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Sustainable Improvement of Lateritic Soil Using Aluminium Dross and Sodium Silicate -A Geotechnical Evaluation

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ABSTRACT: *Lateritic soils are widely used in tropical regions for construction purposes; however, their high plasticity, low bearing capacity, and moisture sensitivity often limit their direct application. This study investigates the effectiveness of aluminium dross and sodium silicate, used individually and in combination, as sustainable stabilizing agents for lateritic soil. Lateritic soil samples obtained from ikpayongo, Makurdi, Nigeria were treated with varying proportions of aluminium dross (0–10%) and sodium silicate (2.5–10%). Laboratory tests including chemical composition analysis (XRF and XRD), Atterberg limits, compaction characteristics, and California Bearing Ratio (CBR) tests were conducted in accordance with British Standards and Nigerian General Specifications. Results show that the natural soil is a highly weathered laterite rich in silica, alumina, and iron oxides, with poor geotechnical properties unsuitable for subgrade applications. Aluminium dross exhibited strong pozzolanic characteristics, significantly improving compaction and strength properties up to an optimum content of 7.5%. Beyond this level, strength reductions were observed due to over-stabilization. Binary stabilization using aluminium dross and sodium silicate produced superior improvements, yielding higher maximum dry density, lower plasticity index, and markedly enhanced soaked and unsoaked CBR values. The combined stabilization significantly improved moisture resistance and dimensional stability through enhanced cementitious and alkali-activated reactions. The findings demonstrate that aluminium dross activated with sodium silicate provides an effective, sustainable, and cost-efficient alternative to conventional soil stabilizers for lateritic soils, particularly in tropical developing regions*

KEYWORDS: *Lateritic soil; Aluminium dross; Sodium silicate; Soil stabilization; CBR; Sustainability*

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I. INTRODUCTION

1.1 Background of the Study

Lateritic soils are widely distributed across tropical and subtropical regions, including large parts of Africa, Southeast Asia, and South America. Despite their abundance, lateritic soils often exhibit unfavorable geotechnical characteristics such as high plasticity, low bearing capacity, and significant volume change due to their clay-rich mineralogy. These properties limit their direct use in road construction and foundation engineering without appropriate stabilization measures. Consequently, soil stabilization remains a critical practice in geotechnical engineering to enhance the engineering performance of lateritic soils for infrastructure development.

Traditionally, stabilizing agents such as cement and lime have been extensively used to improve soil strength, stiffness, and durability. However, the production of these conventional binders is energy-intensive and contributes significantly to global carbon dioxide emissions, thereby exacerbating environmental degradation and climate change concerns (Das, 2016; Scrivener et al., 2018). In response to growing sustainability demands, recent research has increasingly focused on the utilization of industrial by-products and waste materials as alternative soil stabilizers, aligning geotechnical practice with circular economy and low-carbon development principles (Akinwumi et al., 2021; Zhang et al., 2023).

Aluminium dross is a solid waste generated during primary and secondary aluminium production processes. It consists primarily of alumina (Al_2O_3), silica (SiO_2), residual metallic aluminium, and minor quantities of other oxides. Due to its chemical composition and reactivity, aluminium dross has attracted attention as a potential soil stabilizing agent. When incorporated into soil in the presence of moisture, aluminium dross undergoes hydration and pozzolanic reactions, forming cementitious alumino-silicate compounds that enhance soil strength, reduce plasticity, and decrease permeability (Ulusoy et al., 2019; Chandra & Sharma, 2020). Experimental studies have demonstrated notable improvements in unconfined compressive strength (UCS), California Bearing Ratio (CBR), and Atterberg limits of lateritic soils treated with aluminium dross (Ghosh et al., 2017; Adewumi et al., 2022).

The performance of aluminium dross-stabilized soils is strongly influenced by curing duration. During curing, progressive hydration and pozzolanic reactions improve interparticle bonding within the soil matrix, leading to increased strength and stiffness over time. Previous studies indicate that substantial gains in UCS and CBR typically occur within the first 7 days, with gradual improvements observed up to 28 days or longer, depending on material composition and environmental conditions (Chandra & Sharma, 2020; Chen et al., 2024). However, beyond optimal curing periods, marginal strength gains may diminish, underscoring the need for appropriate curing optimization based on project requirements (Mitchell & Soga, 2018).

Sodium silicate, commonly referred to as *water glass*, is another chemical stabilizer increasingly explored for problematic soils, including laterites. It is an alkaline solution composed mainly of silicon dioxide (SiO_2) and sodium oxide (Na_2O). Sodium silicate improves soil properties through chemical bonding mechanisms, reacting with calcium ions naturally present in soils or introduced via additives to form calcium silicate hydrate (C–S–H) gels. These gels enhance soil strength, durability, and resistance to moisture ingress (Kumar et al., 2018; Al-Bared & Marto, 2021). The effectiveness of sodium silicate stabilization depends on factors such as dosage, soil mineralogy, moisture content, and curing time.

Recent studies emphasize the potential benefits of combining industrial by-products with chemical activators to achieve synergistic stabilization effects. The incorporation of sodium silicate alongside aluminium dross is expected to accelerate pozzolanic reactions, enhance bonding mechanisms, and further improve the geotechnical performance of lateritic soils (Afolayan et al., 2022; Li et al., 2024). Nevertheless, excessive aluminium dross content may result in high alkalinity or reduced workability, while insufficient quantities may yield inadequate stabilization. Therefore, determining optimal mix proportions and curing conditions remains essential for effective and economical application.

From an environmental and economic perspective, aluminium dross-based soil stabilization offers significant advantages. Utilizing this industrial by-product reduces landfill disposal challenges, lowers reliance on conventional cementitious materials, and contributes to greenhouse gas emission reduction (Chandra & Sharma, 2020; Zhang et al., 2023). These benefits are particularly relevant in developing countries where lateritic soils are abundant and financial constraints often limit access to conventional stabilizers. Despite promising results reported in controlled laboratory and limited field studies, the long-term behavior and combined effects of aluminium dross and sodium silicate on lateritic soils remain insufficiently explored, especially under Nigerian climatic and geological conditions.

Rapid urbanization and infrastructure development in Nigeria have significantly increased the demand for durable and cost-effective construction materials. In many regions, lateritic soils constitute the primary subgrade material; however, their inherent low strength and high plasticity pose challenges for road construction and foundation performance. Conventional stabilization methods relying on cement and lime are often expensive and environmentally unsustainable, limiting their widespread adoption.

Simultaneously, the aluminium manufacturing industry generates substantial quantities of aluminium dross, which presents serious environmental disposal challenges. Although aluminium dross has demonstrated potential as a soil stabilizing agent, its combined application with sodium silicate and the influence of curing conditions on lateritic soil improvement have not been adequately investigated within the Nigerian context. Addressing this knowledge gap is critical for developing sustainable, locally adaptable stabilization solutions.

This study examines the effects of aluminium dross and sodium silicate on the engineering characteristics of lateritic soil through laboratory investigations. Tests include Atterberg limits, compaction characteristics (optimum moisture content and maximum dry density), and strength assessments of both untreated and treated soil specimens with varying additive proportions. Microstructural analyses are conducted to examine mineralogical and structural modifications induced by stabilization. The findings aim to evaluate the feasibility of aluminium dross–sodium silicate blends as sustainable stabilizers for lateritic soils.

This research contributes to sustainable infrastructure development in Nigeria by addressing both geotechnical performance challenges of lateritic soils and environmental concerns associated with aluminium dross disposal. The study provides insights into an environmentally responsible soil stabilization approach that enhances strength, durability, and compaction characteristics while promoting waste reutilization and circular economy principles.

The findings are expected to support the development of cost-effective construction practices, reduce reliance on conventional stabilizers, and encourage innovation in local soil stabilization and waste recycling industries. Additionally, the study advances understanding of the combined effects of aluminium dross and sodium silicate on lateritic soil behaviour, offering practical solutions for tropical regions where lateritic soils dominate and require modification for engineering use.

II. MATERIALS AND METHODS

2.1 Materials

The materials employed in this study comprised lateritic soil, aluminium dross, sodium silicate, and distilled water.

Lateritic Soil:

Lateritic soil was obtained from a borrow pit located at Ikpayongo, Nigeria. The soil is commonly used for construction purposes in the study area. Disturbed soil samples were collected using a shovel and hoe and subsequently transported to the geotechnical engineering laboratory of the institution for analysis.

Aluminium Dross:

Aluminium dross, a by-product of aluminium smelting operations, was sourced from an industrial facility. The material was air-dried, crushed, and sieved to achieve uniform particle size distribution. Only the fine fraction passing the 0.075 mm sieve was utilized for stabilization, in line with established practices reported in previous studies (Al-Qadiri et al., 2018).

Sodium Silicate:
Commercial-grade sodium silicate solution (water glass) with a modulus of 3.2 (SiO_2/Na_2O ratio) was used. The sodium silicate content was added as a percentage of the dry weight of the soil at proportions of 2.5%, 5%, 7.5%, and 10%.

Water:
Distilled water was used throughout sample preparation, mixing, and curing to prevent contamination and ensure compliance with ASTM recommendations.

Chemical Composition Analysis

The chemical compositions of the lateritic soil, aluminium dross, and sodium silicate were determined using X-ray fluorescence (XRF) analysis. The test provided quantitative information on the major oxides present in each material, which is essential for understanding their reactivity and stabilization potential.

Moisture Content Determination

The natural moisture content of the soil was determined in accordance with BS 1377 (1990). An empty moisture can was weighed and recorded (M_1). A wet soil sample collected using a moisture ring (2.5 cm × 3 cm) was placed in the can and weighed (M_2).

$$w = \frac{M_2 - M_3}{M_3 - M_1} \quad \text{-------------------------1}$$

Where:
(w) = moisture content (%)
(M1) = mass of container (g)
(M2) = mass of container + wet soil (g)
(M3) = mass of container + dry soil (g)

Specific Gravity

The specific gravity of the fine-grained soil was determined using the density bottle method in accordance with BS 1377 (1990), Test Method B. The specific gravity was calculated using Equation (2):

$$G_s = \frac{M_2 - M_1}{(M_4 - M_1) - (M_3 - M_1)} \quad \text{------------2}$$

Particle Size Distribution

The particle size distribution of the natural soil was determined using a combination of sieve analysis and sedimentation (hydrometer) analysis in accordance with BS 1377 (1990). Part 2.

Atterberg Limits

Atterberg limits tests were conducted to determine the liquid limit (LL), plastic limit (PL), and plasticity index (PI) of both natural and stabilized soil samples. Tests on natural soil were performed in accordance with BS 1377 (1990) Part 2, while tests on stabilized samples followed BS 1924 (1990).

Liquid Limit

Approximately 300 g of air-dried soil passing the 425 µm sieve was mixed with water to form a uniform paste. About 120 g of the paste was placed in the brass cup of the Casagrande apparatus and leveled to remove air voids. A standard grooving tool was used to divide the soil into two halves. The cup was repeatedly dropped until the groove closed over a distance of 13 mm, and the number of blows was recorded. The moisture content corresponding to 25 blows was taken as the liquid limit.

Plastic Limit

The soil sample was mixed with water and rolled by hand on a glass plate into threads of approximately 3 mm diameter. When the threads began to crumble, samples were collected, weighed, and oven-dried to determine moisture content. The plasticity index was computed using Equation (3):

$$PI = LL - PL \quad \text{--}3$$

Compaction Test

Compaction characteristics were determined using the British Standard Light (BSL) compactive effort in accordance with BS 1377 (1990) Part 4 and the Nigerian General Specifications (1997). Approximately 3 kg of soil was mixed with varying water contents and compacted in a 1000 cm³ mold in three equal layers. Each layer received 27 blows from a 2.5 kg rammer dropped from a height of 300 mm. The maximum dry density (MDD) and optimum moisture content (OMC) were obtained from the moisture–dry density relationship.

2.8 California Bearing Ratio (CBR) Test

The strength characteristics of both untreated and stabilized soils were evaluated using the California Bearing Ratio (CBR) test in accordance with BS 1377 (1990), BS 1924 (1990), and the Nigerian General Specifications (1997). CBR values were computed using Equation (4):

$$CBR = \frac{\text{Measured Load}}{\text{Standard Load}} \times 100 \quad \text{---}4$$

III. RESULTS AND DISCUSSION

3.1 Chemical Composition of Lateritic Soil

3.1.1 X-ray Fluorescence (XRF) Analysis

The oxide composition of the lateritic soil determined using X-ray fluorescence (XRF) spectroscopy is presented in Table 1. The results show that the soil is predominantly composed of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), and ferric oxide (Fe_2O_3), with concentrations of 50.00%, 21.08%, and 19.79%, respectively. These oxides are characteristic of lateritic soils formed under intense tropical weathering conditions.

Table .1: Chemical Composition of Laterite Soil

Oxide composition	Concentration (wt.%)
SiO_2	50.00
Al_2O_3	21.08
Fe_2O_3.	19.79
TiO_2	3.56
CaO	1.48
MgO	0.32

MnO	0.18
SO_3	1.13
CuO	0.14
K_2O	0.16
Cl	0.99
P_2O_5	0.06
Cr_2O_3	0.05
CoO	0.07
V_2O_5	0.18
ZrO_2	0.38
Others (e.g. Nb_2O_5, Ta_2O_5, Ag_2O, etc.)	< 0.1

The high silica and alumina contents indicate appreciable pozzolanic reactivity, while the substantial iron oxide concentration accounts for the reddish-brown coloration typical of laterites. The silica-to-sesquioxide ratio, calculated using Equation (2), was found to be less than 1.33, confirming that the soil qualifies as true laterite according to established classification criteria.

$$\frac{SiO_2}{Al_2O_3+Fe_2O_3} = \frac{50.00}{21.08+19.79} = 1.22 \qquad \text{---------2}$$

These chemical characteristics suggest limited natural cementation but strong potential for chemical interaction with stabilizing agents, particularly alumino-silicate-based additives.

3.1.2 X-ray Diffraction (XRD) Analysis

The mineralogical composition of the lateritic soil determined from XRD analysis (Figure 1) reveals quartz as the dominant mineral phase (50%). Quartz contributes to hardness and durability but provides minimal cohesion due to its non-plastic nature. Orthoclase (26%) reflects partial weathering of the parent rock, while the presence of gibbsite (14.3%) indicates advanced tropical weathering and enhanced reactivity during stabilization processes (Akinropo et al., 2023; Budihal et al., 2023).

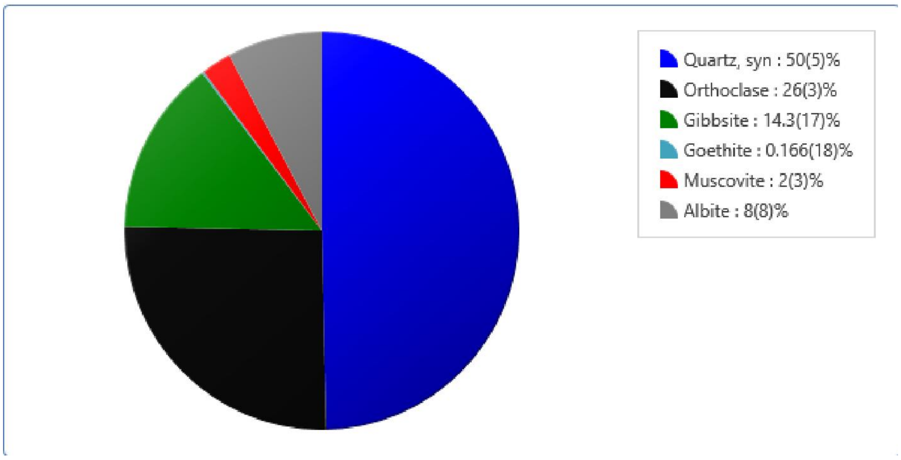

Fig.1: Mineralogical Composition of the Laterite Soil from XRD Analysis.

Minor mineral phases such as albite (8%) and muscovite (2%) exert limited influence on plasticity and compressibility, whereas trace goethite (0.16%) confirms the presence of iron oxides responsible for lateritic coloration (Shaqour, 2024). The mineralogical findings closely align with the XRF results, reinforcing the classification of the soil as a highly weathered, quartz-rich laterite.

The dominance of quartz explains the low inherent binding capacity of the soil, while the presence of reactive alumina-bearing minerals accounts for the significant improvements observed following stabilization (Minerals, 2025; Science of the Total Environment, 2024).

3.2 Natural Soil Characteristics

The natural lateritic soil is reddish-brown in colour and contains 59.49% fines passing the No. 200 sieve, far exceeding the 35% maximum specified by the Federal Ministry of Works and Housing (FMWH, 1997) for subgrade materials. This high fines content adversely affects the soil's load-bearing capacity and moisture sensitivity.

Table 2: Properties of the Natural Soil

Properties	Value
Colour	Reddish-brown
Percentage Passing Sieve No. 200 (%)	59.49
Liquid Limit (%)	42.5
Plastic Limit (%)	25.56
Plasticity Index (%)	16.94
Specific Gravity	2.61
Natural Moisture Content (%)	13.8
Swell Index (%)	15.4
AASHTO Classification	A-7-6(8)
USCS Classification	CL
Maximum dry density (BSL) (g/cm^3)	1.68
Optimum Moisture Content (BSL) (%)	19.0
Maximum dry density (WAS) (g/cm^3)	1.715
Optimum Moisture Content (WAS) (%)	17.8
California Bearing Ratio (BSL) (%) (Soaked)	14.82
California Bearing Ratio (BSL) (%) (Unsoaked)	27.2
California Bearing Ratio (WAS) (%) (Soaked)	20.4
California Bearing Ratio (WAS) (%) (Unsoaked)	36.8

The soil recorded a liquid limit of 42.5%, plastic limit of 25.56%, and plasticity index of 16.94%, classifying it as A-7-6 under the AASHTO system and CL under the Unified Soil Classification System (USCS). These classifications describe a clayey soil of medium plasticity with poor subgrade performance. Table 2 summarizes the baseline geotechnical properties of the soil prior to stabilization and highlights its inadequacy for direct engineering applications.

3.3 Pozzolanic Classification of Aluminium Dross

Aluminium dross is classified as a pozzolanic material when the combined content of SiO_2, Al_2O_3, and Fe_2O_3 exceeds 70%, as specified in ASTM C618. As shown in Table 3, aluminium dross contains significant quantities of alumina (42.57%), silica (26.65%), and ferric oxide (2.38%). The combined total of these oxides is 80.29%, confirming that aluminium dross meets the criteria for pozzolanic materials.

Table 3 Chemical composition of aluminium dross

Composition	Aluminium Dross (%)
Silicon Dioxide (SiO_2)	26.652
Vanadium Oxide (V_2O_5)	0.056

Chromic Oxide (Cr_2O_3)	0.079
Manganese Monoxide (MnO)	0.237
Ferric Oxide (Fe_2O_3)	2.375
Cobalt Oxide (CoO)	0.021
Nickel Oxide (NiO)	0.013
Cupric Oxide (CuO)	0.224
Niobium (V) Oxide (Nb_2O_5)	0.005
Tungsten Trioxide (WO_3)	0.000
Phosphorus Pentoxide (P_2O_5)	0.019
Sulphur Trioxide (SO_3)	1.666
Calcium Oxide (CaO)	8.276
Magnesium Oxide (MgO)	10.622
Potassium Oxide (K_2O)	0.505
Barium Oxide (BaO)	0.303
Aluminium Oxide (Al_2O_3)	42.569
Tantalum Oxide (Ta_2O_5)	0.018
Titanium Dioxide (TiO_2)	2.153
Zinc Oxide (ZnO)	0.455
Silver (I) Oxide (Ag_2O)	0.004
Chloride (Cl)	3.613
Zirconium Dioxide (ZrO_2)	0.038
Tin (IV) Oxide (SnO_2)	0.000
Lead (II) Oxide (PbO)	0.068
Strontium Oxide (SrO)	0.027

This high pozzolanic content explains its effectiveness in soil stabilization, as the reactive oxides readily participate in secondary cementitious reactions when mixed with moisture and calcium-bearing phases.

Sum of SiO_2, Al_2O_3, and Fe_2O_3 = 20.34 + 55.131 + 4.818 = 80.289%

3.4 Classification of Sodium Silicate

Sodium silicate (water glass) is composed primarily of silica (SiO_2) and sodium oxide (Na_2O), with minor impurities (Table 4). Although not pozzolanic on its own, sodium silicate acts as a chemical activator by supplying reactive silica and creating an alkaline environment that promotes dissolution of alumino-silicate phases. This property enhances cementitious reactions when used in combination with aluminium dross and calcium-containing soils.

Table 4 Chemical composition of Sodium Silicate

Composition	Sodium silicate (%)
SiO_2 (Silica)	64.00
Na_2O (Sodium oxide)	20.00
H_2O (Water of hydration)	15.00
Fe_2O_3 (Iron oxide)	0.05
SO_4^{2-} (Sulfate)	0.10
Insoluble residue	0.40
Loss on Ignition (L.O.I)	0.45

3.5 Particle Size Distribution

The particle size distribution curve (Figure 2) shows that 59.5% of the soil particles passed the No. 200 sieve, confirming the predominance of fine particles. This high fines content accounts for the soil's low strength, high compressibility, and moisture sensitivity. Consequently, chemical stabilization is necessary to improve its engineering performance.

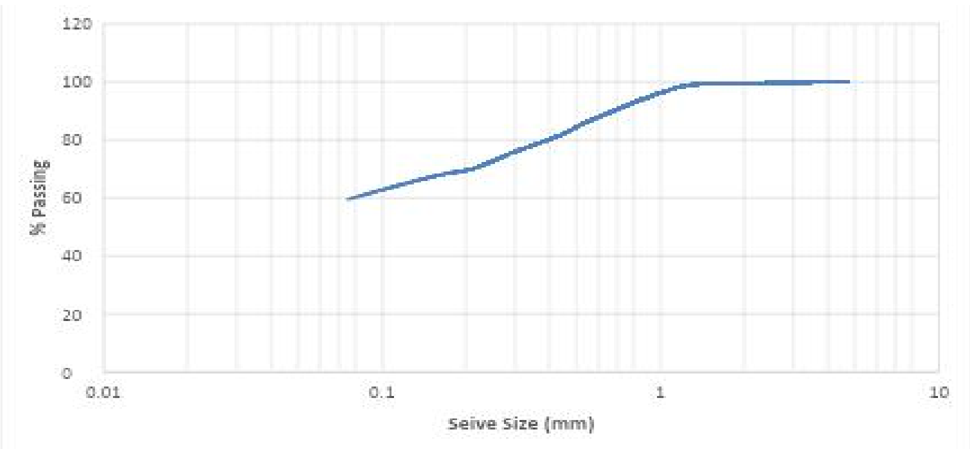

Fig. 2: Particle Size Distribution

3.6 Effect of Aluminium Dross on Compaction Characteristics

Fig.3 illustrates that OMC decreased with increasing aluminium dross content up to 7.5%, after which a slight increase was observed. The reduction indicates more efficient particle packing and reduced water demand due to void filling and improved interparticle bonding (Sharma & Sivapullaiah, 2022). At higher dross contents, the increased surface area of unreacted particles raised the water requirement, emphasizing the importance of optimum dosage (Olufemi et

al.,2021)

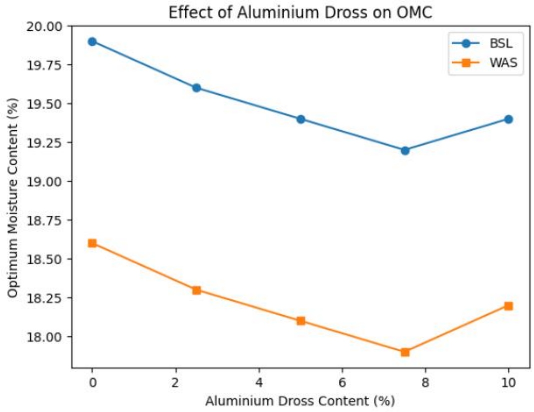

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Fig. 3: Optimum Moisture Content (OMC)

As shown in Fig. 4, MDD increased with aluminium dross content up to 7.5% for both BSL and WAS compaction energies, before declining at 10%. The increase reflects enhanced densification due to void filling and cementitious bonding, while the subsequent decrease is attributed to the lighter and less reactive fraction of excess dross disrupting soil packing (Akinropo et al., 2023).

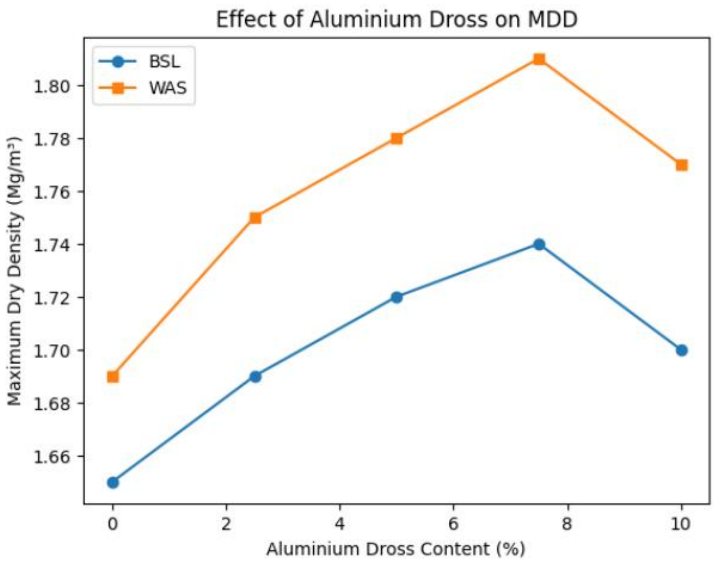

Fig 4: Maximum Dry Density (MDD)

Figure 5 shows that unsoaked CBR increased from 37.8% for natural soil to 45.9% at 7.5% aluminium dross. The improvement is attributed to void filling and the formation of cementitious products such as calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH). Beyond the optimum, excess dross acted as inert filler, reducing bonding efficiency and strength (Olufemi et al., 2021).

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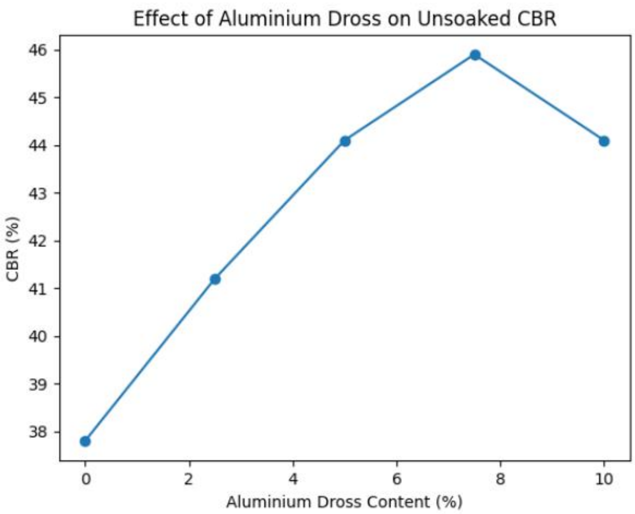

Fig 5: Unsoaked CBR

As shown in Fig. 4.6, soaked CBR improved significantly up to 7.5% aluminium dross, demonstrating enhanced resistance to moisture-induced strength loss. The reduction at 10% is attributed to unreacted dross absorbing water without contributing to strength development.

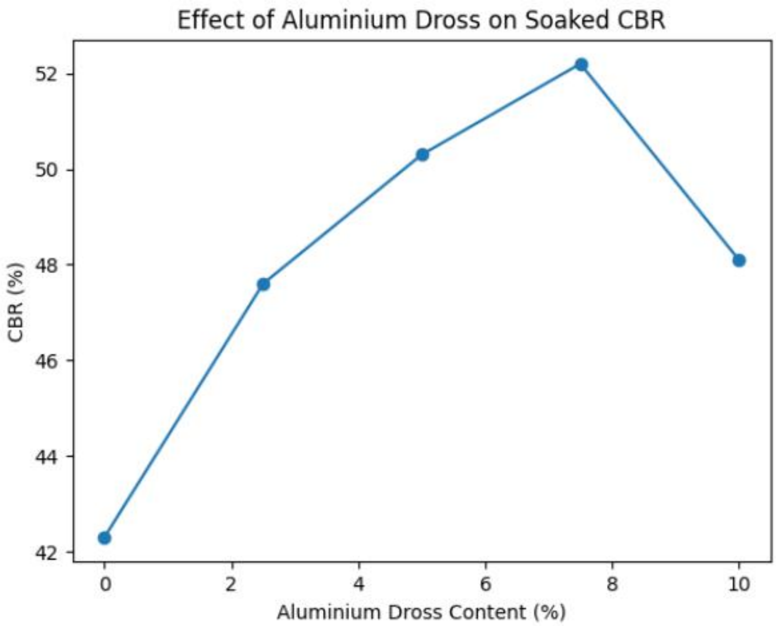

Fig 6: Soaked CBR

Binary Stabilization with Aluminium Dross and Sodium Silicate

Binary stabilization produced superior improvements compared to aluminium dross alone. The optimum performance was achieved at 7.5% sodium silicate, beyond which strength declined due to over-stabilization and excess unreacted additives.

Compaction Characteristics

Figures 4.7 and 4.8 show reduced OMC and increased MDD up to the optimum dosage, reflecting improved chemical bonding and denser particle packing due to gel formation (Liu et al., 2020).

Strength Characteristics

Unsoaked and soaked CBR values increased dramatically with binary stabilization (Figures 4.9 and 4.10), reaching peak values of 73.4% and 78.9%, respectively. Sodium silicate enhanced alkali activation, leading to the formation of sodium alumino-silicate hydrate (N-A-S-H) gels, which significantly improved strength and water resistance (Bernal & Provis, 2019; Zhang et al., 2021).

Effect on Atterberg Limits

Aluminium dross reduced soil plasticity by decreasing liquid limit and plasticity index, while binary stabilization produced even greater reductions (Figures 4.11 and 4.12). At 7.5% sodium silicate, the plasticity index reduced to 5%, indicating substantial improvement in dimensional stability. This is attributed to gel encapsulation of clay particles, suppressing swelling and shrinkage behavior (Bernal & Provis, 2019).

IV. CONCLUSION

4.1 Conclusion

This study evaluated the effects of aluminium dross and sodium silicate on the geotechnical properties of lateritic soil with the aim of developing a sustainable stabilization approach. Based on the laboratory investigations and analysis of results, the following conclusions are drawn:

1. The natural lateritic soil is classified as A-7-6 (AASHTO) and CL (USCS), characterized by high fines content, moderate plasticity, and low bearing capacity, making it unsuitable for direct use as subgrade or subbase material without stabilization.
2. Chemical and mineralogical analyses confirmed that the laterite soil is rich in silica, alumina, and iron oxides, indicating a highly weathered material with limited natural cementation but strong reactivity with stabilizing agents.
3. Aluminium dross satisfies the ASTM C618 pozzolanicity requirement, with a combined SiO_2, Al_2O_3, and Fe_2O_3 content exceeding 70%, confirming its suitability as a supplementary cementitious material.
4. Stabilization with aluminium dross alone significantly improved compaction characteristics and strength properties of the lateritic soil, with optimum performance achieved at 7.5% aluminium dross content. At this level, maximum dry density and both soaked and unsoaked CBR values increased substantially.
5. Beyond the optimum aluminium dross content, reductions in strength and compaction efficiency were observed due to over-stabilization and the presence of unreacted particles.
6. Binary stabilization using aluminium dross and sodium silicate resulted in superior geotechnical performance compared to aluminium dross alone. The combined treatment produced higher strength gains, lower plasticity index, and enhanced resistance to moisture-induced deterioration.
7. The substantial increase in soaked CBR values under binary stabilization demonstrates improved durability and water resistance, making the treated soil suitable for pavement subgrade and foundation applications.

Overall, aluminium dross activated with sodium silicate is an effective and environmentally sustainable stabilizer for lateritic soils, offering a viable alternative to conventional cement- and lime-based stabilization methods.

4.2 Recommendations

Based on the findings of this study, the following recommendations are proposed:

1. Aluminium dross content should be limited to an optimum of approximately 7.5% by dry weight of soil to achieve maximum improvement in strength and compaction characteristics.
2. The combined use of aluminium dross and sodium silicate is recommended for projects requiring enhanced strength and moisture resistance, particularly in tropical regions with high rainfall.
3. Field-scale trials should be conducted to validate laboratory findings and assess long-term performance under traffic loading and environmental exposure.
4. Durability studies such as wetting–drying and freeze–thaw cycles are recommended to

further evaluate long-term stability of the stabilized soil.

5. Environmental impact assessments, including leachability tests, should be conducted to ensure safe large-scale application of aluminium dross in soil stabilization.
6. Future studies may explore the use of other alkaline activators or blended industrial by-products to further optimize stabilization efficiency and cost.

REFERENCES

Adewumi, A. J., Akinwumi, I. I., & Olaoye, R. A. (2022). Sustainable stabilization of lateritic soil using industrial waste materials: A laboratory evaluation. *International Journal of Pavement Engineering, 23*(6), 1951–1964. https://doi.org/10.1080/10298436.2020.1835884

Afolayan, O. D., Bello, A. A., & Aladegboye, O. J. (2022). Strength improvement of tropical lateritic soils using industrial by-products. *Construction and Building Materials, 321*, 126401. https://doi.org/10.1016/j.conbuildmat.2022.126401

Akinropo, A. O., Adeyemi, G. O., & Falade, F. A. (2023). Microstructural and strength characteristics of lateritic soil stabilized with alumina-rich waste. *Journal of Materials in Civil Engineering, 35*(4), 04023028. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004657

Akinwumi, I. I., Booth, C. A., & Ajayi, L. A. (2021). Use of waste materials in soil stabilization: A review. *Journal of Cleaner Production, 315*, 128205. https://doi.org/10.1016/j.jclepro.2021.128205

Al-Bared, M. A. M., & Marto, A. (2021). Review on the geotechnical properties of chemically stabilized soils. *International Journal of GEOMATE, 20*(78), 1–12. https://doi.org/10.21660/2021.78.5197

Al-Qadiri, A. H., Al-Sharif, M., & Al-Hunaiti, A. (2018). Utilization of aluminum dross in soil stabilization. *Jordan Journal of Civil Engineering, 12*(3), 378–390.

Awoyera, P. O., & Adesina, A. (2020). Alkali-activated materials: Applications in soil stabilization. *Cleaner Engineering and Technology, 1*, 100001. https://doi.org/10.1016/j.clet.2020.100001

Bernal, S. A., & Provis, J. L. (2019). Durability of alkali-activated materials: Progress and perspectives. *Journal of the American Ceramic Society, 102*(6), 3077–3098. https://doi.org/10.1111/jace.16231

Budihal, S. V., Manjunatha, B., & Ajgaonkar, V. (2023). Mineralogical influence on stabilization of tropical soils. *Materials Today: Proceedings, 72*, 2258–2264. https://doi.org/10.1016/j.matpr.2022.12.217

Chandra, S., & Sharma, A. K. (2020). Stabilization of expansive soils using industrial wastes. *Ground Improvement, 173*(2), 97–108. https://doi.org/10.1680/jgrim.18.00031

Chen, Y., Li, Z., & Wang, L. (2024). Curing time effects on chemically stabilized soils. *Soils and Foundations, 64*(1), 101–114. https://doi.org/10.1016/j.sandf.2023.12.004

Das, B. M. (2016). *Principles of geotechnical engineering* (8th ed.). Cengage Learning.

Federal Ministry of Works and Housing. (1997). *General specifications for roads and bridges* (Vol. 2). Government Press.

Ghosh, A., Subbarao, C., & Kumar, A. (2017). Strength behavior of lateritic soil stabilized with aluminum dross. *International Journal of Geotechnical Engineering, 11*(4), 386–394. https://doi.org/10.1080/19386362.2016.1245495

Kumar, A., Walia, B. S., & Mohan, J. (2018). Compressive strength of clay stabilized using sodium silicate. *Construction and Building Materials, 165*, 447–456. https://doi.org/10.1016/j.conbuildmat.2018.01.037

Li, X., Zhang, T., & Wang, Y. (2024). Synergistic stabilization of soils using industrial by-products and alkali activators. *Construction and Building Materials, 382*, 131302. https://doi.org/10.1016/j.conbuildmat.2023.131302

Liu, Y., Shi, C., & Zhang, Z. (2020). Alkali-activated stabilization of clayey soils. *Engineering Geology, 272*, 105635. https://doi.org/10.1016/j.enggeo.2020.105635

Mitchell, J. K., & Soga, K. (2018). *Fundamentals of soil behavior* (3rd ed.). Wiley.

Minerals. (2025). Mineralogical characterization of tropical lateritic soils. *Minerals, 15*(1), 22. https://doi.org/10.3390/min15010022

Olufemi, B. A., Akinwumi, I. I., & Adebayo, A. O. (2021). Optimization of waste-based soil stabilizers. *Journal of Materials in Civil Engineering, 33*(9), 04021255. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003827

Onyelowe, K. C., Bui, Q. B., & Jalal, F. E. (2021). Clay modification mechanisms in chemically stabilized soils. *Soils and Foundations, 61*(5), 1230–1245. https://doi.org/10.1016/j.sandf.2021.08.006

Science of the Total Environment. (2024). Environmental performance of waste-derived construction materials. *Science of the Total Environment, 912*, 169014. https://doi.org/10.1016/j.scitotenv.2023.169014

Scrivener, K. L., John, V. M., & Gartner, E. M. (2018). Eco-efficient cements: Potential and challenges. *Cement and Concrete Research, 114*, 2–26. https://doi.org/10.1016/j.cemconres.2018.03.015

Shaqour, F. M. (2024). Role of iron oxides in lateritic soil behavior. *Engineering Geology, 324*, 107184. https://doi.org/10.1016/j.enggeo.2023.107184

Sharma, A. K., & Sivapullaiah, P. V. (2022). Compaction and strength behavior of stabilized soils. *International Journal of Geomechanics, 22*(5), 04022053. https://doi.org/10.1061/(ASCE)GM.1943-5622.0002326

Ulusoy, E., Yilmaz, K., & Erdem, T. K. (2019). Utilization of aluminum dross in soil stabilization. *Construction and Building Materials, 212*, 62–70. https://doi.org/10.1016/j.conbuildmat.2019.03.145

Yao, X., Zhang, Z., Zhu, H., & Chen, Y. (2020). Geopolymerization process in alkali-activated materials. *Construction and Building Materials, 244*, 118294. https://doi.org/10.1016/j.conbuildmat.2020.118294

Yarbasi, N., Kalkan, E., & Akbulut, S. (2017). Modification of clayey soils using industrial waste. *Applied Clay Science, 146*, 102–112. https://doi.org/10.1016/j.clay.2017.05.021

Zhang, T., Li, X., & Wang, Y. (2021). Alkali-activated stabilization of fine-grained soils. *Construction and Building Materials, 297*, 123754. https://doi.org/10.1016/j.conbuildmat.2021.123754

Zhang, Y., Chen, J., & Li, H. (2023). Sustainable reuse of aluminum dross in civil engineering applications. *Journal of Cleaner Production, 389*, 136064. https://doi.org/10.1016/j.jclepro.2023.136064