measures deterioration over the short term, dropped by 21.6 % over the range of blendings, and the second durability index, which considers retention over the longer term, rose from 11.3 to a maximum of approximately 12.7, before tapering off slightly at the very highest loadings.

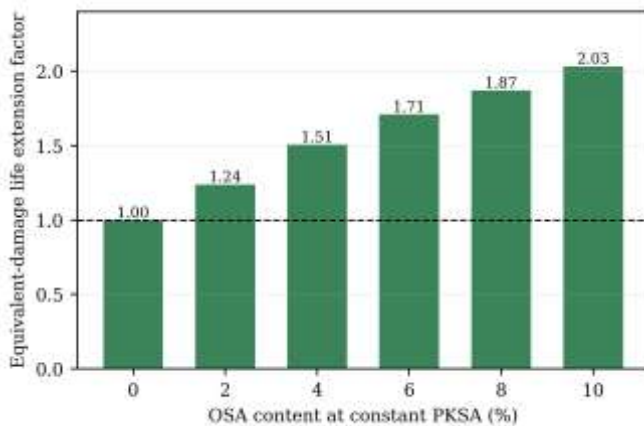


Figure 4. Equivalent-damage service-life extension factor relative to the unmodified control. The material implication is straightforward in arithmetic and demanding in interpretation. If a wearing course that would otherwise be resurfaced every six years instead lasts nine, then over a thirty-year horizon the number of resurfacing cycles falls from five to three, and the primary aggregate, bitumen and hot-mix energy associated with two full resurfacings are avoided. For the 10 km dual two-lane example that is of the order of 34 000 tonnes of mixture not produced, laid or hauled, an avoided burden roughly seventeen times larger than the waste absorbed in the original construction. The second-order saving therefore dominates the first-order one by a wide margin. The interpretive demand is that the extension factor is a laboratory proxy derived from static submergence over fourteen days, not a field service-life prediction. Field deterioration is driven by the combination of moisture with traffic loading, thermal cycling, oxidative ageing and construction variability, none of which is represented here, and the mapping from an accelerated laboratory index to years of service requires calibration against monitored sections. The factors in Table 4 should be read as a relative ranking of moisture durability with a plausible physical interpretation, and the maintenance-cycle arithmetic above as an illustration of the leverage involved rather than a forecast.

3.5 Position within the waste-management hierarchy

The intervention should be properly labeled. It's not waste prevention because the residue is created in a process that's going on anyway. It is not re-use because there is chemical and physical change to the material. It is material recycling in the recovery layer of the waste-management hierarchy, and in particular it is an open loop recycling process: waste from the food and agro-processing industry becomes an input for the construction industry, is incorporated into a long-life intermediate product (building) and is not recovered at end-of-life. The latter is not something to be hidden from the light but emphasized. The use of waste in a pavement is not the closure of a loop, it's merely the transportation of the waste into a durable sink. This is a legitimate and generally favourable outcome for inert mineral residues, because the alternative for these particular streams is open dumping or open burning, but it is not equivalent to a circular material flow and should not be presented as one. The relevant comparison is not against an ideal circular system but against the counterfactual: unmanaged accumulation at mills and landing sites, with the associated leachate, vector, odour and navigational impacts, and the combustion emissions of uncontrolled burning.

Judged against that counterfactual the case is strong. Judged against alternative valorisation routes for the same feedstocks it is more finely balanced. Palm kernel shell has established competing uses as a solid biofuel and as a feedstock for activated carbon; oyster shell has competing uses in soil conditioning, aquaculture substrate and lime production (Silva et al., 2019). A regional strategy should allocate the streams among these routes according to local

demand and transport geometry rather than assume that pavement filler is the highest-value destination for all of it.

3.6 Environmental risks and required safeguards

Four risks qualify the assessment and each carries a corresponding safeguard.

Combustion emissions. The environmental case depends on controlled calcination. Open burning of palm kernel shell releases particulate matter, carbon monoxide and products of incomplete combustion, and produces an ash of variable and unpredictable composition. Calcination should be carried out in a controlled kiln with a specified temperature range and residence time, and the operating window should form part of the material specification rather than being left to the supplier.

Leaching. Neither ash was subjected to leaching assessment in this programme. Alkaline calcium-oxide-bearing material can raise the pH of contacting water, and agro-waste ashes may carry trace elements concentrated by combustion. Because wearing courses in this setting are by definition in prolonged contact with standing water, leaching behaviour is not a peripheral concern. Standardised leaching tests should be completed and cleared against the applicable environmental limits before any field trial, and this is stated as a precondition rather than a recommendation for future work. Occupational and community exposure. Both processing chains generate respirable dust at the grinding and sieving stages, and calcined calcium oxide is caustic. Enclosed grinding, dust extraction and respiratory protection are required, and siting should account for proximity to dwellings. Supply variability. Agro-waste ash composition varies with feedstock origin, moisture content and combustion conditions, and this variability is the most frequently cited obstacle to specification adoption (Yan et al., 2022; Pratiwi et al., 2024). Without batch-level quality control the performance demonstrated in the laboratory will not be reproduced in the field, and a failed trial section would set the technology back further than no trial at all.

3.7 Implementation framework

From the above, a phased approach to adoption ensues. Stage one is characterisation and clearance: instrumental determination of the oxide composition, loss on ignition, fineness and specific gravity of each source, and leaching tests, clear against environmental limits. Stage two is specification, setting a calcination window, a maximum loss on ignition, a fineness requirement and a recommended range for the filler loading, the design basis being the compliance envelope of Fig. 2, and the recommended starting composition 2 % PKSA with 8–10 % OSA. Stage three is a monitored field trial on a representative flood-prone section with an adjacent control, instrumented for at least three wet seasons, since the service-life claims in Section 3.4 cannot be substantiated by laboratory data alone. Stage four is the collection logistics: aggregation points at clusters of palm-oil mills and at waterside markets, with processing co-located to avoid a double haul. Stage five, contingent on the trial, is inclusion in agency specifications with batch-level quality control. Two institutional observations follow. First, the collection stage, not the technical stage, is where comparable initiatives usually fail; the residues are dispersed among many small producers with no existing commercial relationship to the road sector, and an aggregation mechanism must be designed rather than assumed. Second, the intervention aligns with the objectives of sustainable industrialisation and infrastructure, sustainable cities, and responsible consumption and production, but alignment with policy objectives is not evidence of net benefit and should not be offered in place of the site-specific accounting described in Section 3.3.

3.8 Limitations

The assessment is bounded in four respects. It is a material-flow and resource-efficiency analysis, not a life-cycle assessment; no impact-category results are reported, and none should be inferred, because the processing-energy inventory that would dominate such an assessment was not measured. The ash yields governing raw-waste diversion were not determined experimentally and are therefore treated parametrically. The service-life extension factors derive from static submergence over fourteen days and have not been calibrated against field performance. And the compliance envelope reflects one particular criterion set applied to one aggregate gradation, binder grade and layer configuration; a different nominal maximum aggregate size or a stricter VMA requirement would shift the envelope and hence the maximum waste uptake.

4. Conclusions

This study assessed palm kernel shell ash and oyster shell ash as blended asphalt mineral fillers from a waste-management and resource-efficiency standpoint, using a complete factorial laboratory programme to define the envelope within which waste can actually be absorbed. The following conclusions are drawn.

- (1) Specification compliance, not material performance in isolation, determines how much waste a pavement can absorb. Only 11 of 36 blends satisfied all Asphalt Institute criteria simultaneously, and the maximum compliant waste-ash uptake was 12 % by mass of the mixture. Screening against a single criterion, as is common in the waste-filler literature, overstates the available capacity.
- (2) At the envelope maximum, one lane-kilometre of 50 mm wearing course absorbs approximately 51 tonnes of waste ash and displaces an equal tonnage of quarried mineral filler; a 10 km dual two-lane carriageway absorbs approximately 2 040 tonnes.
- (3) Raw-waste diversion is dominated by palm kernel shell and is strongly sensitive to calcination yield. At indicative yields, a mixture at 2 % PKSA and 2 % OSA diverts of the order of 85–170 tonnes of raw palm kernel shell and 14–17 tonnes of raw oyster shell per lane-kilometre. Oyster shell contributes disproportionately to performance and palm kernel shell disproportionately to diverted volume.
- (4) Improved moisture durability yields an equivalent-damage service-life extension factor of 1.24–2.03, arising principally from a higher initial stability and secondarily from a 12.9 % reduction in the degradation rate constant. The avoided material burden from fewer resurfacing cycles is roughly an order of magnitude larger than the waste absorbed at construction.
- (5) The intervention is open-loop material recycling into a durable sink rather than a closed material loop, and its environmental credit is conditional on controlled calcination, cleared leaching behaviour, short collection radii and batch-level quality control. Where shells are open-burned in the field, the intervention may be a net environmental loss.
- (6) A blend of 2 % PKSA with 8–10 % OSA is recommended as the starting composition for field trial, subject to prior leaching clearance and to monitoring over at least three wet seasons. Future work should quantify the processing-energy inventory so that a full life-cycle assessment can be completed, determine ash yields experimentally for regionally representative feedstocks, and establish monitored field sections against which the laboratory durability proxies can be calibrated.

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