

Effects of Kaolin and Sodium Hydroxide on the Geotechnical Properties of Lateritic Soil¹Oluremi, J.R., ²Yusuf, A.L., ³Bamidele, O.A. and ⁴Osuolale, O.M.^{1,2,3,4} Department of Civil Engineering, Ladoké Akintola University of Technology, Ogbomosho, Oyo State.Corresponding Author's E-mail: tomlanre@gmail.com;

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Abstract

Lateritic soils in tropical regions often exhibit high plasticity and moisture sensitivity that compromise pavement performance, even where bearing capacity is otherwise adequate. This study investigated the stabilization of lateritic soil using varying proportions of kaolin (0, 7.5, 15 and 22.5%) and sodium hydroxide, NaOH (0, 0.5, 1.0 and 1.5%) across 16 treatment combinations. Material characterization by X-ray fluorescence (XRF) and X-ray diffraction (XRD) confirmed both soil and kaolin as aluminosilicate materials. Atterberg limits, compaction, and California Bearing Ratio (CBR) tests, were used to evaluate the performance of the stabilized lateritic soil,. The use of Kaolin or NaOH alone produced inconsistent CBR relative to untreated soil, but combined treatment led to improved workability and CBR of the stabilized material at 15% kaolin with 1.5% NaOH, and 7.5% kaolin with 1.0% NaOH, respectively. The admixture of kaolin-NaOH is proved to be a potential stabilizing system for lateritic subgrade improvement, but warrant further validation through replicated trials and comparison with conventional stabilizers.

Keywords: Lateritic soil; Kaolin; Sodium hydroxide; Alkali activation; Soil stabilization; California Bearing Ratio

Introduction

The performance and durability of civil engineering infrastructure are strongly influenced by the engineering properties of foundation and subgrade soils. In tropical and subtropical regions, lateritic soils are widely used in road construction and other geotechnical applications because of their abundance and accessibility (Foko Tamba *et al.*, 2023; Obianyo *et al.*, 2024). These soils are formed through intense weathering processes involving silica leaching and the accumulation of iron and aluminum oxides, which impart their characteristic reddish-brown coloration and variable engineering behavior (Kaze *et al.*, 2022). Despite their widespread utilization, many lateritic soils exhibit poor engineering properties such as high plasticity, low bearing capacity, excessive fines content, and sensitivity to moisture fluctuations (Daimary *et al.*, 2025). These deficiencies often result in pavement deformation, cracking, excessive settlement, and premature failure of road infrastructure, particularly under repeated traffic loading and seasonal wetting and drying conditions (Guimarães *et al.*, 2025).

To improve the engineering behavior of problematic soils, stabilization techniques are commonly employed. Soil stabilization involves the modification of soil properties to enhance strength, reduce compressibility, and improve durability under service conditions (Hung *et al.*, 2026). Conventional stabilizers such as cement and lime have proven effective; however, their increasing cost and environmental impact, particularly the high carbon emissions associated with cement production, have intensified the search for sustainable and economical alternatives (Manaviparast *et al.*, 2025; Yan *et al.*, 2025). The cement industry alone contributes approximately 7–8% of global CO₂ emissions, releasing about 0.8–0.9 tonnes of CO₂ per tonne of ordinary Portland cement produced, while lime production also involves energy-intensive processes contributing significantly to greenhouse gas emissions (Yan *et al.*, 2025; Sambre *et al.*, 2024).

Among the alternative materials investigated for soil stabilization, kaolin has attracted significant attention due to its abundance and aluminosilicate composition. Kaolin is a naturally occurring clay mineral composed mainly of kaolinite $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$, containing appreciable amounts of silica and alumina that can participate in pozzolanic reactions under activated conditions (Tchamo Leussa *et al.*, 2020). In the classical calcium-based pozzolanic reaction, kaolinite acts as an aluminosilicate pozzolan, reacting with calcium hydroxide to form calcium-silicate-hydrates (C–S–H) and calcium-aluminate/silicate-hydrates

(C–A–S–H), which are compounds with cementing properties (Tchamo Leussa *et al.*, 2020). This pathway depends on an external or naturally available calcium source, and is distinct from the sodium-based alkali activation examined in this study, discussed below. However, raw kaolin exhibits low pozzolanic reactivity because of its stable crystalline structure, which limits the release of reactive silica and alumina necessary for strength development (Zhu *et al.*, 2025). Consequently, untreated kaolin often produces limited improvement in soil engineering properties.

To enhance its reactivity, kaolin can be activated through thermal or chemical treatment. While thermal activation through calcination is effective, it is energy-intensive and less sustainable (Guatame-Garcia & Buxton, 2020). Chemical activation using alkaline solutions such as sodium hydroxide (NaOH) has emerged as a promising alternative. Sodium hydroxide is reported to disrupt the crystalline structure of kaolinite, increasing the dissolution of aluminosilicate phases and potentially promoting the formation of reactive species capable of participating in pozzolanic and geopolymerization reactions (Shaqour, 2024). Kaolinite has been reported to react with NaOH at low temperatures to form hydroxysodalite, a stable and hard material, through alkali-activation, which may facilitate the development of cementitious products (Shaqour, 2024). In systems activated primarily by sodium hydroxide rather than a calcium source, such reactions are generally expected to favor sodium-alumino-silicate-hydrate (N-A-S-H) gel formation over calcium-based C-A-S-H, unless sufficient calcium is otherwise available; given the low natural CaO content typical of lateritic soils, either or both gel types could plausibly contribute, and this should be regarded as a hypothesis rather than an established outcome absent direct mineralogical confirmation. Under favorable alkaline conditions, the dissolution of aluminosilicate phases may promote the development of a three-dimensional polymeric gel structure that fills matrix pores and could contribute to strength development (Zhang *et al.*, 2025), though this study relies on strength-based inference rather than post-treatment XRD, FTIR, or SEM-EDX verification of these reaction products.

Previous studies have demonstrated that activated kaolin can significantly improve the engineering performance of soils through reductions in plasticity and increases in strength characteristics. Aksu Alcan *et al.*, (2025) reported that geopolymer stabilization of kaolin clay achieved unconfined compressive strength (UCS) values up to 4.5 times higher than untreated soil, while also reducing carbon index by up to 65%, demonstrating strong sustainability benefits. Similarly, studies on the stabilization of kaolinite and montmorillonite clays using sodium hydroxide-activated fly ash and rice husk ash recorded significant enhancements in UCS, compaction, and microstructural properties (Abbasi *et al.*, 2025). Abdelbaset *et al.*, (2024) observed that adding alkaline-activated binders to low-plasticity kaolin soil resulted in decreases in optimum moisture content (OMC) while increasing maximum dry density (MDD), California bearing ratio (CBR), and UCS. Despite these promising findings, limited studies have investigated the combined influence of sodium hydroxide and kaolin on the stabilization of lateritic soils, particularly with respect to compaction characteristics and CBR, which are critical parameters in pavement design.

The optimum proportions of sodium hydroxide and kaolin required for effective stabilization under tropical conditions remain poorly defined, and the interaction between activated kaolin and the mineralogical constituents of lateritic soil is not well understood. Addressing this gap is essential for developing sustainable, locally sourced, and cost-effective stabilization techniques for highway construction in developing countries.

Materials and Method

Materials

Lateritic soil was collected from a borrow pit in the Aroje area, Ogbomoso, Nigeria, as shown in Figure 1a. A representative bulk sample was air-dried and used, without size reduction, for particle size distribution analysis to preserve the soil's natural gradation, including the coarser gravel fraction. A separate portion of the air-dried soil was pulverized and sieved through a 4.75 mm sieve to prepare the material used for

compaction, CBR, and stabilization testing, consistent with standard practice for laboratory-scale specimen preparation. Kaolin clay (Figure 1b) was sourced from Abeokuta, Ogun State, Nigeria, ground to a fine powder, and sieved through a 75 μm sieve. Anhydrous NaOH of 99.9% purity was obtained from a chemical supplier in Lagos, Nigeria. NaOH solutions were prepared by dissolving the required quantity in distilled water and were allowed to cool to ambient temperature before application.



Figure 1: Samples of (a) Lateritic Soil and (b) Kaolin

Material Characterization

The chemical and mineralogical characterization of both the lateritic soil and kaolin was conducted using X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF) in accordance with BS EN 196-2 (2025). The XRF analysis provided quantitative data on oxide composition expressed as weight percentages, while XRD analysis identified the crystalline mineral phases present in each material. The Hydration Modulus (HM) and Total Reactive Oxide Content (TROC) were derived from the XRF data using Equations 1 and 2 to assess pozzolanic suitability:

$$HM = \frac{CaO}{(SiO_2 + Al_2O_3 + Fe_2O_3)} \quad (1)$$

$$TROC = (CaO + MgO - LOI - (Na_2O + K_2O)) \quad (2)$$

Mix Design and Specimen Preparation

The experimental programme involved blending the lateritic soil with varying proportions of kaolin and sodium hydroxide. Four kaolin content levels were adopted (0%, 7.5%, 15%, and 22.5% by dry weight of soil) and four sodium hydroxide content levels (0%, 0.5%, 1.0%, and 1.5% by dry weight of soil), yielding a total of 16 treatment combinations as presented in Table 1. All proportions were calculated on the basis of the dry weight of soil in accordance with BS 1377-2 (2022).

During specimen preparation, the dry lateritic soil and the required quantity of kaolin were first combined and dry-mixed thoroughly to achieve a uniform blend. The required mass of NaOH, calculated as a percentage of the dry weight of soil for each treatment level (0%, 0.5%, 1.0%, 1.5%), was dissolved in a fixed volume of distilled water immediately before mixing and added gradually to the dry mix while stirring continuously to ensure even distribution of the alkaline activator throughout the soil-kaolin blend. NaOH dosage was controlled on a mass basis relative to dry soil weight rather than solution molarity.

Table 1: Percentage of Kaolin and NaOH Contents

NaOH (%)					
	Kaolin (%)	0	7.5	15	22.5
0		0, 0	0, 7.5	0, 15	0, 22.5
0.5		0.5, 0	0.5, 7.5	0.5, 15	0.5, 22.5
1.0		1.0, 0	1.0, 7.5	1.0, 15	1.0, 22.5
1.5		1.5, 0	1.5, 7.5	1.5, 15	1.5, 22.5

Geotechnical Tests Procedures

A comprehensive suite of geotechnical laboratory tests was conducted on natural lateritic soil and on soil specimens admixed with varying proportions of kaolin and NaOH. The tests comprised specific gravity, particle size distribution analysis, atterberg limits determination (liquid limit, plastic limit, and plasticity index), West African Standard (WAS) compaction, and CBR under both soaked and unsoaked conditions.

Specific Gravity Test

Specific gravity tests were conducted using the pycnometer method in accordance with BS 1377-2 (2022), Section 8.3. Approximately 200 g of oven-dried soil was placed in a clean, dry pycnometer and weighed. Distilled water was added to the soil sample to remove entrapped air, after which the pycnometer was filled to the calibration mark and reweighed. The pycnometer was subsequently cleaned, filled with distilled water only, and weighed again. The specific gravity of the soil was determined using Equation (3):

$$G_s = \frac{M_2 - M_1}{(M_2 - M_1) - (M_3 - M_4)} \quad (3)$$

Where M_1 = mass of empty pycnometer, M_2 = mass of pycnometer with dry soil, M_3 = mass of pycnometer with soil and water, M_4 = mass of pycnometer filled with water only, and G_s = specific gravity of soil.

Particle Size Distribution

Particle size distribution analysis was carried out by wet sieving and mechanical sieve analysis in accordance with BS 1377-2 (2022), Section 9.2. Approximately 500 g of the representative, as-received soil sample (prior to any size reduction) was first wet-washed through a 75 μ m sieve to separate the fine fraction from the coarser particles. Washing was continued until the wash water became clear, indicating complete removal of fines adhering to the coarse particles. The material retained on the 75 μ m sieve was oven-dried at 105°C for 24 h and subsequently subjected to mechanical sieve analysis. The dried sample was arranged in a stack of British Standard sieves in descending order of aperture sizes: 20 mm, 8 mm, 4 mm, 2 mm, 1 mm, 0.425 mm, 0.250 mm, 0.125 mm, and 0.075 mm, with a receiving pan placed beneath the sieve stack. The assembly was mounted on a mechanical sieve shaker and operated for 5 min to ensure adequate particle separation. After sieving, the mass retained on each sieve was measured and recorded. The cumulative percentage retained and percentage passing were then calculated for each sieve size. The particle size distribution curves were plotted on a semi-logarithmic graph of percentage passing against sieve size to evaluate the gradation characteristics of the natural and stabilized soil samples.

Atterberg Limits

Atterberg limit tests were conducted in accordance with BS 1377-2 (2022), Section 5, to evaluate the plasticity characteristics of the natural and stabilized soil samples. The liquid limit (LL) was determined using the Casagrande percussion cup method on soil passing the 425 μ m sieve. Soil paste prepared with distilled water was placed in the Casagrande cup, grooved, and subjected to repeated blows until the groove closed over a distance of 13 mm. The moisture content corresponding to 25 blows obtained from the flow

curve was taken as the liquid limit. The plastic limit (PL) was determined by rolling a portion of the soil paste into threads on a glass plate until a diameter of 3 mm was reached and cracking occurred. The corresponding moisture content was recorded as the plastic limit. The plasticity index (PI) was calculated as the difference between the liquid limit and plastic limit using Equation (4):

$$PI = LL - PL \quad (4)$$

Compaction Test

Compaction tests were performed to determine the MDD and OMC of the natural and stabilized soil mixtures. The compaction procedure was conducted in accordance with BS 1377 (2022), Part 4, Section 3.6. For the WAS compaction, each soil specimen was compacted in a 1000 cm³ cylindrical BS mould in five equal layers. Each layer received 10 blows from a 4.5 kg rammer dropped from a height of 450 mm, delivering a compactive effort of 1.35 kJ/m³ per blow per unit volume. Following compaction, the excess soil above the collar was trimmed level with the top of the mould using a straight-edge. The gross mass of the mould and compacted specimen was recorded, and a representative sub-sample was extracted from the centre of the specimen for moisture content determination. The bulk density and dry density were then calculated for each compaction point, and the data were plotted to obtain the compaction curve. The MDD and OMC were read directly from the peak of the compaction curve. A minimum of five compaction points, at progressively increasing moisture contents, were obtained for each mixture to define the full shape of the curve.

California Bearing Ratio Test

CBR tests were conducted under both unsoaked and soaked conditions to assess the bearing capacity and moisture susceptibility of the stabilized soil mixtures. The test, carried out in accordance with BS 1377 (2022), Part 4, Section 7, measures the penetration resistance of compacted soil relative to a standard crushed-rock material and is widely used in flexible pavement design. For the unsoaked condition, specimens were compacted at their respective OMC and MDD in standard CBR moulds using a heavier compactive effort than the standard WAS procedure (five layers, 27 blows per layer with a 4.5 kg rammer dropped from 450 mm), applied to better replicate field densification of pavement subgrade material. Immediately after compaction, a surcharge load was applied, and the sample was tested in the CBR machine at a constant penetration rate of 1.27 mm/min using a 50 mm diameter piston. Load readings were taken at standard penetration intervals up to 10 mm. CBR values were calculated at 2.5 mm and 5.0 mm penetrations relative to standard loads (13.24 kN and 19.96 kN), with the higher value adopted. For the soaked condition, identical specimens were submerged in water for 72 hours under surcharge loading, then drained for 15 minutes before testing using the same procedure. Soaked CBR values were used to represent worst-case field moisture conditions. The procedure was repeated for all 16 stabilizer combinations.

Statistical Analysis

A two-way Analysis of Variance (ANOVA) without replication was conducted to evaluate the statistical significance of kaolin content and NaOH concentration as independent factors on six key geotechnical response variables: liquid limit, plastic limit, plasticity index, maximum dry density, optimum moisture content, and California bearing ratio. The analysis was performed at a 95% confidence level ($\alpha = 0.05$). The critical F-value (F_{crit}) was determined from the F-distribution table at degrees of freedom $df_{treatment} = 3$ and $df_{error} = 9$, yielding $F_{crit} = 3.863$. A computed F-statistic exceeding this threshold indicates that the respective factor has a statistically significant effect on the response variable at the 5% significance level.

Results and Discussion

Material Characterization

XRD analysis of the lateritic soil confirmed the presence of quartz (SiO₂), kaolinite (Al₂Si₂O₅(OH)₄), goethite (α -FeOOH), and hematite (α -Fe₂O₃) as the dominant mineral phases, characteristic of tropical

lateritic soils formed under intense weathering conditions, as shown in Figure 2a. The XRD pattern of kaolin showed well-crystallized kaolinite as the principal phase, with minor quartz impurities and trace iron oxide phases as illustrated in Figure 2b.

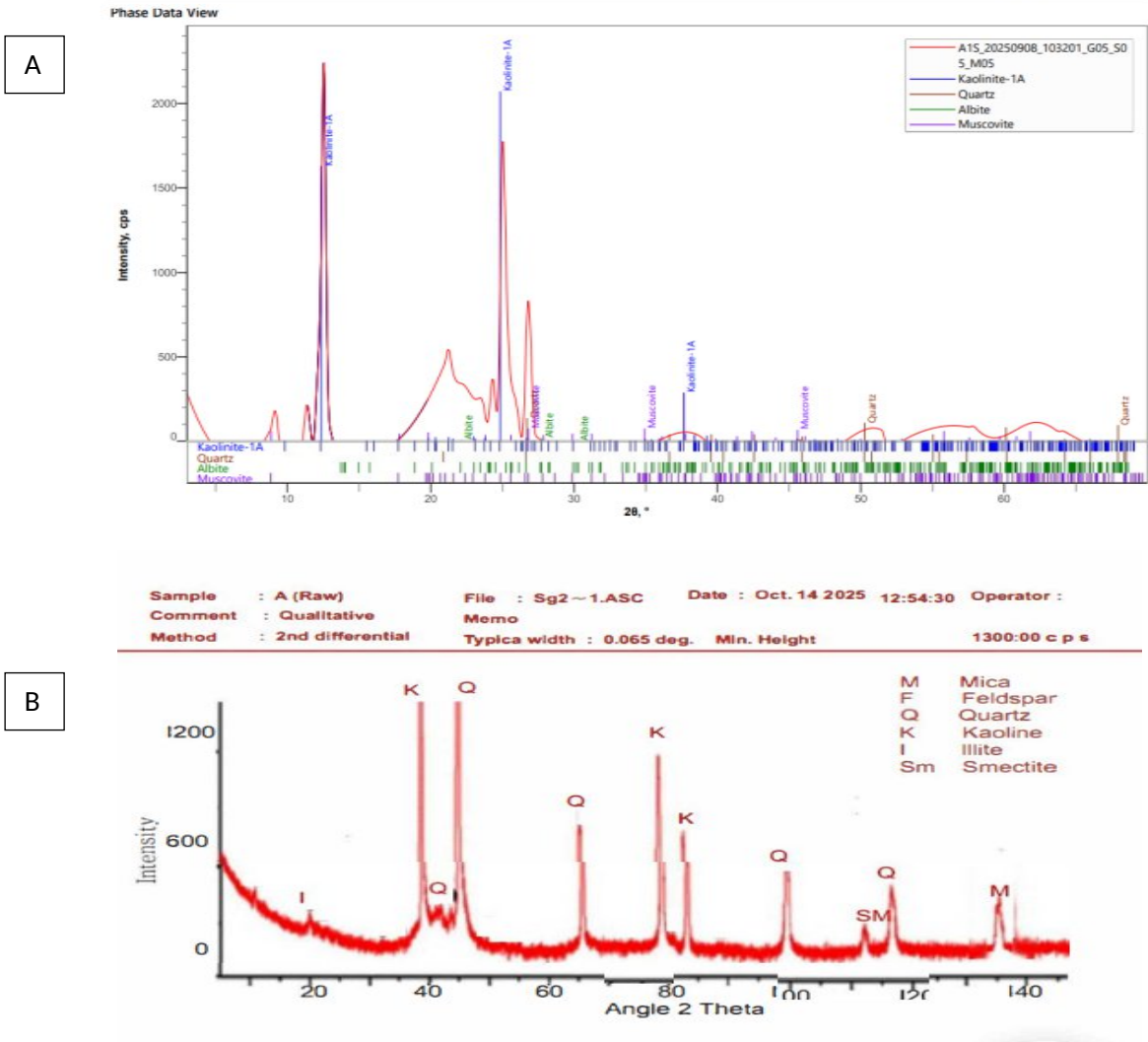


Figure 2: XRD Result of (a) Lateritic Soil and (b) Kaolin

The XRF results, summarized in Table 2, show that both materials are aluminosilicates. The lateritic soil is dominated by SiO_2 (42.48%), Fe_2O_3 (26.18%), and Al_2O_3 (22.61%), while the kaolin contains SiO_2 (43.72%), Fe_2O_3 (20.59%), and Al_2O_3 (24.82%). The combined $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ content of 89.13% for kaolin satisfies the ASTM C618 (2019) minimum oxide-sum threshold of 70% specified for pozzolanic materials in concrete applications. This oxide criterion alone does not demonstrate pozzolanic reactivity, alkali-activation behavior, or geopolymer formation in a soil-stabilization context; it is reported here only as an indicator that the bulk chemistry is consistent with established pozzolan criteria, with actual reactivity assessed through the geotechnical performance tests described below. The low CaO content (0.70%) in both materials underscores the importance of the NaOH activator in potentially initiating alkali-activation reactions in the absence of naturally available calcium.

Table 2: Chemical Composition of the Lateritic Soil and Kaolin Clay

Components	Concentration (%)	
	Lateritic Soil	Kaolin Clay
SiO ₂	42.476	43.716
V ₂ O ₅	0.088	0.098
Cr ₂ O ₃	-	-
MnO	0.110	-
Fe ₂ O ₃	26.180	20.593
NiO	-	-
Co ₃ O ₄	0.113	0.113
CuO	0.052	0.052
Nb ₂ O ₃	0.018	0.018
WO ₃	0.005	0.005
P ₂ O ₅	-	-
SO ₃	0.851	0.851
CaO	0.702	0.702
MgO	1.072	0.964
K ₂ O	0.640	0.650
Al ₂ O ₃	22.611	24.818
Ta ₂ O ₅	0.014	0.011
TiO ₂	0.731	0.731
ZnO	0.034	0.031
Ag ₂ O	0.000	-
Cl	0.626	0.626
ZrO ₂	0.438	0.438

Specific Gravity

The specific gravity of the lateritic soil and NaOH were 2.69 and 2.12, respectively (Figure 3). The value of 2.69 for the lateritic soil is consistent with published ranges for tropical lateritic soils (2.60–2.80) and reflects the composite contribution of quartz, kaolinite, and iron oxide minerals (Ishola *et al.*, 2023). The lower specific gravity of NaOH (2.12) means its addition at dosages of 0.5–1.5% has a negligible effect on the bulk specific gravity of the treated mixtures, though it contributes to modest reductions in maximum dry density observed at higher dosage levels.

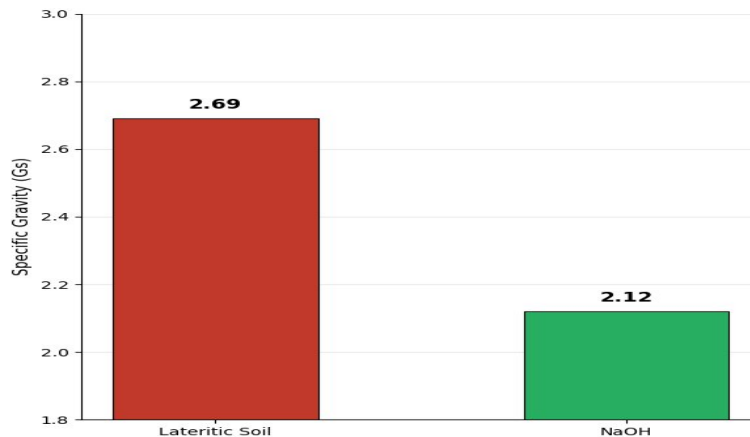


Figure 3: Specific Gravity of Lateritic Soil and NaOH

Particle Size Distribution

The particle size distribution of the natural lateritic soil is presented in Figure 4. The gradation curve reveals a coarse-dominated soil with approximately 46% gravel (>4.75 mm), 30% sand (0.075–4.75 mm), and 23% fines (<0.075 mm). The high gravel content, combined with a continuous gradation from 20 mm down to

the fines fraction, indicates a well-graded material with good particle interlocking potential. Since more than 50% of the material is retained on the 0.075 mm sieve, this soil is coarse-grained by USCS convention; classification symbols such as CL or ML, discussed later in relation to the Atterberg limits, refer to the plasticity character of the fines fraction rather than a whole-soil group symbol, which would instead be gravel- or sand-based (e.g., GC, GM, SC, or SM depending on the fines' plasticity and the gradation parameters of the coarse fraction). The relatively low fines content (23.2% passing the 0.075 mm sieve) falls within the Nigerian Federal Ministry of Works and Housing (FMWH, 1997) regulatory limit of 35% for road construction materials. This fines criterion alone does not establish overall pavement-layer suitability, which also depends on plasticity, CBR, and other layer-specific requirements evaluated elsewhere in this study.

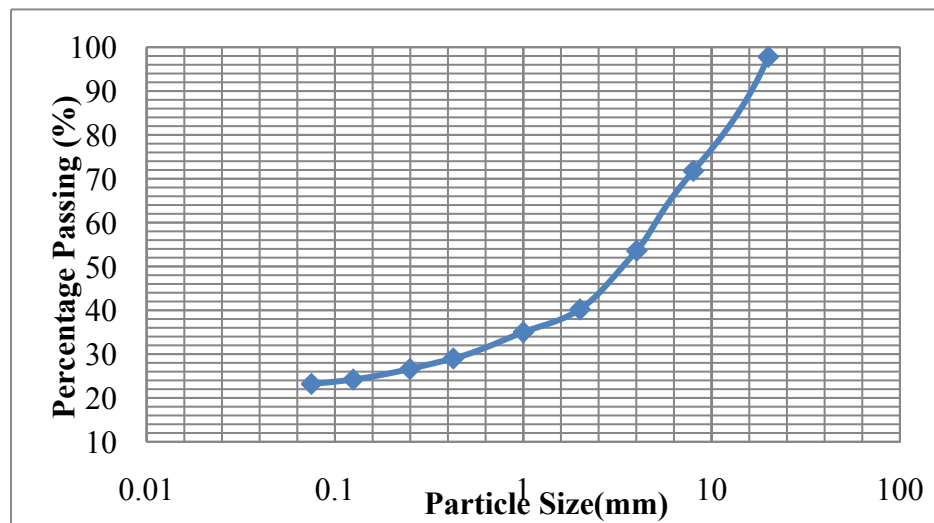


Figure 4: Particle Size Analysis of the Soil Sample

Atterberg Limits

Liquid Limit: Addition of kaolin without NaOH increased the LL progressively (42–50% at 7.5–22.5% kaolin), reflecting the water-absorbing capacity of the additional fines. NaOH addition alone reduced LL modestly (to ~40% at 0.5% NaOH) due to flocculation of clay particles and compression of the diffuse double layer under high pH. In combined treatments, the two effects partially offset each other, with the NaOH-induced flocculation restraining the plasticity increase caused by kaolin additions.

Plastic Limit: The PL increased consistently with NaOH content, rising from 18% (untreated) to approximately 30% at 15% kaolin + 1.5% NaOH as shown in Figure 5. This increase is consistent with flocculation and particle rearrangement under high pH; an early cementitious bonding contribution is plausible but not directly evidenced by the Atterberg data alone, and would require microstructural confirmation. The plastic limit increase was proportionally greater than the liquid limit changes, driving net reductions in PI.

Plasticity Index: PI decreased systematically with increasing NaOH content and showed a non-linear relationship with kaolin content, with minimum values occurring at 15% kaolin. At 15% kaolin + 1.5% NaOH, the PI reached a minimum of 12%, representing a 50% reduction from the untreated value of 24%. This shifted the fine fraction's plasticity from low-plasticity clay-like (CL-range) toward low-plasticity silt-like (ML-range) behavior on the Casagrande chart, indicating substantially improved workability and reduced moisture sensitivity. The minimum PI occurred at 15% kaolin among the four levels tested, with both adjacent levels (7.5% and 22.5%) producing higher PI, indicating an optimum at or near 15% kaolin combined with 1.0–1.5% NaOH, though the discrete four-level design cannot resolve a precise optimal range. Kaolin additions beyond 22.5% reversed the trend by introducing excess fines that overwhelmed the

chemical bonding effects. Comparable PI reductions driven by alkali-activated pozzolanic systems have been reported by Oluremi *et al.* (2026), who observed PI decreasing from 13% in untreated lateritic soil to as low as 1.75% with rice husk ash and sodium carbonate, confirming that cation exchange, flocculation, and cementitious bonding under alkaline activation consistently reduce plasticity index in kaolinitic lateritic soils regardless of the specific pozzolan employed.

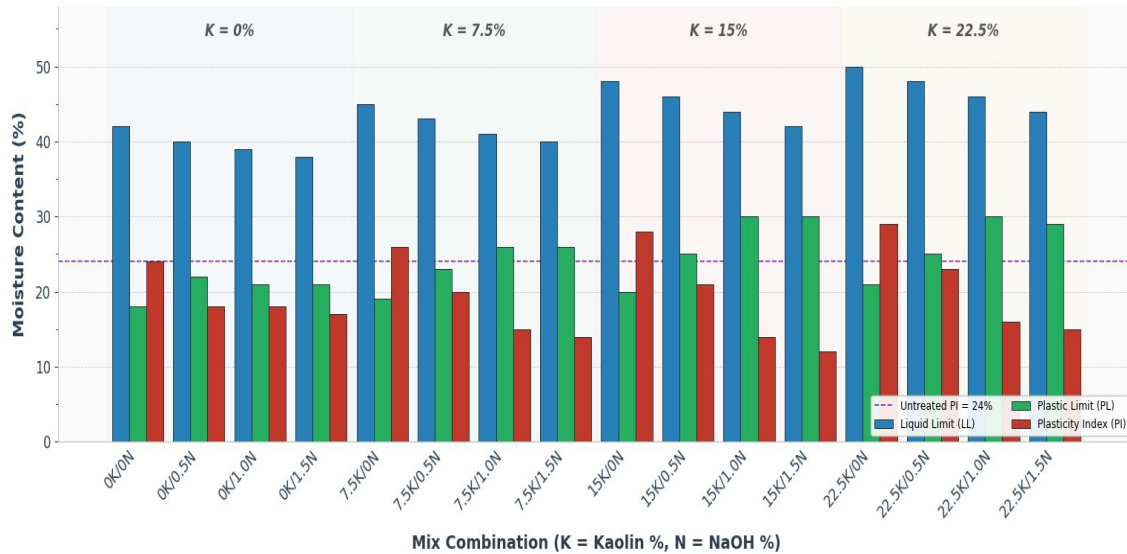


Figure 5: Effect of Kaolin and NaOH on the Atterberg Limits of Lateritic Soil

Compaction Characteristics

Maximum Dry Density: MDD did not follow a single monotonic trend but varied non-uniformly across the kaolin-NaOH matrix, as illustrated in Figure 6. At 0% NaOH, kaolin additions produced 1.99, 2.04, 1.89, and 1.90 Mg/m³ at 0%, 7.5%, 15%, and 22.5% kaolin respectively, a slight rise at 7.5% kaolin before declining at higher dosages. NaOH addition showed a similarly mixed pattern across kaolin levels, with combined values ranging between 1.84 and 1.97 Mg/m³. The lowest MDD recorded across the full matrix, 1.84 Mg/m³, occurred at 15% kaolin + 1.5% NaOH, an 8% reduction from the untreated baseline of 1.99 Mg/m³, attributable to the lower specific gravity of kaolin relative to iron-rich lateritic minerals and to the modified particle packing from increased fines. Despite these reductions, the CBR gains observed at the optimal combinations (discussed below) far outweigh the density decreases, consistent with findings by Liang *et al.* (2025) that chemically bonded soils at 90–95% of untreated MDD can achieve bearing capacities 200–400% higher than untreated compacted soils. This trend is corroborated by Alasinrin *et al.* (2026), who observed that additive-induced increases in porosity and water demand reduced compaction density beyond optimal dosage levels in cement and e-waste stabilized lateritic soil, confirming that MDD reduction is a consistent compaction response across diverse two-component stabilization systems.

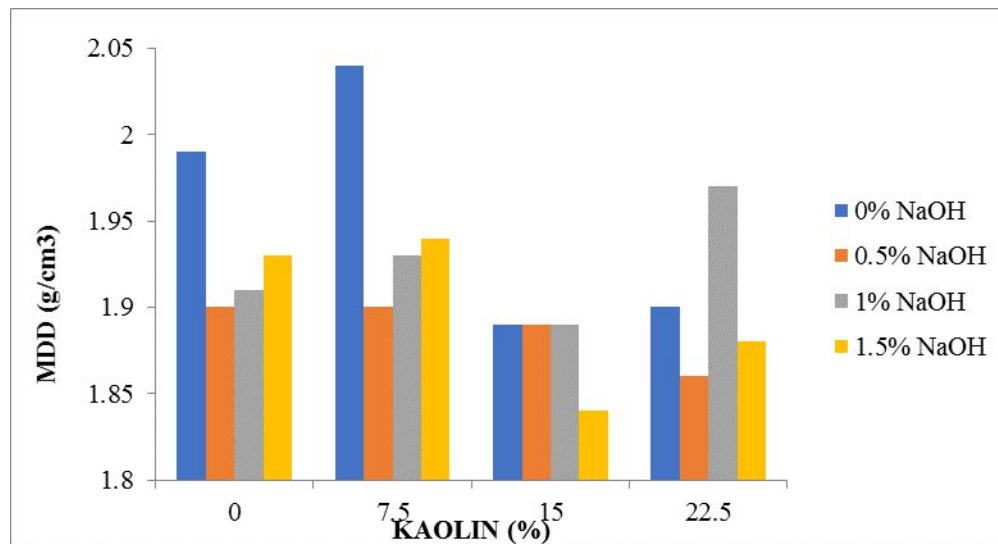


Figure 6: Effect of Kaolin and NaOH on Maximum Dry Density of Lateritic Soil

Optimum Moisture Content: OMC likewise showed a non-uniform response rather than a clean progressive increase, as shown in Figure 7. At 0% NaOH, OMC values were 13.09%, 10.64%, 14.4%, and 13.26% at 0%, 7.5%, 15%, and 22.5% kaolin, a dip at 7.5% kaolin before rising again. NaOH addition raised OMC more consistently, particularly at 1.0% NaOH, where values reached 17.66%, 17.5%, 15.3%, and 16.36% across the kaolin range; the overall maximum of 17.66% occurred at 0% kaolin + 1.0% NaOH rather than at the highest combined dosage. This is consistent with water being consumed in NaOH hydration and early pozzolanic reactions, though the absence of a smooth dosage-dependent trend suggests some sensitivity to mixing or curing conditions that replicated testing could help clarify. These increases have practical construction implications, as moisture conditioning will be required on site to achieve effective compaction.

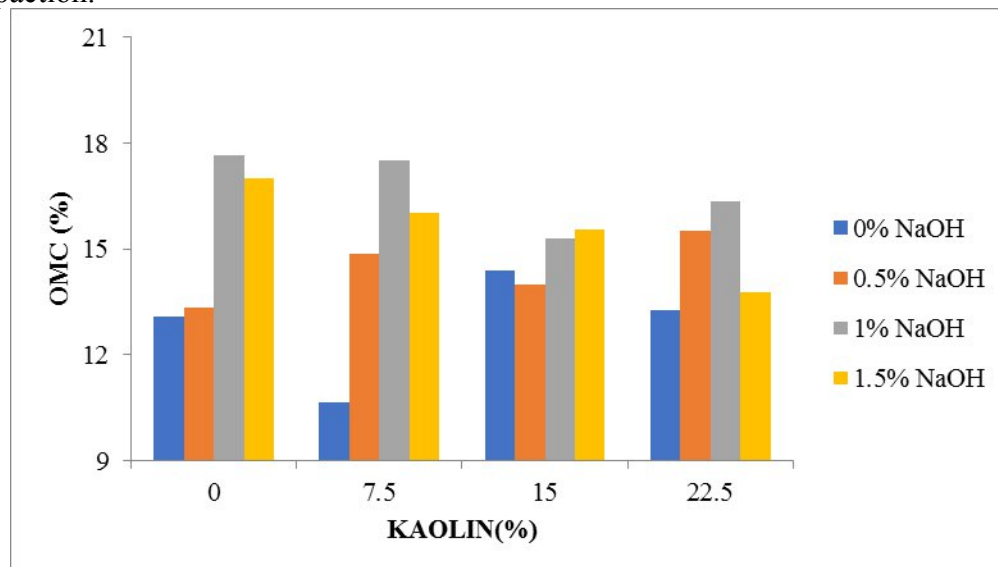


Figure 7: Effect of Kaolin and NaOH on Optimum Moisture Content of Lateritic Soil

California Bearing Ratio

The CBR results are presented in Figure 8. The untreated soil exhibited a naturally high CBR of 75%, attributable to its well-graded gradation, substantial gravel content (46%), and natural iron oxide cementation, consistent with lateritic soils reported to achieve CBR values of 50–100% without treatment

(Nagaraju *et al.*, 2023). Kaolin alone (0% NaOH) reduced CBR at every tested dosage: 38%, 41%, and 21% at 7.5%, 15%, and 22.5% kaolin, indicating that untreated kaolin dilutes the soil's natural cementation without contributing pozzolanic bonding of its own, consistent with Verma *et al.* (2021), who noted that raw kaolin additions above 10% reduce CBR unless combined with an activator. NaOH alone (0% kaolin) showed a different pattern: 88%, 52%, and 44% at 0.5%, 1.0%, and 1.5% NaOH, a brief improvement at low dosage followed by a decline, consistent with an initial flocculating effect that is not sustained as alkalinity increases. The combination of kaolin and NaOH in appropriate proportions produced the strongest gains in the dataset. At 7.5% kaolin + 1.0% NaOH, CBR reached 89%, a 134% improvement over 7.5% kaolin alone and 19% above untreated soil. At 22.5% kaolin + 1.0% NaOH, CBR reached 87%, a 314% improvement over 22.5% kaolin alone and 16% above untreated soil. At 15% kaolin + 1.5% NaOH, CBR reached 86%, a 110% improvement over 15% kaolin alone and 15% above untreated soil. These results demonstrate that balanced proportions of reactive aluminosilicate (kaolin) and alkaline activator (NaOH) are essential: neither component alone is sufficient, and properly activated combinations produce strength gains consistent with C-A-S-H and N-A-S-H gel bonding, the mechanism generally proposed for alkali-activated aluminosilicate stabilization. This study did not include post-treatment mineralogical analysis (e.g., XRD or SEM on cured specimens), so gel formation is inferred from strength behavior rather than directly confirmed; this is identified as a priority for follow-up work.

The three optimal combinations identified; 7.5% kaolin + 1.0% NaOH (CBR = 89%), 22.5% kaolin + 1.0% NaOH (CBR = 87%), and 15% kaolin + 1.5% NaOH (CBR = 86%) all exceed the minimum CBR of 30% required for heavy-traffic subgrades (Liang *et al.*, 2025) and approach values qualifying for subbase applications in lower-volume roads. The high variability across the 4×4 combination matrix (CV ≈ 51.5%) reflects the spread among treatment means rather than replicate-based experimental error, since each treatment combination was tested once; it should therefore be read as a description of how strongly CBR responds to proportioning, not as a measure of test repeatability. It underscores the sensitivity of the system to proportioning, emphasizing the need for rigorous quality control during construction, and for replicated testing to establish a true within-treatment error estimate.

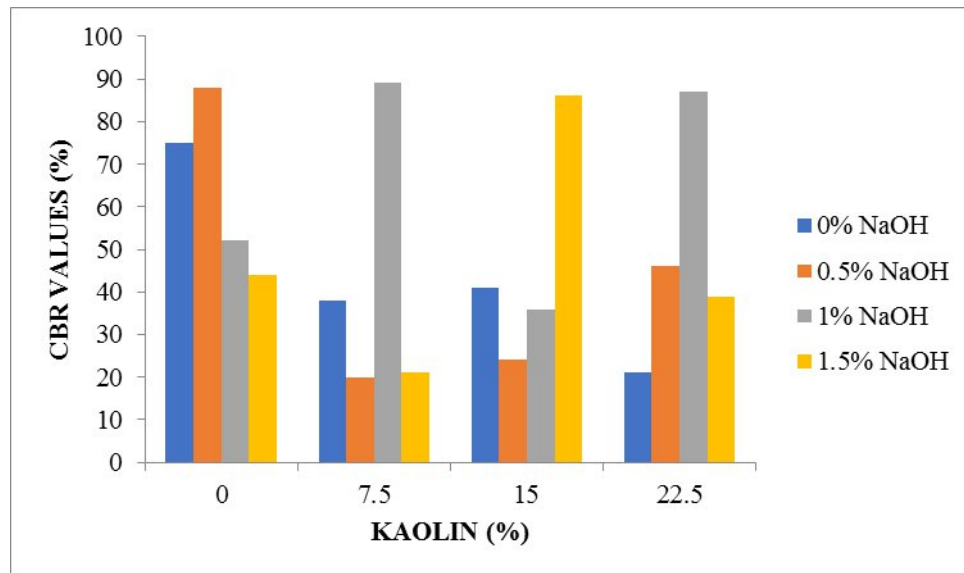


Figure 8: Effect of Kaolin and NaOH on the California Bearing Ratio of Lateritic Soil

Statistical Analysis (ANOVA)

The statistical analysis revealed that kaolin content was the sole statistically significant individual factor governing the system, specifically controlling the PI and OMC ($F = 5.258$, $p = 0.023$ for both), which is attributable to the high water demand and physical dominance of the fine kaolin fractions as depicted in Figure 9. Conversely, neither additive exerted a significant standalone effect on the LL, PL, or MDD,

reflecting opposing mechanisms that effectively cancel out when factor levels are averaged. Furthermore, the main effects of both kaolin ($F = 0.464$, $p = 0.714$) and NaOH ($F = 0.522$, $p = 0.678$) were non-significant for the CBR. Because the design was unreplicated, the residual term used to construct these F-statistics is confounded with any interaction between kaolin and NaOH, so non-significant main effects alone cannot be used to infer a synergistic interaction.

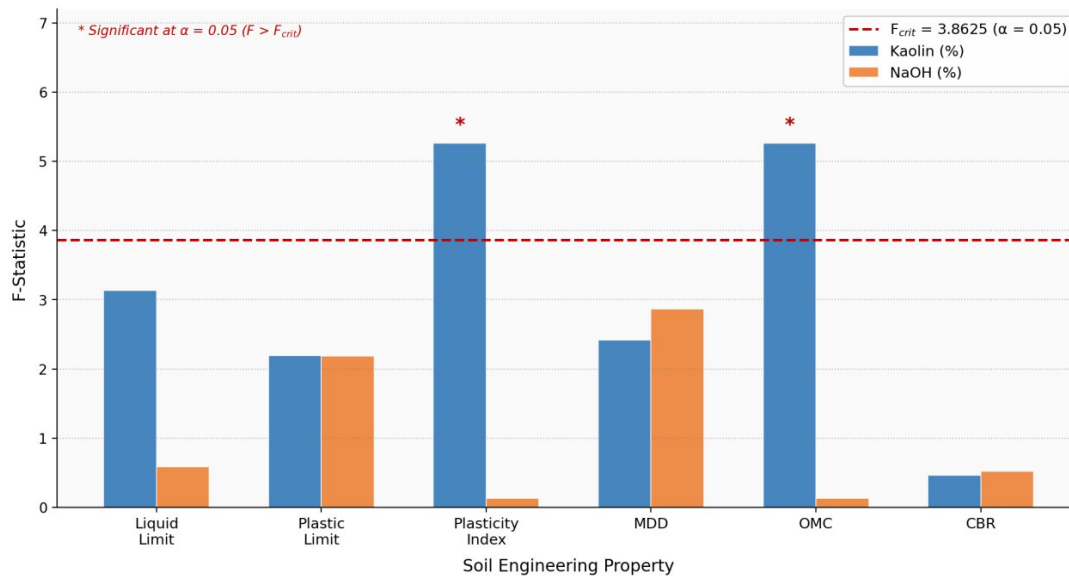


Figure 9: Two-Way ANOVA F-Statistics for the Effects of Kaolin (%) and NaOH (%) on Soil

Engineering Properties (main effects only; $F_{crit} = 3.863$; * denotes significant effect at $\alpha = 0.05$). To probe this further, Tukey's one-degree-of-freedom test for non-additivity was applied to the CBR matrix, isolating a single interaction-shaped component from the residual. This yielded $F(1,8) = 3.08$, $p = 0.117$, a pattern suggestive of non-additive (interactive) behavior between kaolin and NaOH, but not statistically significant at $\alpha = 0.05$. The observed strength gains at specific kaolin-NaOH combinations are therefore best interpreted as an empirically identified pattern rather than a statistically confirmed interaction effect; replicated trials at the optimal combinations would be needed to test this formally. This overarching pattern, where plasticity and moisture parameters show distinct sensitivity to the primary stabilizer while compaction and independent strength metrics remain statistically muted, closely mirrors the stabilization dynamics reported by Adedokun *et al.* (2022) and Oluremi *et al.* (2026), reinforcing the requirement that both constituents must be proportioned jointly to optimize geotechnical performance.

Conclusions

Based on the geotechnical characterization and stabilization performance of lateritic soil admixed with kaolin and sodium hydroxide, the following conclusions are drawn:

1. XRF and XRD analyses confirmed that both the lateritic soil and kaolin are aluminosilicate materials suitable for pozzolanic and geopolymeric reactions, with kaolin's reactive oxide content (89.13%) exceeding the ASTM C618 threshold for pozzolans, while the low natural CaO content in both materials confirmed the necessity of NaOH as an external alkaline activator. This characterization was performed on untreated raw materials only.
2. Kaolin and NaOH, applied individually, did not consistently improve soil performance, but their combination at 15% kaolin and 1.0-1.5% NaOH cut PI by 50% (24% to 12%), shifting the fines' plasticity character toward the low-plasticity silt range.
3. The combined kaolin-NaOH treatment produced strength gains consistent with C-A-S-H and N-A-S-H gel formation, though this mechanism was inferred from CBR behavior rather than confirmed by

post-treatment mineralogical analysis, with three optimal combinations; 7.5% kaolin + 1.0% NaOH (CBR = 89%), 22.5% kaolin + 1.0% NaOH (CBR = 87%), and 15% kaolin + 1.5% NaOH (CBR = 86%), all exceeding the minimum CBR requirement for heavy-traffic subgrades, despite modest reductions in MDD.

4. ANOVA confirmed kaolin as the dominant factor for plasticity and moisture properties. CBR gains at specific kaolin-NaOH combinations were not attributable to either factor's main effect, and a supplementary non-additivity test found a suggestive but non-significant interaction pattern ($p = 0.117$), underscoring the need for replicated trials to formally establish the mechanism behind joint proportioning.

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