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Original Research Article

Chemical, Physicochemical and Engineering Characterization of Agro-Industrial Waste Pozzolans for Laterite Soil Stabilization

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Abstract

Laterite soils widely used in tropical road construction often exhibit high plasticity and inadequate engineering performance. This creates the need for locally available and environmentally sustainable stabilizing materials. This study evaluated the chemical, physicochemical and engineering characteristics of six agro-industrial waste pozzolans such as palm oil fuel ash (POFA), palm oil clinker powder (POCP), corn cob ash (CCA), coal bottom ash (CBA), rice husk ash (RHA) and fly ash (FA), for lateritic soil stabilization. Soil-pozzolan mixtures containing 0 to 10% additive was investigated using XRF, CEC, physicochemical and geotechnical tests. Atterberg limits, compaction, permeability, CBR, UCS and shear-strength analysis were carried out on the samples coupled with statistical analysis. The laterite soil contained 40.25% Fe_2O_3, 31.79% SiO_2 and 25.43% Al_2O_3, but only 0.26% CaO, indicating limited intrinsic cementitious potential. Combined SiO_2+Al_2O_3+Fe_2O_3 contents ranged from 36.69% in CCA to 91.08% in RHA. This confirms substantial chemical diversity. CCA and CBA produced the strongest statistical relationships, with R^2 of 99.69% and 99.49%, respectively, while their regression effects were significant at $p<0.05$. The study concludes that stabilization effectiveness depends on the interaction between pozzolan chemistry, physicochemical characteristics and dosage rather than oxide content alone. It is recommended that CCA and CBA receive further field-scale evaluation and that future studies employ larger datasets, longer curing periods and independent validation to establish reliable performance-based design criteria.

Keywords: Laterite soil, agro-industrial waste Pozzolans, Engineering performance, Geotechnical test, stabilization, physicochemical and engineering characteristics.

1. INTRODUCTION

In tropical road building, lateritic soils make up a significant portion of the earthworks; yet, their seeming richness frequently conceals a challenging technical reality (Chimuanya, 2026; Oyelami *et al.,*2016; Ezreig *et al.,*2022). Umar *et al.,* (2025) noted that a soil may be readily available along a proposed road corridor yet perform poorly once exposed to traffic loading and seasonal wetting. Changes in moisture can alter plasticity, stiffness and bearing capacity, while clay-rich fractions may retain water and interfere with the development of a stable pavement foundation (Imoh *et al.* 2025; Oziegbe and Oziegbe, 2025). Conventional stabilization with cement or lime can correct many of these deficiencies, but the cost of imported binders, energy-intensive production and associated environmental burdens have encouraged renewed interest in locally available waste-derived materials. Agro-industrial residues are particularly attractive because materials such as rice husk ash, corn cob ash and palm-derived ashes contain reactive silica, alumina and alkaline constituents capable of participating in soil–binder reactions. Their use also creates a productive route for diverting residues that might otherwise accumulate around processing and agricultural centers (Torres-Ortega *et al.,* 2025; Akintayo *et al.,* 2025; Hernández *et al.,* 1998; de Moraes *et al.,* 2024).

The engineering ideal is straightforward: a locally available lateritic soil should develop sufficient strength, stiffness and moisture resistance to function reliably as a pavement subgrade or selected structural layer without excessive dependence on conventional stabilizers (Caro *et al.,*2019; Okonkwo *et al.,*2022;

Suebsuk *et al.,*2023; Akinbuluma and Oyewo, 2025). Field practice rarely offers such certainty. Onwo *et al*. (2022) noted that the response of laterite to an ash depends on the mineralogy of the soil, chemical composition of the ash, fineness, dosage, moisture condition and curing history. Consequently, an ash that produces a substantial increase in California Bearing Ratio (CBR) in one soil may give a modest response in another. Recent work continues to report improvements in CBR, plasticity and strength after incorporating agricultural and industrial by-products (Mishra *et al.,*2022; Hasan *et al.,*2026), yet much of the evidence remains centred on engineering indices rather than the processes responsible for those changes.

Earlier investigations provide useful pieces of the mechanism. Several researches connected corn cob ash stabilization with cation exchange and proposed chemical pathways involving alkaline earth elements and soil silica (Mustofa *et al.,*2025; Tanyıldızı, 2025; Macías-Párraga *et al.,*2025; Ogundare *et al.,*2024). Their calculated cation exchange capacity (CEC) relationship also pointed towards a possible explanation for the observed optimum ash content. They nevertheless identified the need for molecular-level investigation to verify the proposed reactions. Other studies have approached the problem mainly through CBR, unconfined compressive strength, Atterberg limits and compaction behaviour. Such tests establish whether a treated soil becomes stronger or less plastic, but they reveal little about why the improvement occurs. Even recent reviews of waste-based stabilization remain heavily weighted toward engineering performance, with comparatively less attention given to linking chemical exchange, mineral-phase alteration and microstructural development within the same experimental framework (Al-Ghouleh, 2015; Sarver *et al.,*2011).

That unresolved link matters for road engineering. When the mechanism is poorly understood, optimum dosage can become an empirical number tied to one soil and one ash rather than a transferable design principle. The consequences extend beyond laboratory uncertainty: inappropriate dosage may increase material demand without proportional strength gain, while insufficient reaction can leave a pavement vulnerable to moisture-induced deterioration and repeated traffic loading. A more useful understanding requires movement across scales, from the exchange of ions at reactive soil surfaces, through changes in mineral phases, to the formation and arrangement of cementitious products that ultimately regulate macroscopic strength.

The underlying proposition is that improvements in stabilized laterite should be interpreted as the combined outcome of cation exchange, particle reorganization and pozzolanic formation of new binding phases rather than as isolated changes in CBR or strength (Mousi *et al.,*2024). Establishing that chain of evidence can move agro-industrial ash stabilization from a trial-and-error treatment approach toward a more mechanistically informed basis. This will enhance the selection and designing of sustainable lateritic soil stabilizers for road engineering infrastructure. Therefore, the central question to the study is: how do the chemical composition and dosage of different agro-industrial waste pozzolans interact with the native chemistry of lateritic soil and curing conditions to control the formation of reaction products and, ultimately, the mechanisms and effectiveness of soil stabilization?

Despite growing evidence that agro-industrial waste pozzolans can improve the engineering performance of lateritic soils, existing research remains fragmented, with most studies emphasizing empirical indices such as CBR, UCS, Atterberg limits and compaction while providing limited integration of the chemical, physicochemical and engineering factors governing stabilization. In particular, insufficient attention has been given to systematically comparing chemically diverse agro-industrial pozzolans under a common experimental framework and establishing how their oxide composition, cation exchange capacity, dosage and moisture-related properties translate into measurable engineering responses. This limits the development of transferable criteria for selecting and proportioning waste-derived stabilizers for lateritic soils. The present study addresses this gap by comparatively characterizing selected agro-industrial waste pozzolans and linking their chemical and physicochemical properties with the engineering performance of stabilized lateritic soil, thereby providing a more evidence-based basis for sustainable stabilizer selection and pavement application.

2. MATERIALS AND METHODS

2.1 Materials and Experimental Design

The study investigated the suitability of six agro-industrial waste pozzolans such as palm oil fuel ash (POFA), palm oil clinker powder (POCP), coal bottom ash (CBA), corn cob ash (CCA), rice husk ash (RHA) and fly ash (FA), for stabilizing lateritic soil. The lateritic soil was air-dried, pulverized and prepared according to relevant ASTM/AASHTO procedures. Each pozzolan was processed and sieved before use. Soil-pozzolan mixtures were prepared at 0, 2, 4, 6, 8 and 10% additive contents by dry mass of soil, with the untreated soil serving as the control.

2.2 Chemical and Physicochemical Characterization

The chemical composition of the soil and individual pozzolans was determined using X-ray fluorescence (XRF). Major oxides, particularly SiO_2, Al_2O_3, Fe_2O_3 and CaO, were quantified and used to compare the chemical characteristics of the six wastes. The combined content of $SiO_2 + Al_2O_3 + Fe_2O_3$ was also calculated as a comparative chemical index, without treating total oxide content alone as proof of pozzolanic reactivity. Cation exchange capacity (CEC) was determined for the pozzolans and soil–pozzolan mixtures to evaluate changes in the exchange environment with increasing additive content. Total dissolved solids (TDS), electrical conductivity (EC) and moisture content were also determined to characterize the soluble and physicochemical properties of the wastes.

2.3 Geotechnical Characterization and Stabilization Assessment

The untreated lateritic soil was characterized through particle-size distribution, specific gravity, Atterberg limits, AASHTO classification, compaction and hydraulic conductivity. For the treated mixtures, changes in liquid limit, plastic limit, plasticity index, maximum dry density (MDD), optimum moisture content (OMC), permeability, California bearing ratio (CBR), unconfined compressive strength (UCS) and shear-strength parameters were evaluated. Where curing was applicable, specimens were tested at predetermined curing periods to assess strength development. CBR and UCS were used as principal indicators of stabilization performance, while changes in plasticity, compaction and permeability were used to assess broader engineering effects.

2.4 Mineralogical Analysis and Statistical Evaluation

X-ray diffraction (XRD) was performed on selected untreated and stabilized materials to identify mineralogical phases and examine changes associated with treatment. The chemical, physicochemical and engineering datasets were compared across pozzolan types and dosages. Analysis of variance (ANOVA) was used to test differences among treatments, while correlation analysis was used to examine relationships between chemical/physicochemical characteristics and engineering performance at a significance level of $p < 0.05$. The final assessment identified the pozzolan and dosage providing the most balanced improvement across the measured engineering properties.

3. RESULTS AND DISCUSSION

3.1 Characterization and Chemical Composition Properties of Lateritic soils

The XRF results in Table 4.1 show that the lateritic soil is strongly dominated by Fe_2O_3 (40.25%), SiO_2 (31.79%) and Al_2O_3 (25.43%), which together constitute 97.47% of the detected oxides. This chemical signature is characteristic of a highly weathered, ferruginous lateritic material and provides an important basis for interpreting its subsequent response to agro-industrial pozzolans. The predominance of iron oxide is particularly notable because Fe_2O_3 exceeds both SiO_2 and Al_2O_3, indicating substantial accumulation of iron during laterization. This agrees closely with observations from ferric lateritic soils reported by researchers working in tropical environments, where Fe_2O_3 commonly occurs at high concentrations while CaO, K_2O, MgO and other mobile oxides remain comparatively low because of prolonged weathering and leaching (Mvogo *et al.,*2025). The present Fe_2O_3 concentration is therefore not anomalous; rather, it places the material toward the iron-rich end of the chemical spectrum reported for lateritic soils.

Table 1: Chemical Constituents of Soil sample

Metal Oxide	Soil (%)
Fe_2O_3	40.2541
SiO_2	31.7878
Al_2O_3	25.4287
CaO	0.2596
P_2O_5	0.8531
SO_3	0.2439
K_2O	0.3032
CuO	0.0645
TiO_2	0.5092
ZnO	0.0502
NiO	0.0889
Cr_2O_3	0.1569

The SiO_2-Al_2O_3-Fe_2O_3 assemblage is particularly important to the multi-scale stabilization framework adopted in this study. The combined concentration substantially exceeds the 70% threshold commonly used to identify materials with strong pozzolanic potential, although this criterion should not be interpreted as evidence that the untreated soil is itself an effective cementitious binder. Recent investigations have similarly demonstrated that lateritic soils can contain very high proportions of these three oxides while remaining non-self-cementing because the oxides may occur within relatively stable crystalline minerals rather than readily reactive amorphous phases. This distinction is critical because chemical abundance alone does not determine reactivity. The high Fe_2O_3 content may also influence particle aggregation, surface chemistry and the development of iron-rich mineral phases, potentially affecting how silica and alumina released from the added pozzolans interact with the soil during stabilization.

A striking feature of the result is the extremely low CaO content (0.26%). This suggests that the natural soil has limited internal capacity to generate calcium-bearing cementitious products through conventional pozzolanic reactions. Similar lateritic soils with low native CaO have been described as having limited natural cementation potential, with calcium supplied externally through lime, cement or calcium-rich waste materials to initiate reactions with soil-derived and additive-derived silica and alumina. This finding provides a strong mechanistic justification for incorporating agro-industrial pozzolans into the present stabilization system. Where the selected wastes contain appreciable reactive silica and alumina, their interaction with an external calcium source can promote the formation of C-S-H and C-A-H phases, while alkaline conditions facilitate dissolution of aluminosilicate surfaces.

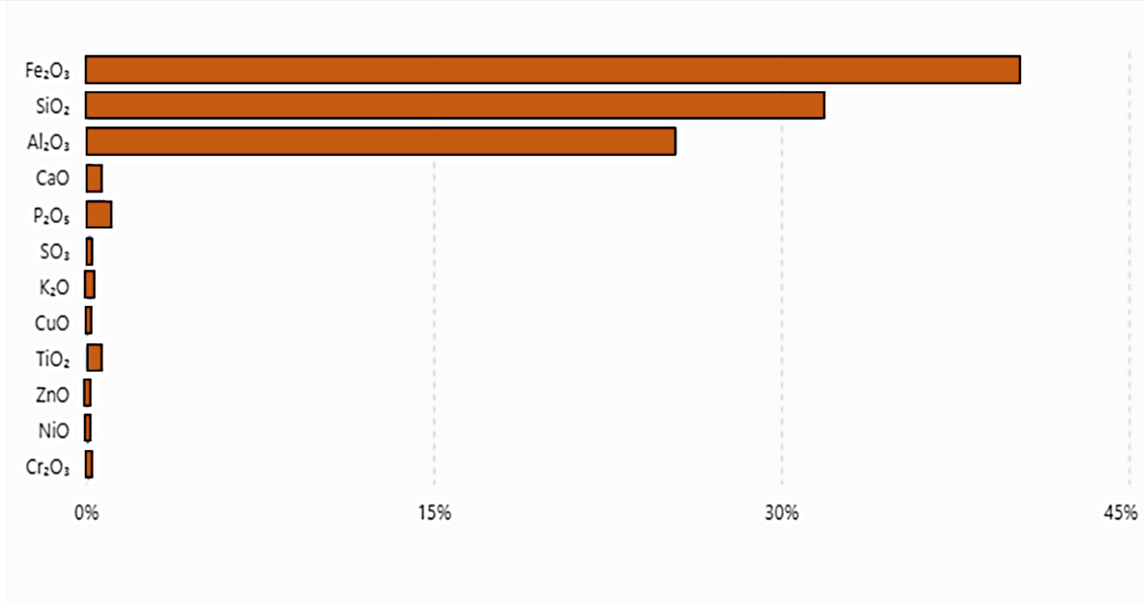

Figure 1: Concentration of major and minor metal oxides in the lateritic soil

The very low concentrations of K_2O (0.30%), SO_3 (0.24%), CaO (0.26%) and the trace transition-metal oxides as indicated in Figure 1 further indicate extensive depletion of mobile elements during weathering. This is consistent with the geochemical behaviour of strongly laterized soils, where leaching progressively removed more soluble constituents while Fe and Al become concentrated. From an engineering perspective, the result establishes an important baseline: the soil possesses abundant aluminosilicate and iron-bearing constituents but lacks sufficient native calcium to support substantial cementitious bonding. Consequently, successful stabilization is likely to depend less on simply increasing the quantity of pozzolan and more on achieving an appropriate chemical balance between reactive Si-Al species, available calcium, alkalinity and curing conditions. This supports the central premise of the study that lateritic soil stabilization should be examined across interacting chemical, mineralogical and microstructural scales rather than evaluated solely through macroscopic strength indicators.

3.2 XRF Analysis of the Soil samples POFA, POCP, CCA, RHA and FA

The XRF results in Table 2 reveal substantial compositional differences among the agro-industrial ashes, which provides an important chemical basis for interpreting their subsequent stabilization performance. The combined SiO_2, Al_2O_3 and Fe_2O_3 contents ranged from 36.69% in CCA to 91.08% in RHA, indicating considerable variation in the concentration of the principal oxide constituents associated with pozzolanic reactions. RHA recorded the highest combined content (91.08%), followed by FA (83.40%) and CBA (82.43%), while POCP and POFA contained 69.72% and 66.17%, respectively. CCA had markedly lower combined reactive-oxide content at 36.69%. This compositional variability suggests that the materials should not be treated as chemically interchangeable stabilizers, and it provides a basis for examining whether oxide composition corresponds with differences in mechanical and physicochemical performance.

Table 2: XRF Composition of the Agro-Industrial Pozzolans Used for Lateritic Soil Stabilization (wt.%)

Metal oxide	POFA	POCP	CBA	RHA	CCA	FA
Fe_2O_3	8.7615	8.7115	22.2055	0.5568	28.8847	17.4049
SiO_2	55.8502	59.3861	45.7510	90.2651	7.5534	49.0678
Al_2O_3	1.5548	1.6204	14.4730	0.2612	0.2493	16.9225
CaO	10.4914	6.8971	9.5160	1.6970	3.0334	8.1793
MgO	1.7250	1.9595	1.1887	0.3208	0.7083	0.8554
P_2O_5	4.7984	4.3053	1.0916	2.1944	3.5153	1.6074
SO_3	0.8682	0.1991	0.6886	0.5145	1.0346	0.8522
Cl	0.6253	0.1439	—	0.1785	4.3747	—
K_2O	4.0864	16.0808	2.2714	3.2407	49.4160	2.0661
MnO	0.2929	0.4298	0.2287	0.3277	0.2094	0.2041
CuO	0.1084	0.1050	0.0484	—	0.1150	0.0607
Rb_2O	0.0989	0.0903	0.0302	0.0249	0.2329	—
SrO	0.0562	0.0312	0.2708	—	0.4302	—

Metal oxide	**POFA**	**POCP**	**CBA**	**RHA**	**CCA**	**FA**
ZrO_2	0.0396	0.0392	0.8500	0.0370	0.2130	—
Rh_2O_3*	0.6427	—	0.3753	0.4185	—	—
TiO_2	—	—	1.7756	—	—	1.9862
Y_2O_3	—	0	—	—	—	0.0266
ZnO	—	—	—	—	0.5415	0.0423
Br	—	—	—	—	—	0.0941
NiO	—	—	—	—	—	0.0769
Cr_2O_3	—	—	—	—	—	—
$SiO_2 + Al_2O_3 + Fe_2O_3$	**66.1665**	**69.7180**	**82.4295**	**91.0831**	**36.6874**	**83.3952**

RHA was strongly silica-dominated, with SiO_2 accounting for 90.27% of its composition. Its relatively low concentrations of Al_2O_3 (0.26%) and Fe_2O_3 (0.56%) indicate that its potential pozzolanic contribution is principally associated with silica rather than balanced aluminosilicate chemistry. The high silica content is potentially favorable for reaction with calcium-bearing phases generated during stabilization, particularly where sufficient Ca^{2+} is available. However, the relatively low CaO content of RHA (1.70%) indicates that RHA itself contributes little calcium, meaning that its effectiveness may depend strongly on the calcium environment of the treated laterite.

FA displayed a more balanced reactive-oxide composition, containing 49.07% SiO_2, 16.92% Al_2O_3 and 17.40% Fe_2O_3. Its combined SAF content of 83.40% indicates a substantial concentration of the principal oxide constituents. Importantly, the relatively high Al_2O_3 concentration distinguishes FA from RHA, POFA and POCP. This alumina-rich composition may facilitate the formation of calcium–aluminate and calcium-silicate-aluminate reaction products when adequate calcium and moisture are present. Thus, FA may contribute to stabilization through a broader range of reaction pathways than a predominantly silica-rich ash.

CBA also exhibited a high SAF content (82.43%), but its composition was dominated more strongly by Fe_2O_3 (22.21%) and Al_2O_3 (14.47%) than POFA or POCP. Its SiO_2 content was 45.75%, while CaO was 9.52%. This combination suggests that CBA possesses both aluminosilicate and calcium-bearing constituents that could contribute to secondary cementitious reactions. The relatively high Fe_2O_3 content should not, however, be interpreted as equivalent to reactive silica or alumina; rather, it contributes to the overall oxide chemistry and may influence the mineralogical environment of the stabilized soil.

POFA and POCP showed broadly similar silica-rich characteristics, although POCP contained a substantially higher K_2O concentration (16.08%) than POFA (4.09%). POCP recorded 59.39% SiO_2, 8.71% Fe_2O_3 and 1.62% Al_2O_3, producing a SAF value of 69.72%. POFA contained 55.85% SiO_2, 8.76% Fe_2O_3 and 1.55% Al_2O_3, giving 66.17%. Their CaO contents were also appreciable, particularly POFA at 10.49%. The simultaneous presence of silica and calcium-bearing phases makes these materials chemically relevant for lateritic soil stabilization, although their comparatively lower SAF values than RHA, FA and CBA indicate a different reactive-oxide balance.

CCA presented the most distinctive chemical profile. Its SAF content was only 36.69%, largely because of its very low SiO_2 (7.55%) and Al_2O_3 (0.25%) contents. In contrast, CCA contained an exceptionally high K_2O concentration of 49.42% and a relatively high Fe_2O_3 content of 28.88%. This result is particularly significant because it demonstrates that a high mechanical stabilization response cannot necessarily be predicted from the conventional SAF index alone. If CCA subsequently produces meaningful improvements in CBR, plasticity or other engineering properties, such behaviour would require interpretation through additional mechanisms, including alkalinity, ionic exchange, particle interaction, surface chemistry and the contribution of calcium-bearing phases rather than through SAF content alone.

Figure 2 (A- D) provides a complementary interpretation of the chemical composition of the six agro-industrial waste pozzolans and offers an important chemical basis for understanding their potential mechanisms in lateritic soil stabilization. Rather than considering the XRF results as isolated oxide concentrations, the combined panels reveal substantial differences in the chemical character of POFA, POCP, CBA, RHA, CCA and FA, which are expected to influence their dissolution behaviour, reaction products and eventual contribution to soil strength.

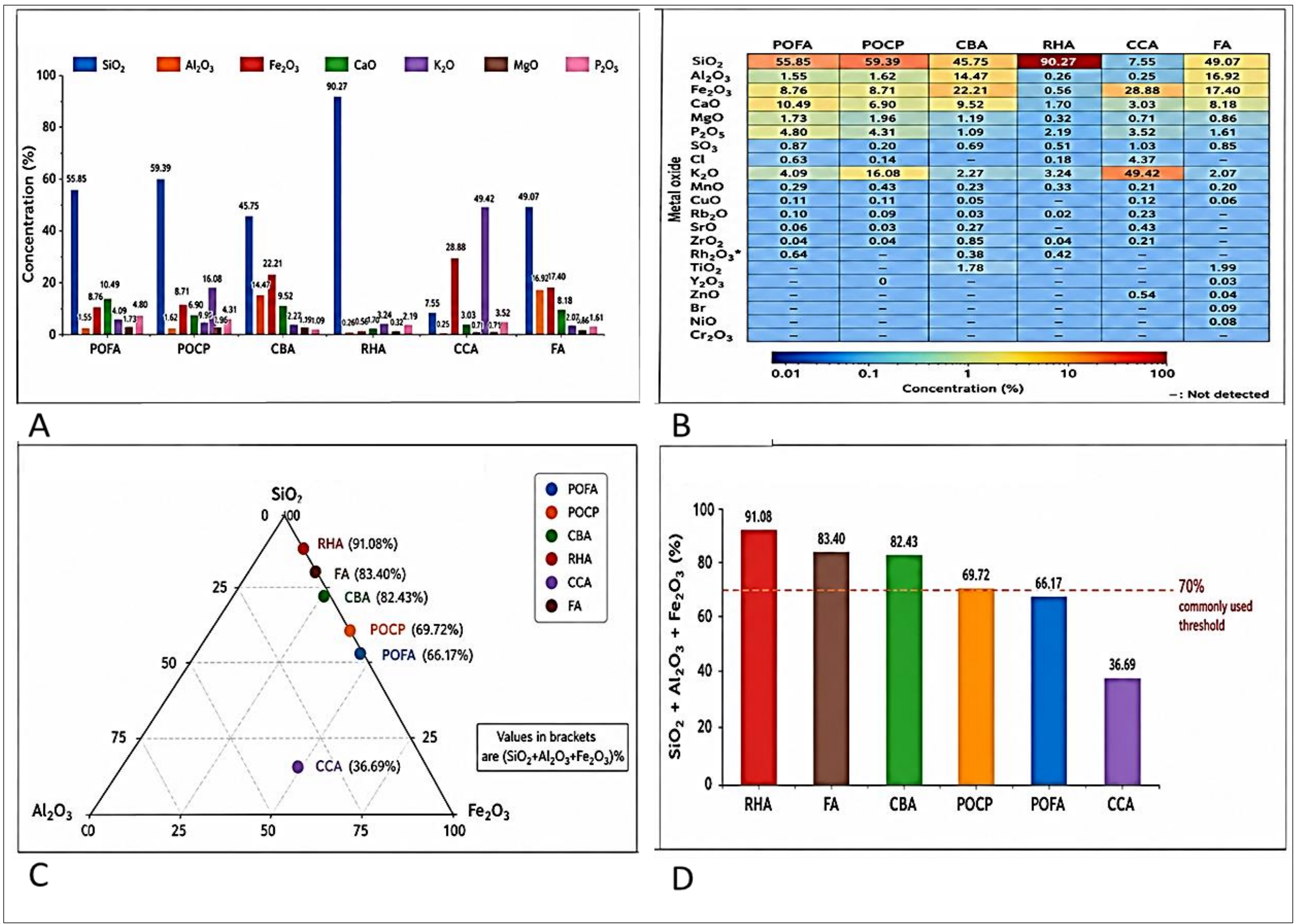

Figure 2 (A – D): (A) Major oxide composition of agro-industrial waste pozzolans; (B): Heatmap of complete XRF oxide composition (%); (C): SiO_2 – Al_2O_3 – Fe_2O_3 ternary diagram; (D): Combine SiO_2 +Al_2O_3 +Fe_2O_3 content

Figure 2 (A) shows the different composition of oxides in the pozzolans as indicated in Table 2. These differences are important because stabilization performance cannot be attributed to silica content alone. Reactive Si and Al provide the principal aluminosilicate species required for pozzolanic reactions, while Ca availability and the alkaline environment influence the formation and development of cementitious reaction products. Consequently, the chemical diversity shown in Figure 2 (A) provides a plausible explanation why different pozzolans may produce different strength, compaction and durability responses when incorporated into the same lateritic soil.

Figure 2 (B) provides a more comprehensive chemical fingerprint by displaying both major and minor oxides simultaneously. The heatmap makes the contrasting composition of the materials particularly clear. RHA is overwhelmingly silica-rich, FA has a relatively balanced SiO_2-Al_2O_3-Fe_2O_3 composition, and CCA is strongly enriched in K_2O and Fe_2O_3. POFA and POCP also contain comparatively substantial CaO concentrations of 10.49% and 6.90%, respectively. This distinction is highly relevant to stabilization mechanism because the availability of calcium may influence the extent to which dissolved silicate and aluminate species can develop calcium-bearing cementitious phases. The heatmap therefore supports a multi-component interpretation of stabilization rather than the assumption that a high SiO_2 concentration automatically indicates superior performance.

Figure 2 (C) further clarifies this relationship through the SiO_2-Al_2O_3-Fe_2O_3 ternary composition. RHA occupies the most silica-rich position, followed by FA and CBA, whereas CCA is displaced strongly toward the Fe_2O_3-rich field. POFA and POCP occupy intermediate compositional positions. The ternary distribution is significant for the present study because these three oxides constitute the principal framework for evaluating the aluminosilicate contribution of the wastes to soil stabilization. It also demonstrates why the materials should not be treated as chemically interchangeable. Their different Si-Al-Fe proportions may affect mineral dissolution, secondary phase formation and particle-scale bonding during curing.

Figure 2 (D) reinforces this distinction by ranking the materials according to their combined SiO_2 + Al_2O_3 + Fe_2O_3 content: RHA (91.08%), FA (83.40%), CBA (82.43%), POCP (69.72%), POFA (66.17%) and CCA (36.69%). RHA, FA and CBA exceed the commonly referenced 70% compositional criterion, whereas POCP, POFA and particularly CCA fall below it. However, this should not be interpreted as direct evidence of pozzolanic activity, since oxide composition does not establish whether the constituent phases are sufficiently amorphous or chemically reactive. This distinction is central to the multi-scale framework of the research: XRF establishes the chemical potential, while XRD must determine mineralogical phase characteristics, SEM/EDS must demonstrate microstructural and elemental changes, and mechanical tests must establish whether these chemical changes translate into improved engineering performance.

Generally, Figure 2 (A – D) demonstrate that the six wastes possess distinct chemical signatures rather than a uniform pozzolanic character. This finding is important because it suggests that the stabilization of lateritic soil is likely to depend on the interaction between the chemical composition of each waste, the native chemistry of the soil, dosage, curing conditions and the development of new reaction characteristics.

3.3 Integrated Engineering Baseline for Lateritic soil Stabilization

Table 3 presents the index, compaction, hydraulic and shear-strength characteristics of the untreated lateritic soil used in this study. The results provide the baseline engineering properties against which the effects of the agro-industrial waste pozzolans can subsequently be evaluated. The soil exhibited a specific gravity of 2.66, a sand fraction of 60% and a silt fraction of 40%, with no clay fraction reported in the particle-size distribution. The consistency limits yielded a liquid limit (LL) of 48%, plastic limit (PL) of 17% and plasticity index (PI) of 31%. The soil was classified as A-7-5 under the AASHTO system. Its maximum dry density (MDD) was 1.86 Mg/m³ at an optimum moisture content (OMC) of 15%, while the measured coefficient of permeability was 1.446×10^{-4} m/day. The triaxial parameters included a Young's modulus of 35,750 kPa, cohesion of 240 kPa and an angle of internal friction of 35°. These properties indicate a soil with appreciable plasticity and relatively low hydraulic conductivity, but with measurable intrinsic shear resistance.

Table 3: Laboratory Result of the Soil Properties

Property	Lateritic Soil
Specific Gravity	2.66
Grain Size Distribution (%)	
Sand	60
Silt	40
Consistency Limits (%)	
Liquid Limit	48
Plastic Limit	17
Plasticity Index	31
Soil Classification	
AASHTO	A-7-5
Compaction	
MDD (Mg/m³)	1.86
OMC %	15
Permeability Constant (*K*)m/day	$1.446 \text{ X } 10^{-4}$
Tri-axial Test	
Young's Modulus E	35,750KPa
Cohesion (KPa)	240
Angle of Friction	35
Dilatancy Angle	0

3.3.1 Specific Gravity and Particle-Size Characteristics

The specific gravity of 2.66 falls within the range commonly reported for mineral soils dominated by quartz, feldspathic and aluminosilicate constituents. This value is also consistent with the predominantly inorganic nature of the lateritic material investigated. The relatively moderate specific gravity suggests that the soil mineralogy is not dominated by exceptionally dense minerals, although specific gravity alone cannot establish the mineralogical composition.

The grain-size distribution consisted of 60% sand and 40% silt. This relatively high sand content indicates that the soil possesses a substantial coarse fraction, which can contribute to particle interlocking and frictional resistance under loading. However, the 40% silt fraction is sufficiently large to influence moisture sensitivity, plastic behaviour and drainage. The absence of a separately reported clay fraction should be interpreted cautiously because the plastic response of lateritic soils can still be substantial where fine particles contain active clay minerals or where iron and aluminium oxides promote aggregation of finer particles. The coexistence of a relatively large sand fraction with a considerable fine fraction is particularly important for stabilization. The sand particles provide a comparatively stable granular skeleton, whereas the finer fraction occupies pore spaces and governs much of the soil's moisture-related behaviour. Addition of pozzolanic materials may therefore modify the packing arrangement, pore structure and interparticle bonding of the soil rather than simply changing its particle-size distribution.

3.3.2 Consistency Characteristics and Plasticity Behaviour

The lateritic soil recorded a liquid limit of 48%, a plastic limit of 17% and a plasticity index of 31% (Figure 3). The PI, calculated as the difference between the liquid and plastic limits, indicates a pronounced range of moisture content over which the soil remains plastic. This behaviour is important from a pavement-engineering perspective because soils with substantial plasticity generally exhibit greater sensitivity to variations in moisture content and may experience undesirable changes in volume and strength under wetting and drying conditions.

The LL of 48% places the soil close to the boundary commonly used to distinguish relatively low- and high-liquid-limit fine soils in conventional soil-classification systems. More importantly, the PI of 31% demonstrates that the soil possesses appreciable plastic behaviour despite its reported 60% sand content. This suggests that the engineering response of the soil is controlled not merely by its sand fraction but also by the characteristics of its fine fraction and associated mineralogical interactions.

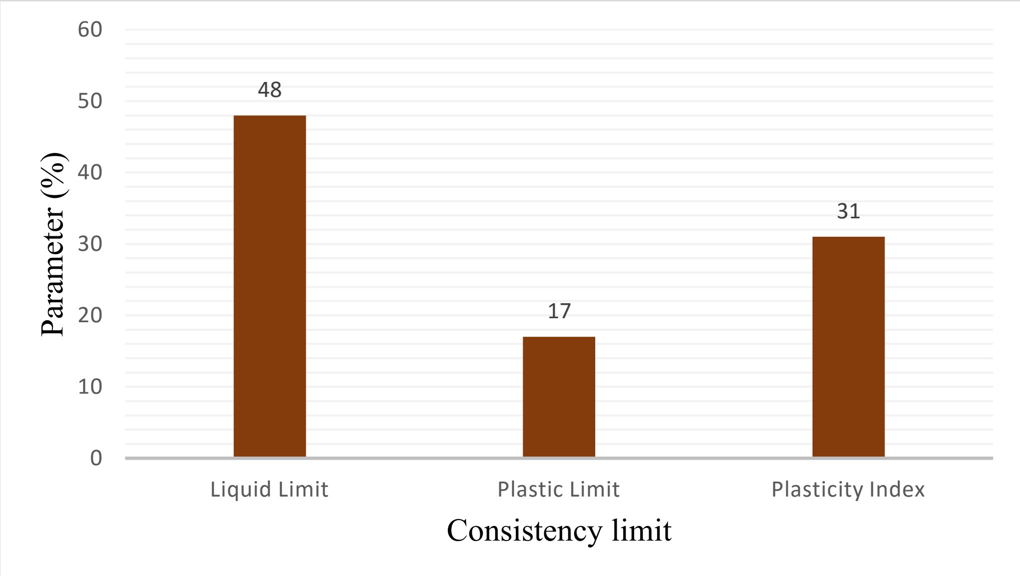

Figure 3: Consistency limits and plasticity characteristics of the untreated lateritic soil

The relatively high PI has direct implications for the suitability of the untreated soil as a pavement subgrade. High plasticity can promote loss of stiffness when the soil becomes wet, increase susceptibility to deformation and complicate the maintenance of stable pavement performance under fluctuating environmental conditions. These characteristics provide a strong engineering rationale for chemical stabilization. In the present study, the use of agro-industrial waste pozzolans is therefore particularly relevant because their incorporation may reduce the effective plastic fraction, alter surface activity, promote particle aggregation and generate cementitious products through pozzolanic reactions.

A key consideration, however, is that reduction in PI following stabilization should not automatically be interpreted as evidence of pozzolanic reaction. Changes in plasticity may initially result from physical dilution, particle rearrangement, flocculation-agglomeration or modification of the soil-water interaction. Stronger evidence of chemical stabilization requires complementary mineralogical and microstructural observations, particularly XRF, XRD and SEM results. This distinction is important for establishing the multi-scale mechanism of stabilization proposed in this study.

3.3.3 AASHTO Classification and Engineering Implication

According to the reported classification, the soil falls within the **A-7-5** group of the AASHTO soil classification system. This classification is significant because A-7 soils are generally associated with fine-grained materials having relatively poor subgrade characteristics compared with granular A-1, A-2 and A-3 materials. The A-7-5 designation further reflects the relationship between the liquid limit, plasticity index and plastic limit, indicating that the soil possesses a substantial plastic component.

The classification reinforces the need for treatment where the material is intended for applications requiring reliable load-bearing performance, particularly pavement subgrades and selected earthworks. Although classification systems provide useful screening information, they do not by themselves determine whether a soil will perform satisfactorily after stabilization. The subsequent mechanical response of the soil to pozzolan addition is therefore more important for evaluating its engineering transformation. The A-7-5 classification also establishes a useful baseline for evaluating whether agro-industrial pozzolans can convert a marginal or problematic lateritic soil into a material with improved engineering characteristics. Such improvement would be particularly valuable in regions where conventional stabilizers are expensive or where large quantities of agricultural and industrial residues are generated.

3.3.4 Compaction characteristics and hydraulic conductivity

The untreated soil achieved a maximum dry density of 1.86 Mg/m³ at an optimum moisture content of 15%. The MDD represents the maximum degree of dry packing obtained under the adopted compactive effort, while the OMC represents the moisture condition at which this packing was achieved. The compaction behaviour is particularly relevant to stabilization because incorporation of pozzolanic materials can modify both MDD and OMC. The direction and magnitude of these changes depend on the specific gravity, particle morphology, surface area, mineralogy and water affinity of the additive. A relatively dense pozzolan may increase MDD, whereas a lightweight, porous or highly absorptive ash may reduce MDD while increasing OMC. Thus, differences observed among POFA, POCP, RHA, CCA, FA and CBA in subsequent treatment stages should be interpreted in relation to their physicochemical characteristics rather than dosage alone.

The baseline MDD of 1.86 Mg/m³ provides an important reference for determining whether stabilization produces denser particle packing. An increase in MDD would suggest improved packing or stronger interparticle association during compaction, whereas a reduction could indicate replacement of heavier soil particles by lower-density ash particles or increased internal voids. Similarly, changes in OMC can provide indirect evidence of altered water demand. However, compaction results should be interpreted alongside SEM and mineralogical evidence because density changes can arise from both physical packing and chemical reactions.

The measured permeability coefficient was 1.446×10^{-4} m/day, indicating relatively low hydraulic conductivity. This behaviour is consistent with the presence of a substantial fine fraction and the plastic nature of the soil. The low permeability suggests that water movement through the compacted soil matrix is restricted, which can be advantageous where reduced seepage is required but potentially problematic where rapid drainage is necessary.

The hydraulic behaviour is important because water availability strongly influences the performance of lateritic subgrades. Under prolonged wet conditions, a low-permeability soil may retain moisture and experience a corresponding reduction in stiffness or shear resistance. Conversely, limited water transmission may reduce the rate at which external water penetrates the soil mass. The engineering significance therefore depends on the interaction between permeability, degree of saturation, compaction state and drainage conditions. The permeability result also provides an important mechanistic baseline for assessing pozzolan treatment. If stabilization reduces permeability, the change may indicate pore refinement resulting from particle rearrangement and the formation of cementitious reaction products. Conversely, an increase in permeability may reflect pore connectivity caused by agglomeration or changes in the packing structure. Consequently, hydraulic conductivity should be interpreted together with compaction and microstructural results rather than as an isolated performance indicator.

At the microstructural scale, pozzolanic reactions may consume reactive silica and alumina in the presence of calcium and water to produce calcium silicate hydrate (C-S-H), calcium aluminate hydrate and related cementitious phases, depending on the chemical composition of the system. These products can occupy pore spaces and bind adjacent particles. The extent to which this occurs will depend strongly on the CaO availability and reactive $SiO_2 + Al_2O_3$ content of each agro-industrial ash, making the XRF and XRD results particularly important for explaining the observed engineering response.

3.3.5 Triaxial Strength and Deformation Parameters

The triaxial test produced a cohesion value of 240 kPa and an internal friction angle of 35°, while the Young's modulus was reported as 35,750 kPa. These values indicate that the untreated soil possesses both cohesive and frictional components of shear resistance. The cohesion contribution reflects interparticle bonding and interactions within the fine fraction, whereas the relatively substantial friction angle is consistent with the significant sand fraction reported in the particle-size distribution.

The measured angle of friction is particularly relevant because it suggests that particle interlocking and frictional resistance make an important contribution to the soil's shear behaviour. The 60% sand content provides a granular framework capable of mobilizing friction under loading, while the fine fraction contributes to apparent cohesion and controls moisture-dependent behaviour.

The Young's modulus of 35.75 MPa provides an indication of the soil's resistance to elastic deformation under the adopted testing conditions. For pavement applications, stiffness is critical because repeated traffic loading can induce cumulative deformation even where peak shear strength is adequate. Consequently, an effective stabilization treatment should ideally improve both strength and stiffness rather than merely increasing one parameter. The cohesion and friction angle also provide a useful framework for evaluating the mechanism of pozzolan stabilization. An increase in cohesion following treatment would indicate enhanced bonding between particles, potentially resulting from cementitious reaction products and physicochemical interactions. An increase in the friction angle would suggest improved particle interlocking, aggregation or changes in the soil fabric. If both parameters increase, the stabilization mechanism would likely involve simultaneous modification of the soil fabric and development of additional interparticle bonding.

3.3.6 Engineering Performance Criteria for Pozzolan Stabilization

The results demonstrate that the untreated lateritic soil has sufficient engineering limitations to justify stabilization, particularly because of its high plasticity and A-7-5 classification. At the same time, its 60% sand fraction, 35° friction angle and 1.86 Mg/m³ MDD indicate that the soil is not inherently devoid of useful engineering characteristics. This distinction is important because effective stabilization should enhance an existing soil structure rather than simply compensate for fundamentally unsuitable material.

The subsequent assessment of agro-industrial waste pozzolans should therefore focus on performance transformation rather than isolated numerical improvement. The most effective pozzolan should be identified based on its ability to produce a balanced improvement in plasticity, compaction, hydraulic behaviour, stiffness and shear strength at an appropriate dosage and curing period. Such an approach is more rigorous than ranking the materials according to a single parameter, since stabilization performance depends on the interaction between the soil's initial properties, the chemical and physical characteristics of each ash. The baseline results confirm that the lateritic soil presents a suitable test matrix for investigating multi-scale stabilization mechanisms. The combination of substantial plasticity, appreciable fine content, moderate density, low permeability and measurable cohesive-frictional strength creates a clear engineering basis for examining how agro-industrial pozzolans modify soil behaviour.

3.4 Cation Exchange Capacity and Physicochemical Characteristics of the Pozzolans

The results in Table 4 show relatively narrow differences in the reported cation exchange capacity (CEC) of the six agro-industrial pozzolans, ranging from 0.0190 for POFA and POCP to 0.0211 for RHA. RHA therefore recorded the highest CEC, followed by CBA (0.0201), FA (0.0198) and CCA (0.0196), while POFA and POCP showed the lowest values. Although the numerical differences are modest, they indicate that the wastes do not possess identical surface-exchange characteristics. This distinction is relevant because cation exchange can contribute to flocculation, modification of particle interactions and changes in water affinity during stabilization. Previous research has established that CEC is closely associated with surface activity and the capacity of soil minerals to retain exchangeable cations, while fly-ash treatment can reduce soil CEC through particle aggregation and the formation of coarser reaction products. The present results extend this understanding by showing that even closely grouped waste pozzolans may differ in their initial exchange characteristics, potentially contributing to differences in their subsequent stabilization behaviour.

Table 4: Cation Exchange Capacity (CEC) of various pozzolanic materials used for the chemical stabilization of laterite soils

PARAMETERS	POFA	POCP	CBA	CCA	RHA	FA
CEC	0.0190	0.0190	0.0201	0.0196	0.0211	0.0198
Total Dissolved Solid (mg/L)	176	176	169	373	171	160
% Moisture	25.0	23.2	22.8	23	23	22.1
Conductivity (mS/cm)	0.24	0.23	0.23	0.50	0.24	0.21

The relatively high CEC of RHA is particularly noteworthy as seen in Figure 4. Recent work on rice-husk-ash-based stabilization has demonstrated that RHA can alter cation-related soil chemistry and contribute to changes in effective CEC (Onyelowe *et al.,*2021), while recent POFA-based research has linked cation exchange with reductions in optimum moisture content and improvements in compaction and strength (Alhokabi *et al.,*2022). However, CEC alone should not be treated as a direct measure of pozzolanic reactivity. The small separation among the six materials suggests that other characteristics, particularly reactive SiO_2 and Al_2O_3, available CaO, amorphous content, fineness and surface morphology, are likely to control the extent to which exchange reactions develop into sustained cementitious reactions. This is consistent with literature identifying fly-ash reactivity as dependent on chemical composition, fineness and reactive constituents rather than CEC alone.

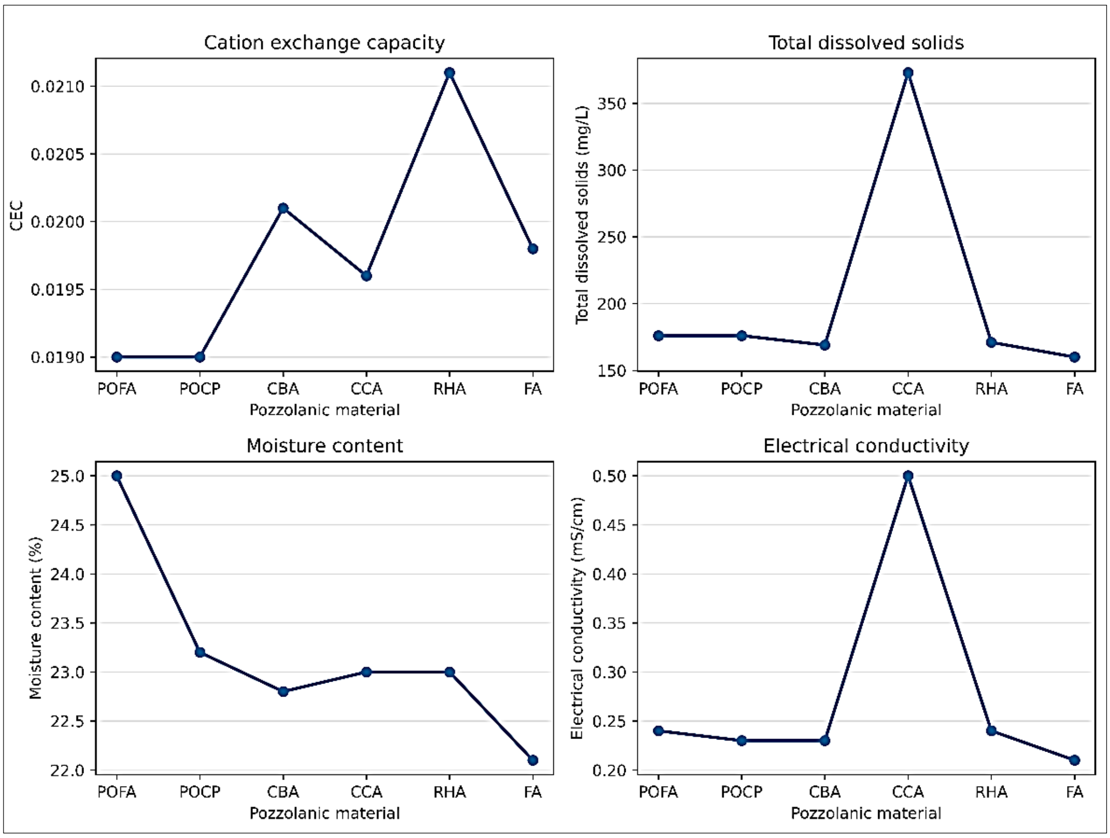

Figure 4: Physicochemical characteristics of agro-industrial waste pozzolans

The accompanying TDS and conductivity results provide further evidence of differences in the ionic environment created by the wastes. CCA recorded the highest TDS (373 mg/L) and conductivity (0.50 mS/cm), substantially exceeding the other materials, whereas FA showed the lowest values (160 mg/L and 0.21 mS/cm). This pattern suggests greater release of soluble ionic species from CCA and may influence early-stage ion exchange and reaction kinetics. Such behaviour is consistent with earlier work showing increased electrical conductivity when fly ash introduces soluble salts into stabilized soil mixtures. The implication for engineering practice is that pozzolan selection should not rely on a single chemical indicator. The contrasting CEC, TDS and conductivity profiles indicate that each waste establishes a different chemical environment, and its actual stabilization potential must therefore be assessed alongside XRF, XRD, SEM, dosage and curing response.

4. Cation Exchange Response to Increasing Pozzolan Content

The progressive decline in CEC from 0.0219 at 0% additive to 0.0168–0.0206 at 10% additive across all six treatments (Table 5) provides a consistent indication that pozzolan incorporation altered the exchange environment of the lateritic soil. The reduction was most pronounced for POFA and POCP, which reached 0.0168 and 0.0171, respectively, whereas RHA retained the highest CEC at 10% (0.0206). This general behaviour agrees with Nalbantoglu and Gucbilmez (2001), who demonstrated that CEC can be used to track physicochemical changes in fly-ash-treated soil and associated reductions in plasticity and water-absorption potential. Their work also linked cation exchange with flocculation and subsequent cementation through pozzolanic reaction products.

Table 5: Combined CEC Values for Different Additives at Various Percentages

% Additive	POFA	POCP	CBA	CCA	RHA	FA
0%	0.0219	0.0219	0.0219	0.0219	0.0219	0.0219
2%	0.0212	0.0210	0.0210	0.0213	0.0216	0.0212
4%	0.0201	0.0200	0.0201	0.0207	0.0214	0.0205
6%	0.0190	0.0190	0.0192	0.0201	0.0211	0.0198
8%	0.0179	0.0181	0.0183	0.0196	0.0209	0.0191
10%	0.0168	0.0171	0.0174	0.0190	0.0206	0.0184

The response is nevertheless not uniform among the additives as seen in Figure 6, and this distinction is important. At 10% addition, the CEC reduction relative to the untreated soil was approximately 23.3% for POFA, 21.9% for POCP, 25.1% for CBA, 13.2% for CCA, 5.9% for RHA and 16.0% for FA. RHA and CCA therefore produced substantially smaller reductions than POFA, POCP and CBA. This divergence suggests that the effect of dosage cannot be separated from the intrinsic chemistry and surface characteristics of each waste. The literature supports this interpretation according to Tian *et al.,* (2021); Ambrus and Mucsi, (2023) indicating that the effectiveness of fly ash depends on reactive silica, free lime, iron, carbon content and fineness, while the CaO content and CaO/(SiO_2 + Al_2O_3) ratio can strongly influence subsequent strength development. The present results therefore caution against treating CEC as a direct proxy for pozzolanic reactivity.

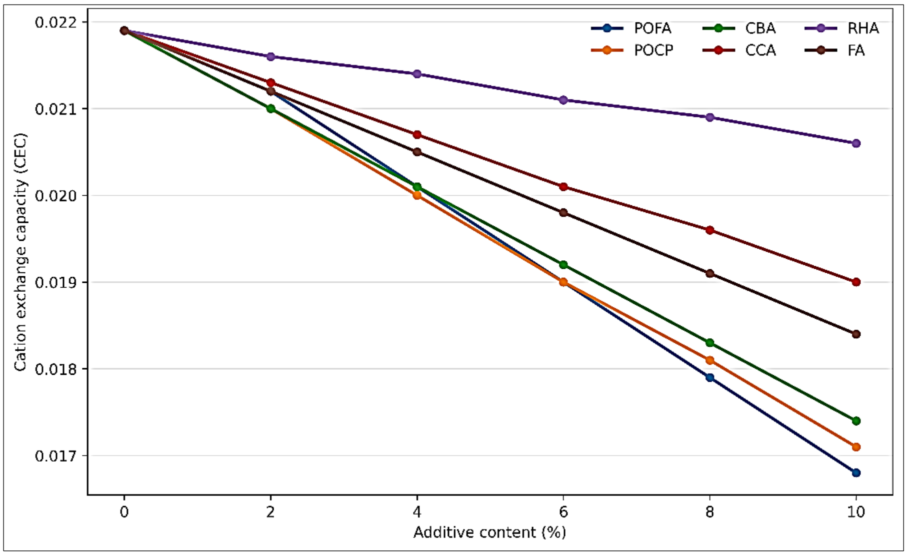

Figure 6: CEC response of lateritic soil to increasing agro-industrial pozzolan content

The near-monotonic decline in CEC with increasing additive content in Figure 7 also has practical significance. Rather than interpreting a lower CEC as evidence that higher pozzolan contents are automatically superior, the result is better understood as evidence of progressive alteration of the soil's exchange system. Paul *et al.,*(2026), similarly argued that although cation exchange contributes to early soil modification, subsequent pozzolanic reactions can become the dominant mechanism responsible for longer-term strength development through C-S-H and C-A-H formation. This distinction is particularly relevant to the present study because the six wastes display different CEC responses despite being assessed at identical dosages. The CEC trends therefore provide evidence of chemical modification, but they cannot establish the nature or extent of cementitious reaction on their own (Figure 8). The subsequent XRF, XRD and SEM analyses are consequently necessary to determine whether the observed reductions arise primarily from cation exchange and particle aggregation, dilution effects, or the development of new reaction products.

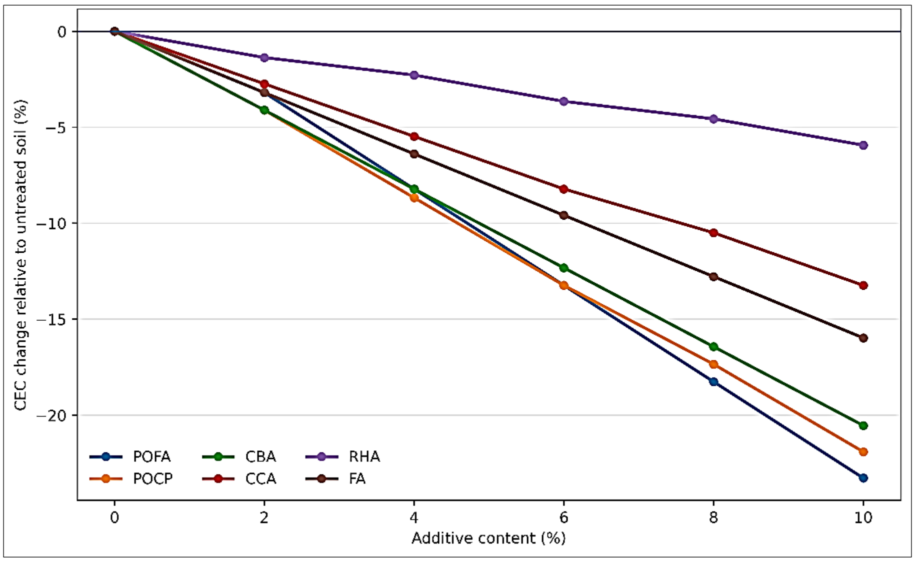

Figure 7: Relative CEC change with increasing pozzolan content

The findings support a shift away from selecting stabilizers on the basis of a single chemical indicator. Barman and Dash (2022) describe cation exchange as an important short-term stabilization process because multivalent cations can replace exchangeable ions, reduce water-film thickness and promote flocculation-agglomeration; however, they also caution that excessive exchange may affect the availability of ions required for subsequent pozzolanic reactions.

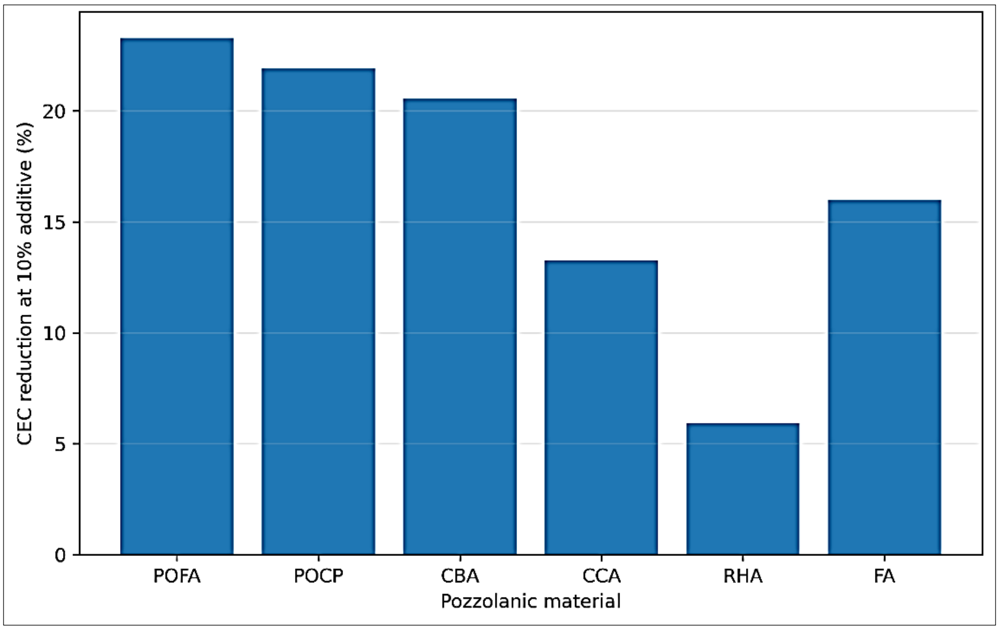

Figure 8: CEC reduction relative to untreated soil at 10% additive

The present results reinforce this concern: the most desirable pozzolan cannot be identified simply as the material producing the largest CEC reduction. Instead, the CEC response must be interpreted alongside plasticity, compaction, strength, oxide composition, mineralogical transformation and microstructural development.

5. Statistical Analysis

The regression analysis provides useful evidence that the response of the lateritic soil to agro-industrial waste stabilization is strongly associated with the selected explanatory parameters, but the results also require careful statistical interpretation because of the very small sample size and some internal inconsistencies in the reported regression output. The POFA model in Table 6,7, and 8 produced a high Multiple R of 0.975 and an R^2 of 0.950, indicating that approximately 95.0% of the variation in the response variable was accounted for by the selected predictors.

Table 6: Model Summary for the POFA-Stabilized Soil

Regression Statistics	
Multiple R	0.974764
R Square	0.950166
Adjusted R Square	0.250276
Standard Error	0.000419
Observations	6

Similarly, the POCP model (Table 9, 10, and 11) yielded R = 0.958 and R^2 = 0.917, while CCA, CBA and RHA produced R^2 values of 0.997, 0.995 and 0.973, respectively (Table 12 - 20). These high coefficients of determination initially suggest strong predictive relationships and are consistent with the broader experimental evidence that agro-industrial ashes can substantially modify the physicochemical and engineering behaviour of lateritic soils. Previous studies have reported improvements in strength, bearing capacity, plasticity and compaction characteristics following treatment with POFA, CCA and RHA, although the magnitude and optimum dosage vary considerably with soil mineralogy, ash chemistry, processing and curing conditions.

Table 7: ANOVA of Selected Parameters for POFA-Stabilized Soil

	df	SS	MS	F	Significance F
Regression	4	1E-05	2.51E-06	28.59968	0.139231
Residual	3	5.27E-07	1.76E-07		
Total	7	1.06E-05			

5.1 Coefficients for the Model Equation

Table 8: Coefficients for the Model Equation for the POFA-Stabilized Soil

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-0.0223	0.046299	-0.48165	0.663008	-0.16965	0.125045	-0.16965	0.125045
POFA	-0.00139	0.001014	-1.37496	0.262837	-0.00462	0.001833	-0.00462	0.001833
MC	0.002	0.002095	0.954669	0.410174	-0.00467	0.008667	-0.00467	0.008667
TCC	0	0	65535	-	0	0	0	0
OGC	0	0	65535	-	0	0	0	0

The ANOVA results further indicate marked differences among the stabilizers. The CCA model recorded the strongest apparent statistical performance, with F = 478.50 and Significance F = 0.0343, while CBA produced F = 290.74 and Significance F = 0.0440. Both therefore satisfy the conventional 5% significance criterion and suggest that the predictors collectively exert a statistically meaningful influence on the response. This finding is particularly important because CCA has previously demonstrated beneficial effects on lateritic soils, including improvements in CBR and UCS, although reported optimum contents differ among studies.

Table 9: Model for the POCP-Stabilized Soil

Regression Statistics	
Multiple R	0.9576846
R Square	0.9171598
Adjusted R Square	0.1952663
Standard Error	0.0004749
Observations	6

Table 10: ANOVA of Selected Parameters for POCP-Stabilized Soil

	df	SS	MS	F	Significance F
Regression	4	7.49E-06	1.87E-06	16.60714	0.181768
Residual	3	6.77E-07	2.26E-07		
Total	7	8.17E-06			

Table 11: Coefficients for the Model Equation for the POCP-Stabilized Soil

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.03295	0.05248	0.627857	0.57464	-0.13407	0.199965	-0.13407	0.199965
POCP	-0.000281	0.00044	-0.63745	0.56915	-0.00168	0.00112	-0.00168	0.00112
MC	-0.0005	0.002375	-0.21056	0.846722	-0.00806	0.007057	-0.00806	0.007057
TCC	0	0	65535	-	0	0	0	0
OGC	0	0	65535	-	0	0	0	0

The present finding therefore supports the established potential of CCA while extending previous work by demonstrating a strong multivariate relationship involving the selected physicochemical parameters rather than considering strength improvement in isolation. The CBA result is similarly noteworthy because bottom ash is less frequently investigated than conventional fly ash or agricultural ashes, suggesting a potentially valuable avenue for converting an underutilized combustion residue into an engineering material.

Table 12: Model for the CCA-Stabilized Soil

Regression Statistics	
Multiple R	0.998436
R Square	0.996875
Adjusted R Square	0.328125
Standard Error	8.98E-05
Observations	6

Table 13: ANOVA of Selected Parameters for CCA-Stabilized Soil

	df	SS	MS	F	Significance F
Regression	4	7.71E-06	1.93E-06	478.5	0.034271
Residual	3	2.42E-08	8.06E-09		
Total	7	7.73E-06			

Table 14: Coefficients for the Model Equation for the CCA-Stabilized Soil

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.027425	0.009918	2.765226	0.069846	-0.00414	0.058988	-0.00414	0.058988
CCA	-0.00026	5.13E-05	-4.97383	0.015615	-0.00042	-9.2E-05	-0.00042	-9.2E-05
MC	-0.00025	0.000449	-0.55709	0.616332	-0.00168	0.001178	-0.00168	0.001178
TCC	0	0	65535	-	0	0	0	0
OGC	0	0	65535	-	0	0	0	0

The coefficient estimates provide further insight into the direction of these relationships. POFA (-0.00139), POCP (-0.000281), CCA (-0.00026), CBA (-0.00040) and RHA (-0.00009) all have negative coefficients, implying an inverse association between increasing stabilizer representation and the model response as defined in the analysis. However, only CCA and CBA coefficients are statistically significant at $p < 0.05$, with $p = 0.0156$ and 0.0160, respectively. The POFA, POCP and RHA coefficients are not statistically significant, despite their high R^2 values. This distinction is important: a high R^2 should not be interpreted as evidence that every individual predictor is significant. Indeed, the POFA coefficient ($p = 0.263$), POCP ($p = 0.569$) and RHA ($p = 0.279$) indicate considerable uncertainty around their individual effects.

Table 15: Model for the CBA-Stabilized Soil

Regression Statistics	
Multiple R	0.99743
R Square	0.994867
Adjusted R Square	0.324779
Standard Error	8.98E-05
Observations	6

Table 16: ANOVA of Selected Parameters for CBA-Stabilized Soil

	df	SS	MS	F	Significance F
Regression	4	4.68E-06	1.17E-06	290.7414	0.043954
Residual	3	2.42E-08	8.06E-09		
Total	7	4.71E-06			

Table 17: Coefficients for the Model Equation for the CBA-Stabilized Soil

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.027425	0.009918	2.765226	0.069846	-0.00414	0.058988	-0.00414	0.058988
CBA	-0.0004	8.06E-05	-4.93434	0.01596	-0.00065	-0.00014	-0.00065	-0.00014
MC	-0.00025	0.000449	-0.55709	0.616332	-0.00168	0.001178	-0.00168	0.001178
TCC	0	0	65535	-	0	0	0	0
OGC	0	0	65535	-	0	0	0	0

Nevertheless, previous research demonstrates that these materials can improve lateritic soil performance under appropriate conditions. POFA, for example, has produced substantial strength gains when combined with an activator, while RHA has been reported to improve lateritic soil properties at specific dosages. The apparent discrepancy therefore likely reflects differences in formulation, dosage, response variables and, importantly, the restricted dataset used in the present regression rather than an absence of stabilization potential.

Table 18: Model for the RHA-Stabilized Soil

Regression Statistics	
Multiple R	0.986608
R Square	0.973394
Adjusted R Square	0.288991
Standard Error	8.98E-05
Observations	6

Table 19: ANOVA of Selected Parameters for RHA-Stabilized Soil

	df	SS	MS	F	Significance F
Regression	4	8.84E-07	2.21E-07	54.87931	0.100859
Residual	3	2.42E-08	8.06E-09		
Total	7	9.08E-07			

Table 20: Coefficients for the Model Equation for the RHA-Stabilized Soil

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.027425	0.009918	2.765226	0.069846	-0.00414	0.058988	-0.00414	0.058988
RHA	-9E-05	6.84E-05	-1.31959	0.27864	-0.00031	0.000127	-0.00031	0.000127
MC	-0.00025	0.000449	-0.55709	0.616332	-0.00168	0.001178	-0.00168	0.001178
TCC	0	0	65535	-	0	0	0	0
OGC	0	0	65535	-	0	0	0	0

The FA model in Table 21, 22, and 23 is statistically exceptional, with R = 1.000 and R^2 = 1.000, an F-statistic of approximately 2.55×10^{30} and an almost zero standard error. Although this appears to demonstrate perfect predictive performance, it should not be interpreted as evidence of a universally perfect relationship. Such an outcome strongly suggests an exact or near-exact mathematical dependency among the observations and predictors, potentially arising from the structure or scaling of the dataset. Previous investigations have nevertheless established that fly ash can improve lateritic soil plasticity and mechanical properties, including CBR, with performance generally becoming less pronounced beyond an optimum dosage. Thus, the exceptionally high FA statistics are plausible in terms of model fit but require independent validation before being used for engineering prediction.

Table 21: Model for the FA-Stabilized Soil

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	0.333333
Standard Error	1.3E-18
Observations	6

Table 22: ANOVA of Selected Parameters for FA-Stabilized Soil

	df	SS	MS	F	Significance F
Regression	4	8.58E-06	2.14E-06	2.55E+30	4.7E-16
Residual	3	5.04E-36	1.68E-36		
Total	7	8.58E-06			

Table 23: Coefficients for the Model Equation for the FA-Stabilized Soil

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.0219	9.38E-19	2.33E+16	1.73E-49	0.0219	0.0219	0.0219	0.0219
FA	-0.00035	1.55E-19	-2.3E+15	1.91E-46	-0.00035	-0.00035	-0.00035	-0.00035
MC	0	0	65535	-	0	0	0	0
TCC	0	0	65535	-	0	0	0	0
OGC	0	0	65535	-	0	0	0	0

From a civil engineering perspective, the results nevertheless reinforce an important practical principle: agro-industrial wastes should not be treated as interchangeable stabilizers. The statistically stronger CCA and CBA responses indicate that material selection should be based on measured chemical and physicochemical characteristics and verified through engineering performance testing rather than assumed pozzolanic application alone. This agrees with recent studies showing that optimum stabilization depends on ash composition, activation, dosage and soil characteristics. The principal novelty of the present study therefore lies in demonstrating, across several waste-derived pozzolans, that their predictive relationships with stabilized-soil behaviour are material-specific. For field application, however, the models should be recalculated using a substantially larger experimental dataset, independent validation samples and clearly defined response variables before they are adopted for pavement design or specification. This would transform the current statistical evidence from a promising laboratory indication into a defensible engineering prediction framework.

6. CONCLUSION

This study investigated the chemical, physicochemical and engineering characteristics of six agro-industrial waste pozzolans such as POFA, POCP, CCA, CBA, RHA and FA, and evaluated their potential for stabilizing lateritic soil, with particular emphasis on establishing relationships between waste chemistry, cation exchange behaviour and engineering performance. The untreated lateritic soil exhibited appreciable engineering limitations, including a liquid limit of 48%, plasticity index of 31% and A-7-5 classification, although its 60% sand fraction, maximum dry density of 1.86 Mg/m³ and friction angle of 35° indicated an exploitable granular framework. The chemical characterization demonstrated substantial compositional diversity among the wastes, with the combined SiO_2–Al_2O_3–Fe_2O_3 content ranging from 36.69% for CCA to 91.08% for RHA, while POFA and POCP provided appreciable CaO contents of 10.49% and 6.90%, respectively. These findings demonstrate that agro-industrial residues cannot be treated as chemically interchangeable stabilizers and that conventional oxide-based pozzolanic indices alone are insufficient to predict stabilization performance.

The physicochemical results further showed relatively narrow but meaningful differences in CEC among the pozzolans, with RHA recording the highest value and POFA and POCP the lowest, indicating differences in their potential to modify particle interactions, flocculation and water affinity. The engineering assessment confirms that stabilization should therefore be evaluated through a combination of plasticity, compaction, hydraulic behaviour, stiffness and strength rather than through a single performance index. The statistical analysis reinforces this material-specific behaviour: although very high R^2 values were obtained for all models, CCA and CBA showed statistically significant overall relationships, with F-values of 478.50 and 290.74, respectively, while their stabilizer coefficients were also significant at $p < 0.05$. The perfect fit obtained for FA should, however, be regarded cautiously because it is likely influenced by the structure and size of the dataset rather than interpreted as evidence of universally perfect predictive capability.

For civil and road infrastructure engineering, the principal implication is that sustainable stabilization should move beyond empirical selection of an ash based solely on availability or nominal silica content. The contrasting chemical signatures demonstrate that stabilizer selection should consider the balance among reactive Si–Al species, calcium availability, alkalinity, exchange characteristics, dosage and curing conditions. This provides a stronger basis for converting locally abundant agricultural and industrial residues into functional pavement materials while reducing dependence on conventional binders and simultaneously addressing waste-management challenges. The findings particularly support further investigation of CCA and CBA as potentially valuable alternatives, but their field adoption should follow performance-based verification rather than the statistical results alone.

Several limitations constrain the generalization of the findings. The regression models were developed from a small dataset, and inconsistencies between the reported number of observations and degrees of freedom. Independent validation, larger replicated datasets and multivariate modelling across multiple lateritic soil types are therefore necessary. Future research should also examine longer curing periods, durability under wet–dry cycles, field-scale performance, leachability and life-cycle environmental and economic impacts, while more directly quantifying mineralogical and reaction-product development. Generally, this study advances understanding by demonstrating that the effectiveness of agro-industrial pozzolans is determine not by a single chemical criterion but by the interaction of chemical composition, physicochemical behaviour and engineering response, providing a more defensible foundation for mechanistically informed and sustainable chemical stabilization of lateritic soils.

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