

Influence of Omni Processor Ash Incorporation on the Atterberg Limits and Compaction Behaviour of a Laterite from Thick, Senegal: Physicochemical Characterization and Preliminary Study

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ABSTRACT

Turning sanitation by-products into construction materials advances circular-economy goals and lowers the environmental footprint of road infrastructure. Here we examine how small additions of ash from an Omni Processor affect the Atterberg limits and compaction response of a lateritic soil sampled at Thick, Senegal. The raw laterite was characterized by sieve analysis and X-ray diffraction (XRD); the bottom ash (CFOP) was assessed by X-ray fluorescence (XRF), XRD, and SEM-EDS. Six laterite-CFOP blends (0, 1, 1.5, 2, 2.5, and 3% ash) underwent Atterberg limit and Modified Proctor compaction testing. Quartz (55.7%) and kaolinite (27.1%) dominate the laterite, 28.4% of which passes the 0.08 mm sieve. The CFOP contains 33.9% SiO₂ and 17.4% CaO; SiO₂+Al₂O₃+Fe₂O₃ together total 54.7%, short of the 70% ASTM C618 benchmark for some pozzolanic materials. Plasticity evolved non-monotonically with CFOP content: the plasticity index climbed from 12.5% (untreated) to 16.9% at 1% CFOP before falling to 10.8% at 3%.

Compaction followed a similar pattern, with maximum measured dry density peaking at 2.093 g/cm³ (from 2.00) at 1% CFOP before declining at higher dosages, while the corresponding water content rose to 14.53% at 2.5% before easing to 12.92% at 3%. All blends met the CEBTP (1984) plasticity threshold for a foundation layer; only the 1% blend exceeded the base-layer limit. Meeting the plasticity criterion alone, however, does not confirm overall fitness for road use. Further testing (particle size, CBR, strength, durability, and leaching of the blends) remains necessary before any conclusion on pavement use.

Keywords: Laterite; Sewage sludge ash; Omni Processor; Atterberg limits; Proctor compaction; Road geotechnics; Circular economy

1. INTRODUCTION

Lateritic gravels occur abundantly across many tropical regions and offer an economically attractive material for road pavement construction. Yet their natural geotechnical properties, among them water

sensitivity, variable plasticity, and, at times, an unsuitable particle-size distribution, often call for detailed characterization and, in some cases, treatment beforehand so that base- and sub-base-layer requirements can be met.

This variability among West African lateritic materials, together with the resulting need for characterization ahead of road use, is well documented in the literature; Gidigas (1991) [1] in particular offers a reference synthesis on the characterization and use of tropical gravels for pavement construction across West Africa.

Several studies have looked at correcting the properties of Senegalese laterites using locally available materials. Ndiaye et al. (2013) [2] examined the improvement of Senegalese laterites through dune-sand addition, and Ndiaye et al. (2022) [3] investigated lithostabilization of a laterite from south-eastern Senegal using dolerite from Mansadala for base-layer use. Together, these studies point to the range of local materials that can be drawn on to address specific shortcomings of lateritic soils.

Lime and cement, as hydraulic or calcic binders, represent another conventional route for improving specific properties of tropical lateritic soils (Ola, 1978) [4]. Their use, however, carries economic and environmental costs, which motivates the search for alternatives grounded in by-product valorization.

Meanwhile, the spread of on-site sanitation technologies across West Africa has encouraged the deployment of thermal sludge-treatment systems such as Omni Processors, a technology whose underlying principle was developed by Ankur Scientific among others (Ankur Scientific, n.d.) [5]. These systems shrink sludge volume and yield several by-products, one of which is a mineral ash fraction. Rowles et al. (2022) [6] examined how such technologies operate and perform environmentally, and Gueye et al. (2022) [7] reported on the characterization of ash from an Omni Processor operating in Senegal.

Ash valorization from the thermal treatment of sewage sludge has already found its way into a number of applications, cementitious materials and soil improvement among them. Donatello and Cheeseman (2013) [8] reviewed the principal valorization routes for incinerated sewage sludge ash, and both Kadhim et al. (2021) [9] and Chen and Lin (2009) [10] examined its role in soil improvement. Sah et al. (2025) [11] more recently produced a review focused on its use for subgrade-soil improvement.

Documentation on using Omni Processor ash as an additive for lateritic materials in geotechnical applications nonetheless remains scarce in Senegal, and closing this gap is the central motivation for the present study. It is also worth noting that combining plant ash with lime has recently shown promise for improving lateritic soils (Parayil and Salini, 2025) [12]; while useful as background, this finding cannot be extrapolated directly to the behaviour of a sludge-derived ash.

Silica, alumina, iron oxide, and calcium contents in sewage sludge ashes tend to vary considerably (Cabalar et al., 2026) [13]. Where clay minerals are present in a soil, introducing calcic species can alter physicochemical particle interactions, for instance through calcium-fixation mechanisms and changes to the electrochemical diffuse double layer, as described in other clayey settings (Abbaslou et al., 2020) [14], and can thereby affect plasticity and compaction behaviour. Absent direct confirmation through dedicated tests on the mixtures, however, such mechanisms remain interpretive hypotheses rather than established facts.

This study is grounded in a circular-economy rationale applied to urban sanitation. Faecal sludge management remains a pressing issue for West African cities, where on-site sanitation is still the norm. While thermal treatment technologies shrink sludge volumes and generate mineral residues, they leave open the question of how best to valorize what remains.

Given the sheer volume of granular material that road infrastructure consumes, road construction stands out as a plausible outlet for such residues. Valorizing them this way could ease pressure on natural deposits while giving a sanitation by-product a genuine second use.

This work represents the opening phase of a wider research programme evaluating the potential use of this ash in road materials. It encompasses the physicochemical and mineralogical characterization of both the laterite and the ash, along with an assessment of how low ash dosages influence the Atterberg limits and Proctor compaction behaviour.

A full assessment of the material's suitability for road use would additionally require California Bearing Ratio (CBR),

mechanical-strength, and durability testing; as these have not yet been carried out, they fall outside the scope of the present article.

The central aim, then, is to assess how incorporating 0 to 3% of Omni Processor bottom ash affects the plasticity and compaction properties of a laterite sampled at Thicky, with a view to flagging formulations worth pursuing in further geotechnical investigation.

2. MATERIALS AND METHODS

2.1. Materials studied

The soil under study is a laterite drawn from a borrow site at Thicky, located in the Diass commune, Mbour department, Thiès region, Senegal: a red-brown lateritic gravelly material representative of the local weathering formation.



Fig. 1. Raw Thicky laterite, as sampled on site before sieving and sample preparation.

Thicky village sits near national road N1, between Diass and Sindia, not far from Blaise Diagne International Airport and the Bandia reserve; Figure 2 shows the location of the study site.



Figure 3 presents the local geological context. The sampling point falls within a formation mapped as C5-6, corresponding to the undifferentiated Diass Group and

comprising, among other lithologies, sandstones and clays of Campanian–Maastrichtian age (Roger et al., 2009) [15].

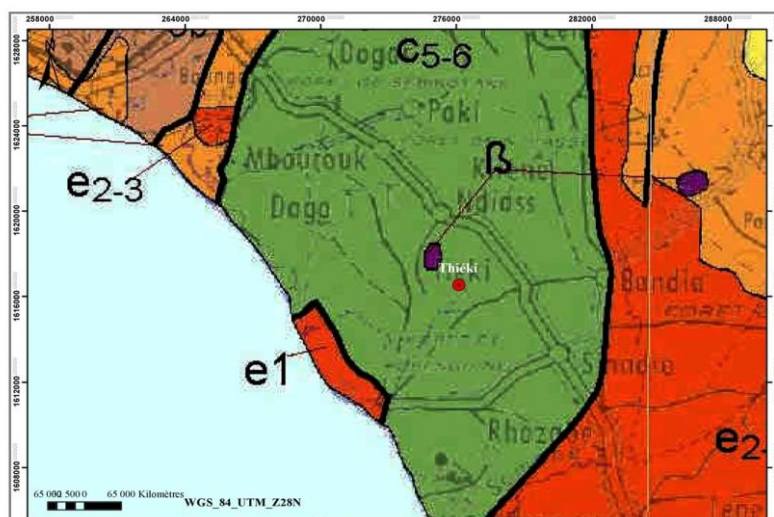


Fig. 3. Excerpt from the geological map of Senegal, locating the Thicki laterite sampling point. Source: Geological map of Senegal at 1/500,000, north-west sheet, produced under PASMI (Mining Sector Support Project) (Roger et al., 2009) [15].

The additive examined here originates from the thermal treatment of septic-tank faecal sludge in an Omni Processor installed at the Cambérène treatment plant in Dakar. The process yields two distinguishable ash

fractions, fly ash and bottom ash; only the latter, designated CFOP throughout this article, was used in the laterite-ash mixture tests.



Fig. 4. Weighing of Omni Processor ash during preparation of the laterite-ash mass dosages.

The chemical-characterization data for the ash reported in Tables 4, 7, and 8 draw on earlier work carried out on this same Omni Processor ash (Gueye, 2023 [16]; Sall, 2021 [17]), whereas the geotechnical tests on the

laterite-CFOP mixtures presented here constitute the results of the present study.

2.2. Physicochemical and mineralogical characterization

Sieving after washing on a 0.08 mm sieve, per standard NF P94-056 [18], was used to determine the particle-size distribution of the raw laterite, starting from an initial dry mass of 5000 g. Once washed, the dry mass retained across the full set of sieves, tare deducted, came to 3587 g.

Cumulative passing and retained percentages were computed relative to that initial dry mass, and log-linear interpolation of the particle-size curve yielded the characteristic diameters D30 and D60. Because the fraction passing the 0.08 mm sieve already exceeded 10%, D10 could not be obtained from sieving alone and would instead require a complementary test on the fine fraction.

Powder X-ray diffraction was used to determine the laterite's mineralogical composition, with phase quantities obtained through Rietveld refinement following the method of Hill and Howard (1987) [19]; the resulting refinement factors are $R_{wp} = 7.37$ and $R_{exp} = 2.36$.

X-ray fluorescence (XRF) served to determine the chemical composition of the laterite. Because the instrument's calibration is optimized for cementitious materials rather than a non-cementitious lateritic soil, it tends to underestimate silica and reports a CO₂ content that does not correspond to a directly measured major oxide. This CO₂ value was accordingly excluded from the mass balance and replaced with the loss on ignition (LOI), measured independently by calcination; the major oxides were then renormalized to 100% using this LOI while preserving their original relative proportions, a correction that

at least partly offsets the silica underestimation noted above.

X-ray fluorescence (XRF) was likewise used to establish the bottom ash's chemical composition, while its mineralogy was examined by XRD and its morphology by scanning electron microscopy coupled with an energy-dispersive spectrometer (SEM-EDS), using a JEOL IT 300 microscope.

Laser diffraction (combining Fraunhofer diffraction and Mie scattering; Cyr and Tagnit-Hamou, 2001) [20], performed on a Cilas Particle Size Analyser 1064, provided the CFOP's particle-size distribution, with the corresponding data taken from Gueye (2023) [16].

The sum SiO₂ + Al₂O₃ + Fe₂O₃ is reported here purely for comparison against the chemical criterion set out in ASTM C618 [21]; this comparison does not amount to a qualification of the ash under that standard, which was in fact developed for coal fly ash and natural pozzolans used in certain cementitious applications.

Trace-element and soluble-ion contents are similarly compared against reference values drawn from international technical texts; these comparisons serve only as benchmarks and do not represent Senegalese regulatory criteria specific to sludge-treatment ash used in road geotechnics.

2.3. Mixture preparation

Dry mixing was used to prepare the laterite-CFOP blends: ash was added to the laterite at the chosen mass dosages and homogenized before water was progressively introduced to reach each test point.



Fig. 5. Incorporation of ash into the lateritic soil during dry mixing (preparation of a test point).



Fig. 6. Homogenized laterite-ash mixture batch, prepared for geotechnical testing.

Dosages of 0, 1, 1.5, 2, 2.5, and 3% were examined.

Atterberg limits were established for each of these mixtures, while Proctor compaction testing spanned the full 0 to 3% dosage range.

Several water contents were examined at each dosage so that the relationships required to derive the geotechnical parameters could be established.

2.4. Geotechnical testing

Standard NF P94-051 [22] governed the determination of Atterberg limits, carried out on the fraction passing the 0.40 mm sieve.

The Casagrande apparatus was used to determine the liquid limit (LL). Water contents recorded across the different blow counts were fitted by log-linear regression using the relationship $W = a \ln(N) + b$, where W denotes water content and N the number of blows, with the liquid limit taken as the water content at $N = 25$ blows.

The plastic limit (PL) is the average water content recorded when the material is rolled into threads roughly 3 mm in diameter, and the plasticity index follows as $PI = LL - PL$. Modified Proctor compaction testing followed standard NF P94-093 [23] using a 2085 cm³ mould, with several water contents tested at each dosage; dry density at each test point was calculated from the compacted wet mass together with the measured water content.

Because the W_{opt} and $\gamma_{d,max}$ values reported here correspond to the single test point of highest dry density rather than to a mathematically fitted optimum, they are referred to throughout as the water content corresponding to the maximum measured dry density and the maximum measured dry density, respectively.

For geotechnical interpretation, plasticity-index values are set against the indicative CEBTP (1984) thresholds [24], namely $PI \leq 15\%$ for a base layer and $PI \leq 25\%$ for a foundation (sub-base) layer, treated independently of other particle-size and mechanical requirements.

3. Statistical Methods

Because this preliminary characterization is exploratory and relies on single specimens, no inferential statistical tests, such as analysis of variance, were applied to the geotechnical results. Two data-treatment procedures were nonetheless applied to derive the reported parameters from raw measurements: log-linear regression of water content against blow count ($W = a \ln(N) + b$) to obtain the liquid limit at $N = 25$ blows (section 2.4), and Rietveld refinement of the powder XRD pattern to quantify mineral-phase proportions, yielding goodness-of-fit indicators $R_{wp} = 7.37$ and $R_{exp} = 2.36$ (section 2.2). For the Proctor tests, the W_{opt} and $\gamma_{d,max}$ values reported are the single experimental point of highest measured dry density at each dosage rather than an optimum derived from a mathematical fit of

the compaction curve (section 2.4); this distinction is upheld consistently throughout the Results and Discussion.

4. RESULTS

4.1. Initial characterization of the laterite and the ash

4.1.1. Particle-size distribution of the laterite

Particle-size analysis reveals a raw laterite with a Dmax of 40 mm and 49.7% retained at 2 mm.

Table 1 presents the cumulative passing values.

Table 1. Sieve particle-size analysis of the Thick laterite (NF P94-056)

Sieve size (mm)	40	31.5	25	20	10	5	2	0.5	0.08
Cumulative passing P (%)	100.0	100.0	99.2	95.2	61.6	61.3	50.3	47.7	28.4

D30 is estimated at 0.093 mm and D60 at 4.49 mm; D10, however, could not be determined from sieving alone, since 28.4% of the material already passes the 0.08 mm

sieve, meaning the uniformity and curvature coefficients cannot be calculated without a complementary characterization of the fine fraction.

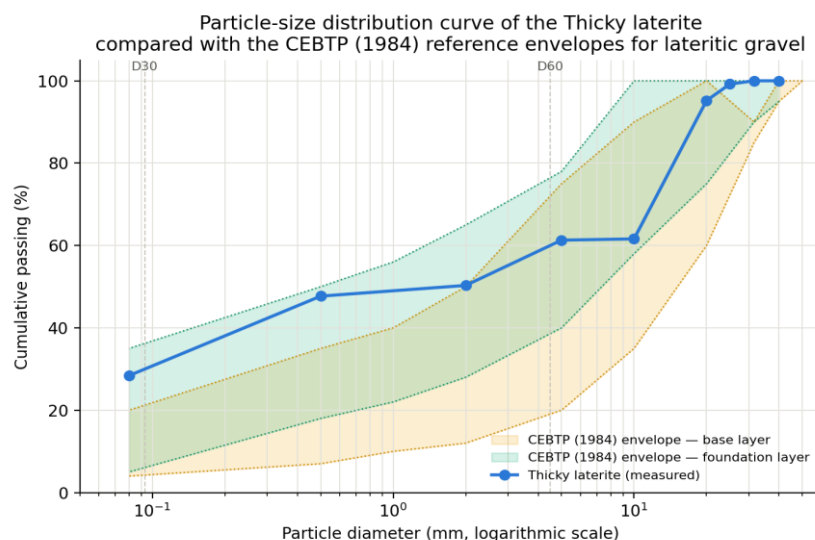


Fig. 7. Particle-size distribution curve of the Thick laterite obtained by sieving (NF P94-056), compared with the CEBTP (1984) reference envelopes for lateritic gravel in base and foundation layers, with the characteristic diameters D30 and D60 indicated (D10 not determinable by sieving alone).

With a fines content below 0.08 mm of 28.4%, the material falls within the 5–35% reference range set out in CEBTP (1984)

[24], although its fraction retained at 2 mm sits just under the 50% threshold.

Table 2. Comparison of the raw laterite with CEBTP (1984) particle-size specifications

Criterion	CEBTP reference	Measured value	Interpretation
Maximum grain size Dmax	≤ 50 mm	40 mm	Compliant
Retained at 2 mm	≥ 50 %	49.7 %	Slightly below threshold
Fines < 0.08 mm	5 – 35 %	28.4 %	Compliant

Overall, the laterite's particle-size distribution is broadly consistent with the reference ranges adopted for lateritic materials, even though the 2 mm retained

criterion sits just below the adopted threshold.

4.1.2. Chemical composition of the laterite

Table 3b sets out the chemical composition obtained by XRF.

Table 3b. Chemical composition (major oxides) of the Thicky laterite (XRF, wt%, profile 46)

Oxide/parameter (%)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	Cl	P ₂ O ₅	LOI
Thicky laterite	44.78	8.10	36.95	0.99	0.12	0.03	0.23	0.08	0.03	0.58	8.11

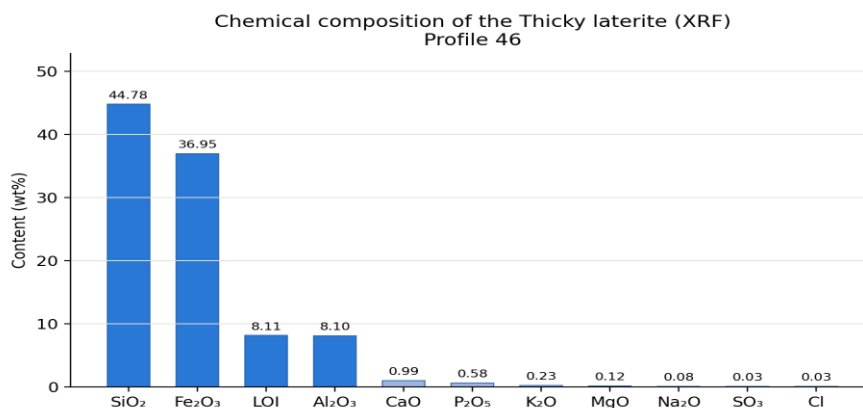


Fig. 8. Major-oxide chemical composition of the Thicky laterite (XRF, profile 46).

Once renormalized by the method set out in section 2.2 (replacing the XRF software's reported CO₂ with the loss on ignition measured by calcination, then rescaling the major oxides to 100% using this LOI), the composition is dominated by silica and iron oxide.

SiO₂ + Al₂O₃ + Fe₂O₃ together account for roughly 89.8%, a figure noted here purely as an indicator of mineral composition rather

than as any criterion of the laterite's suitability as a pozzolanic material.

4.1.3. Mineralogical composition of the laterite

XRD combined with Rietveld refinement shows a mineralogical composition dominated by quartz (55.7%) and kaolinite (27.1%).

Table 3. Mineralogical composition of the raw laterite (XRD)

Mineral phase	Quartz	Kaolinite	Illite	Magnesite	Pyrite	Albite	Dolomite	Anorthite
Mass content (%)	55.7	27.1	7.3	5.4	1.7	1.5	0.9	0.4

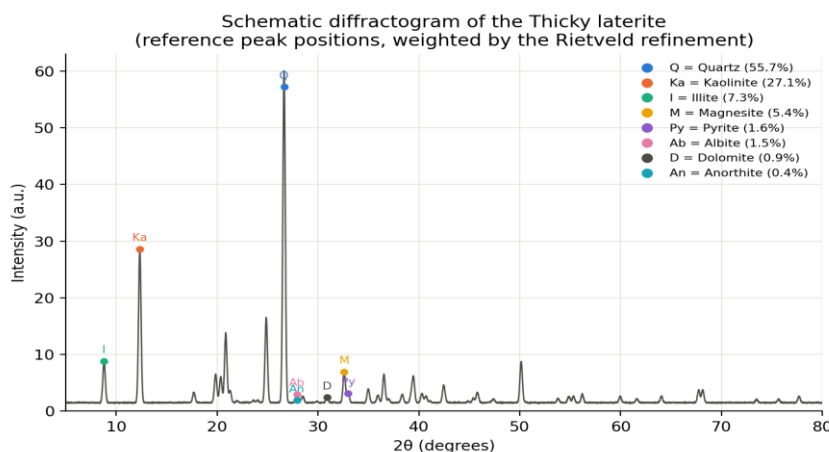


Fig. 9. Schematic diffractogram of the Thicky laterite (reference peak positions by phase, intensities weighted by the Rietveld quantification in Table 3).

Quartz therefore stands as the majority mineral phase, with kaolinite the principal clay phase identified. This mineralogy is consistent with the chemical composition reported in Table 3b: silica (44.78%) derives mainly from quartz and, to a lesser degree, kaolinite, whereas alumina (8.10%) is essentially attributable to kaolinite, the sole

alumina-bearing phase detected by XRD. The agreement between chemical composition and mineralogical assemblage fits with the material's ferrallitic character.

4.1.4. Chemical composition of the CFOP

Table 4 reports the chemical composition of the bottom ash.

Table 4. Chemical composition (major oxides) of the Omni Processor ash (XRF, wt%)

Oxide (%)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	TiO ₂	MnO	SO ₃	P ₂ O ₅
Bottom ash (CFOP)	33.90	12.19	8.58	17.40	1.80	2.51	0.51	0.07	0.56	3.86

SiO₂ + Al₂O₃ + Fe₂O₃ together reach 54.67%, below the 70% threshold applied to certain material classes in ASTM C618 [21]; this alone, however, does not warrant concluding that the ash lacks pozzolanic activity, and ASTM C618 is not applied here as a qualification standard for the CFOP.

CaO content reaches 17.4%, with calcium notably tied to mineral phases such as calcite and anhydrite identified by XRD.

Beyond the in-house data available on Omni Processor ash (Gueye, 2023 [16]; Sall, 2021 [17]), this composition can also be viewed against sewage sludge ashes studied elsewhere internationally. A recent synthesis drawing on a large body of studies reports average contents of roughly 29.6% for SiO₂, 13.6% for Al₂O₃, and 17.5% for CaO, albeit with substantial variability across studies (Liang et al., 2022) [25]. The CFOP examined here shows an SiO₂ content slightly above this average, an Al₂O₃

content just below it, and a CaO content nearly matching it: evidence that the CFOP's composition falls within the variability already documented for this type of by-product, though it does not yet support any general conclusion beyond the Cambérène site.

4.1.5. Mineralogy and particle size of the CFOP

XRD analysis of the CFOP points mainly to quartz, accompanied by secondary phases such as anhydrite and calcite, along with minor or trace phases.

This mineralogy explains, at least qualitatively, the chemical composition given in Table 4: quartz supplies most of the silica measured by XRF, while calcium derives largely from the carbonate and sulfate phases identified, calcite and anhydrite.

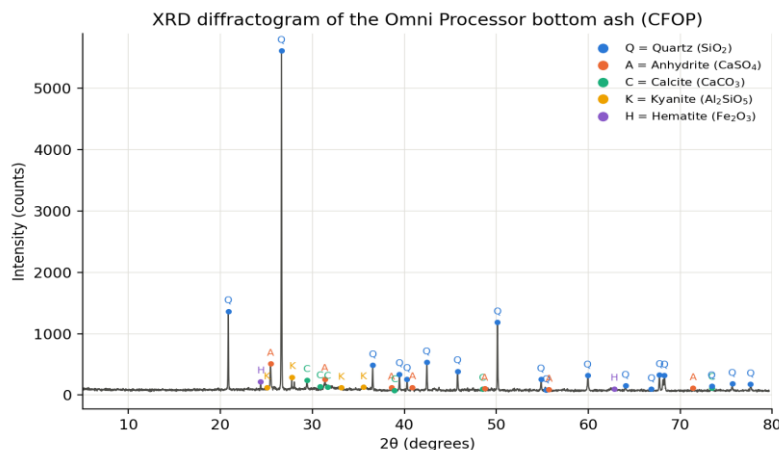


Fig. 10. XRD diffractogram of the Omni Processor bottom ash (CFOP), after Gueye (2023) [16].

Table 4b presents the particle-size distribution obtained by laser diffraction.

Table 4b. Characteristic diameters (D10, D50, D90) of the Omni Processor bottom ash (CFOP) by laser diffraction (Gueye, 2023) [16]

Fraction	D10 (μm)	D50 (μm)	D90 (μm)
Bottom ash (CFOP)	6	36	130

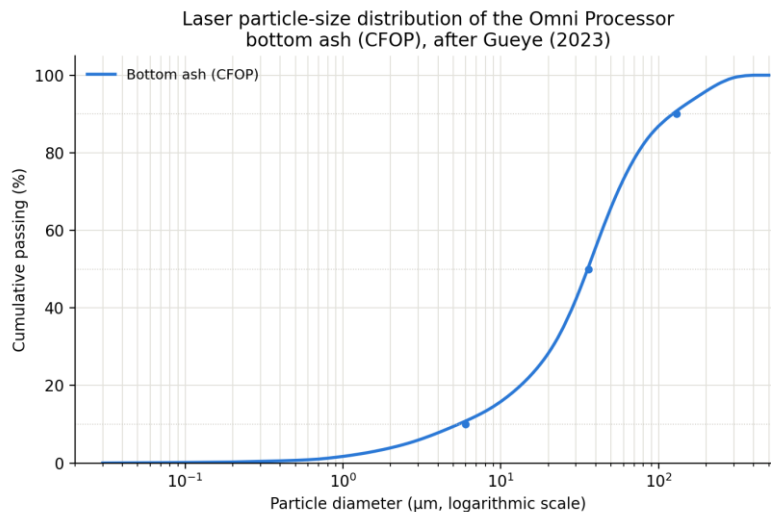


Fig. 11. Laser particle-size distribution of the Omni Processor bottom ash (CFOP), after Gueye (2023) [16].

The CFOP is thus markedly finer-grained than the laterite, with nearly all ash particles falling below one millimetre, a point

confirmed by overlaying both distributions on a common diameter scale (Figure 12).

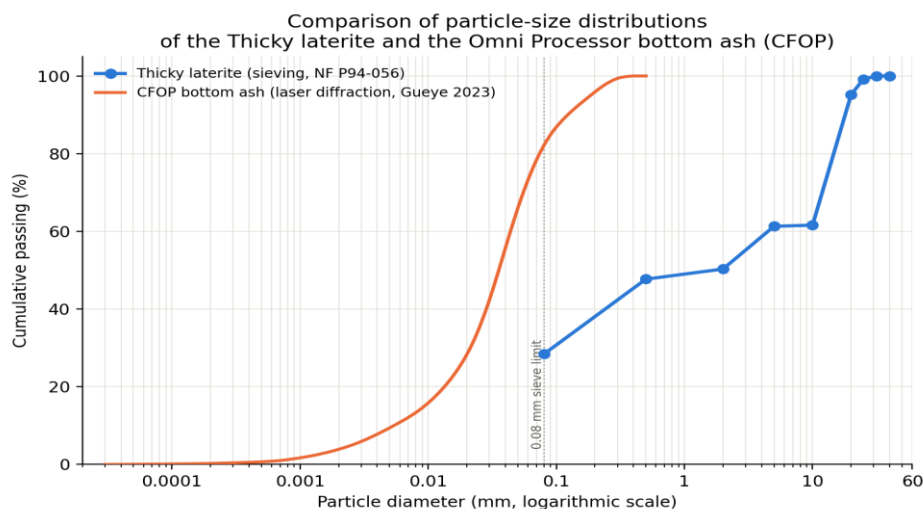


Fig. 12. Comparison of the particle-size distributions of the Thickly laterite (sieving, NF P94-056) and the Omni Processor CFOP bottom ash (laser diffraction, Gueye 2023), on a common diameter scale.

This difference in particle size raises the possibility that incorporating CFOP alters the particle distribution and partially fills intergranular voids, a hypothesis that will

need confirming through direct particle-size analysis of the mixtures.

4.1.6. Trace metal elements

The CFOP's trace-element contents are given below.

Table 7. Trace metal elements of the Omni Processor ash (XRF, mg/kg)

Element	Pb (mg/kg)	Cu (mg/kg)	Cr (mg/kg)	Zn (mg/kg)	As (mg/kg)
CFOP	66	553	67	1156	6
Comparison value	6000	7000	2000	10000	—

Measured Pb, Cu, Cr, and Zn contents all fall below the comparison values used, while no reference value is given here for arsenic. While these figures offer a reassuring first indication, they are not sufficient on their own to draw conclusions about the ash's

environmental behaviour; leaching tests, on the ash itself and especially on compacted mixtures, would be needed.

4.1.7. Soluble ions and pH

Table 8. Free/total ions and pH of the Omni Processor ash

Sample	Total Cl ⁻ (%)	Free Cl ⁻ (%)	Total SO ₄ ²⁻ (%)	Free SO ₄ ²⁻ (%)	Free CaO (%)	pH
CFOP	0.39	0.14	12.25	1.3	1.46	11.57
EN 450-1 benchmark	—	< 0.1	—	< 3	< 1.5	—

Free chloride content in the CFOP reaches 0.14%, above the 0.1% EN 450-1 benchmark; this comparison, though, calls for caution, since EN 450-1 targets fly ash used in concrete rather than sludge-treatment ash used in geotechnics. Free sulfate content stands at 1.30%, under the 3% benchmark, while free CaO content,

at 1.46%, sits just below the 1.5% benchmark. The CFOP's pH is strongly basic at 11.57.

4.2. Evolution of the Atterberg limits

Table 5 presents the Atterberg limit results.

Table 5. Atterberg limits of the laterite-ash mixtures

CFOP dosage (%)	LL (%)	PL (%)	PI (%)	Interpretation (PI criterion alone)
0.0	33.5	21.0	12.5	≤ 15 %
1.0	41.1	24.2	16.9	≤ 25 %
1.5	45.0	30.8	14.2	≤ 15 %
2.0	42.8	29.3	13.5	≤ 15 %
2.5	29.8	16.7	13.2	≤ 15 %
3.0	40.8	30.0	10.8	≤ 15 %

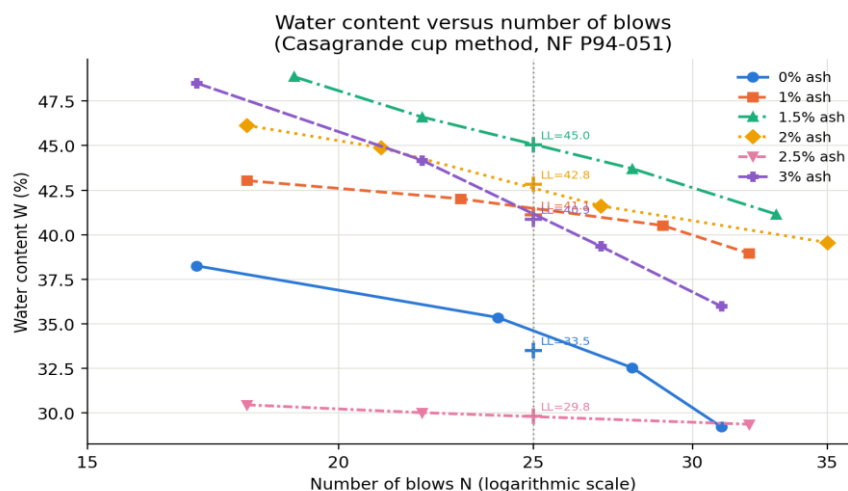


Fig. 13. Water content versus number of blows (logarithmic scale), one curve per ash dosage tested (0% to 3%).

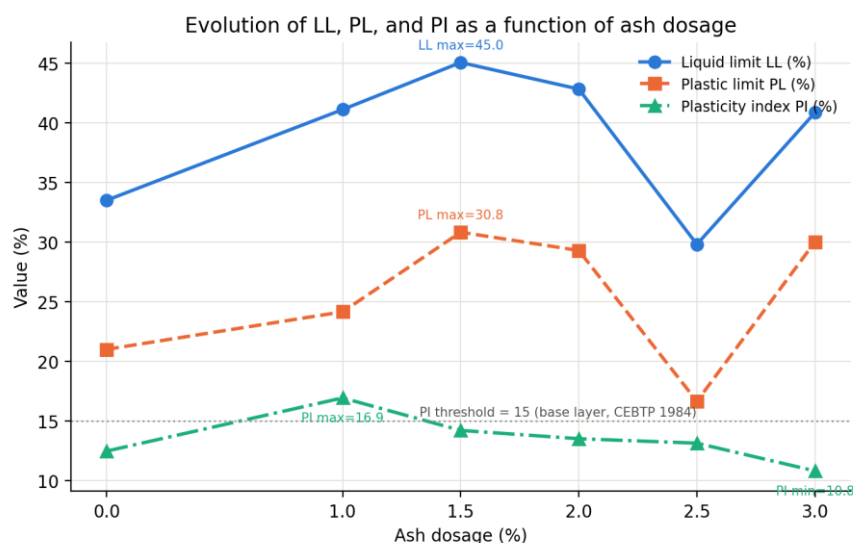


Fig. 14. Evolution of LL, PL, and PI as a function of ash dosage (0% to 3%).

With 1% CFOP added, LL rises from 33.5% to 41.1% and PL from 21.0% to 24.2%, pushing the plasticity index up from 12.5% to 16.9%.

At the 1.5% dosage, LL reaches 45.0% and PL rises to 30.8%, giving a PI of 14.2%.

By 2%, LL falls to 42.8% and PL to 29.3%, for a PI of 13.5%.

A sharper drop in LL, to 29.8%, appears at 2.5%, alongside a PL of 16.7%; PI, however, stays close to the values seen at 1.5% and 2%.

At the 3% dosage, PI reaches 10.8%, the series' lowest value.

PI thus evolves non-monotonically overall, a pattern that may reflect changes in particle distribution together with physicochemical interactions between the ash and the laterite's fine fraction. The available data, though, do not allow the various candidate mechanisms behind this evolution to be distinguished quantitatively.

4.3. Proctor compaction behaviour

Table 6 sets out the compaction parameters obtained.

Table 6. Proctor parameters of the laterite-ash mixtures

CFOP dosage (%)	Wopt (%)	Maximum measured dry density $\gamma_{d,max}$ (g/cm ³)
0	9.11	2.000
1.0	10.69	2.093
1.5	13.84	1.997
2.0	14.47	2.001
2.5	14.53	1.985
3.0	12.92	1.982

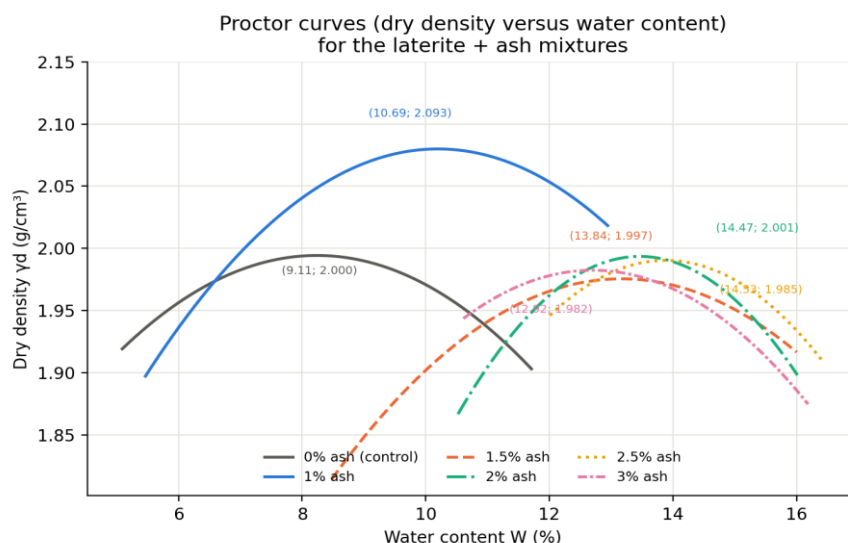


Fig. 15. Proctor curves (dry density versus water content) for the laterite alone (control, 0%) and the laterite + ash mixtures (1% to 3%).

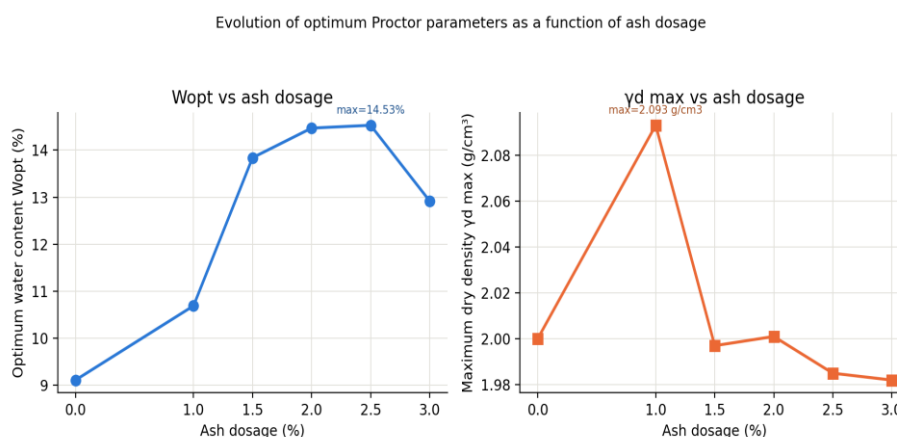


Fig. 16. Evolution of W_{opt} and $\gamma_{d,max}$ as a function of ash dosage (0% to 3%).

For the control laterite, the water content corresponding to the maximum measured dry density is 9.11%, at a dry density of 2.00 g/cm^3 .

At 1% CFOP, maximum measured dry density climbs to 2.093 g/cm^3 , a gain of 0.093 g/cm^3 over the control.

Past 1%, this value declines: it reaches 1.997 g/cm^3 at 1.5%, then ranges between 1.985 and 2.001 g/cm^3 across the 1.5% to 2.5% dosages.

At the 3% dosage, maximum measured dry density reaches 1.982 g/cm^3 .

Over the same range, the water content matching this density climbs from 9.11% for the control to 14.53% at 2.5%, then eases back to 12.92% at 3%.

Two main trends thus emerge from these results: a localized rise in maximum measured dry density at 1% CFOP, and a growing water demand up to the 2.5% dosage.

5. DISCUSSION

5.1. Influence of CFOP on plasticity

Incorporating CFOP drives a non-monotonic evolution in the plasticity index. The rise observed at 1% could stem from a shift in the fine fraction combined with interactions between the ash constituents and the clay minerals present in the laterite.

That initial rise in PI is nonetheless followed by a decline at higher dosages, to the point where, at 3%, PI drops below that of the control material.

Such behaviour suggests that the ash's effect cannot be captured by a simple monotonic relationship with dosage. Several factors may contribute: the laterite's mineralogical nature, the CFOP's very fine particle size, and the presence of calcic compounds and soluble phases.

Of the mechanisms considered above, the particle-size effect stands out as the most likely explanation for a response already visible at the mixing stage: CFOP particles, whose D50 (36 μm , Table 4b) is markedly finer than that of the laterite's fine fraction, partially fill voids and alter the fine fraction. Since testing was performed on fresh mixtures with no curing period, slower physicochemical mechanisms such as calcium flocculation or possible pozzolanic activity had little time to develop. This ranking remains, all the same, a qualitative interpretation that direct characterization of the mixtures' particle size and specific surface area will need to confirm.

A complementary physicochemical contribution cannot be ruled out, however. On one hand, the CFOP carries available calcium, present as calcite and anhydrite, with a free CaO content of 1.46% and a strongly basic pH of 11.57 (Table 8); on the other, the laterite holds a substantial clay fraction dominated by kaolinite (27.1%). Once in contact with these clay minerals, that available calcium could trigger a calcium-clay flocculation mechanism from the mixing stage onward, one able to explain, at least in part, the initial rise in plasticity index at 1% CFOP before a dilution or granular-filling effect takes over at higher dosages. Offered here cautiously, this chemical hypothesis would thus complement the particle-size explanation already developed above, even though it has not been directly verified through dedicated tests on the mixtures.

Confirming these hypotheses would require further analysis of the mixtures' particle-size distribution, specific surface area, and mineralogy after incorporation.

5.2. Influence on compaction behaviour

Adding 1% CFOP coincides with a rise in maximum measured dry density, from 2.00 to 2.093 g/cm^3 .

This localized gain may reflect improved particle arrangement within the granular skeleton along with partial void-filling by the fine CFOP particles.

Beyond the 1% dosage, however, maximum measured dry density falls and drops slightly below that of the control material.

In parallel, the water content matching the maximum measured dry density rises up to 2.5%, a trend that could relate to the growing fine fraction and stronger interaction between water and the ash particles.

As section 5.1 notes, the lack of a curing period before compaction testing likewise favours a predominantly particle-size explanation here over a slower physicochemical mechanism, though this remains to be confirmed.

Until the microstructure of the mixtures and their particle-size distribution after incorporation are characterized, these interpretations remain hypotheses.

5.3. Interpretation with respect to geotechnical criteria

Judged solely on the plasticity-index criterion, every mixture studied meets the $\text{PI} \leq 25\%$ threshold used for a foundation (sub-base) layer.

Against the $\text{PI} \leq 15\%$ threshold considered for a base layer, only the 1% CFOP mixture exceeds this limit, with a PI of 16.9%, while formulations from 1.5% to 3% satisfy it.

Notably, the 3% dosage yields the series' lowest PI, at 10.8%.

These findings are encouraging from a plasticity standpoint, but they do not by themselves establish the mixtures' overall suitability for a pavement layer.

The raw material itself already shows 49.7% retained at 2 mm, just below the adopted 50% threshold, and the particle-size distribution of the laterite-CFOP mixtures has not yet been measured directly.

Determining CFOP's actual effect on particle-size distribution will therefore require a dedicated characterization of the mixtures.

Finally, PI and compaction results alone cannot settle the question of suitability for pavement-layer use; CBR tests, soaked CBR in particular, along with mechanical and durability testing, remain essential.

5.4. Environmental considerations

Pb, Cu, Cr, and Zn concentrations measured in the CFOP stay below the comparison values used in this study, a first favourable sign though not sufficient to establish the ash's environmental harmlessness.

At 0.14%, the CFOP's free chloride content exceeds the 0.1% benchmark used in EN 450-1; this comparison should be treated as indicative only, since the standard concerns fly ash for concrete rather than ash from the thermal treatment of faecal sludge.

The presence of chlorides nonetheless warrants vigilance, particularly in applications potentially exposed to water circulation.

Free CaO content reaches 1.46%, just under the 1.5% benchmark, a favourable sign relative to that threshold though not one that by itself rules out a possible expansion phenomenon.

Characterizing the environmental and physicochemical behaviour of the mixtures after incorporation and compaction would call for dedicated dimensional-stability and leaching tests.

5.5. Study limitations

This study represents a first characterization phase.

The laterite's particle-size distribution was determined by sieving alone, without a complementary sedimentometric characterization of the fraction below 0.08 mm, so D₁₀ and the uniformity and curvature coefficients could not be established.

The particle-size distribution of the laterite-CFOP mixtures themselves was not measured, so the precise effect of ash

addition on the treated material's particle-size distribution cannot be quantified.

The laterite's XRF composition (Table 3b) likewise needed a methodological correction, since the instrument's calibration, optimized for cementitious materials, underestimates silica and reports a CO₂ value unrepresentative of a non-cementitious soil; the values were accordingly renormalized to 100% using the loss on ignition measured by calcination, a step that reduces but does not fully eliminate the associated uncertainty.

Chemical and environmental data on the ash come from earlier work on this same ash, whereas the geotechnical tests on the mixtures are results generated by the present study.

The Proctor parameters reported correspond to the experimental point of highest dry density rather than an optimum derived from a robust mathematical fit.

Finally, the compacted mixtures have not yet undergone any CBR, mechanical-strength, durability, or leaching testing.

These limitations need to be borne in mind when interpreting the results, and they justify carrying the experimental programme further.

6. CONCLUSION

This preliminary study characterized a laterite sampled at the Thicky site in Senegal alongside a bottom ash from an Omni Processor, and evaluated how low dosages of this ash influence the plasticity and compaction properties of the lateritic material.

The laterite examined shows a predominantly coarse structure (a D_{max} of 40 mm, 49.7% retained at 2 mm, and a fines content of 28.4%) with quartz (55.7%) and kaolinite (27.1%) dominating its mineralogical composition.

The CFOP carries substantial SiO₂ (33.9%) and CaO (17.4%) contents, with SiO₂ + Al₂O₃ + Fe₂O₃ together reaching 54.67%, below the 70% threshold used for certain material classes in ASTM C618, though this

comparison neither confirms nor rules out pozzolanic activity in the ash studied.

Incorporating CFOP drives a non-monotonic evolution in the plasticity index, which climbs from 12.5% for the control material to 16.9% at 1% before progressively falling to 10.8% at 3%.

Compaction behaviour follows a similarly non-monotonic path: maximum measured dry density rises from 2.00 g/cm³ for the control to 2.093 g/cm³ at 1% CFOP before declining at higher dosages, while the corresponding water content climbs to 14.53% at 2.5% before easing to 12.92% at 3%.

On the plasticity-index criterion alone, every formulation meets the 25% threshold used for a foundation layer; formulations from 1.5% to 3% also meet the 15% threshold considered for a base layer, while the 1% dosage yields a PI of 16.9%.

These results do not, however, establish the mixtures' overall suitability for pavement-layer use; assessing a road material's suitability requires weighing particle-size, geotechnical, mechanical, hydric, and environmental criteria together.

The results point to the 1–1.5% CFOP range as a zone worth further investigation, though an optimal dosage cannot yet be defined at this stage.

Future work should focus mainly on:

1. characterizing the particle-size distribution of the laterite-CFOP mixtures;
2. carrying out CBR tests, soaked CBR in particular, in keeping with recent work demonstrating how mineral by-products can contribute to the bearing capacity of road foundation materials (Ahmed et al., 2024) [26];
3. assessing the mechanical performance of the mixtures;
4. examining their long-term behaviour and durability;
5. conducting leaching tests on the compacted mixtures;
6. investigating dimensional stability and expansion potential;

7. analyzing the physicochemical mechanisms behind the observed variations in plasticity and compaction.

These investigations will ultimately show whether the preliminary geotechnical changes observed translate into a genuine improvement in the performance required for CFOP's potential use in road materials.

Declaration by Authors

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