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Clay-Modified Laterite Soil as Low-Hydraulic Conductivity Liner Material for Tailings Dam Construction

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ABSTRACT

The economic hardship in many developing countries, coupled with rising global demand for gold, has led to a significant increase in small-scale gold mining activities. Tailings dams are commonly used to store mining waste; however, conventional geomembrane liners, though effective, are often too expensive for small-scale operations. The increasing volume of tailings generated poses a growing risk of groundwater contamination, necessitating cost-effective and reliable alternatives. This study evaluates the suitability of clay-modified laterite soils as an economical liner material for tailings dams. Natural clay, laterite, and their blends were characterised through physical, hydraulic, chemical, and mineralogical tests. Results indicate that increasing clay content enhances fine fraction and plasticity while reducing maximum dry density. The hydraulic conductivity of laterite–clay blends established practical design thresholds (30–40% clay content) required to meet international liner requirements ($\leq 1 \times 10^{-9}$ m/s), depending on the particle gradation of the laterite soil. An empirical model developed to predict hydraulic conductivity from basic soil properties achieved a root-mean-square error of about 0.8, demonstrating good predictive capability. This study introduces a predictive framework and establishes optimal blending thresholds for clay-laterite liners tailored to artisanal mining applications.

Keywords: *Laterite; Clay liners; Tailings dam; hydraulic conductivity; Fractal dimension.*

1. Introduction

Mine tailings are fine-grained waste generated during the crushing and grinding of mineral ores for metal extraction. They constitute the largest volume of waste produced by the mining industry and are typically stored on-site in engineered containment facilities [1-2]. In 2010, global tailings production was estimated to exceed 14 billion tonnes, a figure expected to rise significantly as mining increasingly targets lower-grade ores due to the depletion of high-grade deposits. Exploiting low-grade ores inherently generates greater volumes of tailings per unit of recovered metal, intensifying environmental and management challenges [2].

Gold-bearing ores are commonly associated with sulphide minerals, including pyrite (FeS_2), sphalerite (ZnS), galena (PbS), arsenopyrite (FeAsS), and chalcopyrite ($CuFeS_2$). These sulphide phases often serve as the primary hosts for gold. A study by Wang *et al.* [3] on a gold deposit in the North-Western Province of Zambia reported that gold is predominantly finely disseminated within sulphide minerals, particularly pyrite and arsenopyrite. This mode of mineralisation has serious implications for sulphide oxidation and the potential generation of acid mine drainage (AMD) [1].

Heavy metals such as lead, arsenic, chromium, copper, and mercury occur naturally in mineralised rocks. However, mining activities enhance their mobility by increasing reactive surface areas and altering geochemical conditions [4]. The use of mercury and cyanide during gold extraction

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further exacerbates contamination risks, particularly in artisanal and small-scale mining operations. Acidic conditions associated with AMD increase metal solubility, facilitating their transport in tailings effluents, leading to widespread environmental and human health impacts.

Exposure to heavy metals originating from tailings has been linked to severe health effects, including kidney dysfunction, neurological impairment, and developmental disorders [5]. Contaminants released from tailings impoundments can enter food chains through soil–plant uptake, posing long-term risks to food security and public health. A notable example is the Minamata disaster of the mid-1950s in Japan, where mercury-contaminated industrial effluent discharged into Minamata Bay led to widespread poisoning, causing approximately two thousand deaths and leaving many survivors with permanent disabilities [6-7].

To mitigate environmental risks, tailings are typically stored in engineered containment facilities such as tailings dams. Regulatory frameworks mandate that these structures incorporate low-permeability liner systems to prevent the migration of contaminants into surrounding soils, surface water, and groundwater [8-9]. In sub-Saharan Africa, inadequate tailings management remains a critical concern, particularly in small-scale gold mining. Studies in southern Ghana have reported widespread absence of engineered tailings containment systems, resulting in direct discharge of untreated tailings effluents into surrounding soils and water bodies [10-11]. Duncan [12] investigated the concentrations of heavy metals in the Fena River within a small-scale mining community in Ghana and reported levels exceeding acceptable environmental and health safety thresholds. Similar conditions have been reported at small-scale mining sites in Zambia, where poor tailings containment has contributed to soil and crop contamination [13]. It has also been reported that maize cultivated in the Kabwe mining area contained lead concentrations far exceeding the FAO/WHO permissible limit for food crops [14].

Common liner materials include synthetic liners such as high-density polyethylene (HDPE) and geosynthetic clay liners (GCLs), as well as mineral liners comprising compacted clay or concrete. While synthetic liners provide excellent hydraulic performance, their high material costs often render them impractical for artisanal and small-scale mining operations, particularly in developing countries [9, 15]. Consequently, increasing attention has been directed toward the use of compacted natural soils and chemically modified soils as cost-effective alternatives for tailings containment [9, 16, 17].

Lateritic soils are tropical residual soils formed through prolonged chemical weathering and silica leaching under high-rainfall conditions, resulting in enrichment of iron and aluminium oxides. These soils are widespread in semi-humid and equatorial regions and exhibit highly variable particle-size distributions, ranging from gravel and sand to silt and clay fractions [18-19]. Clay soils, on the other hand, are typically derived from the chemical weathering of igneous, metamorphic, and sedimentary rocks and are found globally, with extensive deposits reported in Africa, Asia, and North America [20-21].

For use as liner materials, compacted soils must exhibit very low hydraulic conductivity. Regulatory guidelines generally specify a maximum hydraulic conductivity of 1×10^{-9}m/s or lower and require minimum clay content, fines percentage, plasticity, and grading characteristics [8, 22]. The hydraulic conductivity of compacted soil liners is influenced by multiple factors, including mineralogical composition, compaction effort, moisture content, particle size distribution, degree of saturation, and the properties of the permeating fluid [23-24].

Clay mineralogy plays a critical role in governing the hydraulic performance of compacted liners. Expansive clay minerals such as montmorillonite have high specific surface area and swelling potential, which reduce pore connectivity and result in very low permeability when hydrated [23]. In contrast, kaolinitic soils tend to form aggregated structures with larger interconnected pores, leading to higher hydraulic conductivity under similar compaction conditions [25]. In contrast, most laterite soils often fail to meet the hydraulic conductivity regulatory requirement because of low clay activity and a dominance of non-expansive minerals [26].

The use of bentonite–laterite blends has been widely reported as an effective means of enhancing liner performance. Bentonite addition introduces montmorillonite-rich clay that swells upon hydration and forms a dense, dispersed microstructure that blocks pore channels and significantly reduces hydraulic conductivity to values acceptable for engineered liners [27-29]. However, limited

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attention has been given to the use of locally available natural clays as alternative modifiers for laterite soils. Bentonite is often not readily available in many developing regions, particularly in artisanal and small-scale mining areas. Consequently, reliance on bentonite-based liners may not be economically feasible for such operations.

Boadu [30] indicated that the gravel and sand fractions largely control hydraulic conductivity in coarse-grained soils. These coarse particles create large, interconnected pores that facilitate fluid movement. The author suggested that the gradual introduction of fine particles slightly reduces hydraulic conductivity by filling some of the large voids. However, when the fine content increases beyond a critical threshold, fines dominate the pore structure, block major flow channels, and significantly reduce permeability.

Most hydraulic conductivity predictive models make use of a specific area of the soil. This parameter is difficult to measure, and the model's accuracy depends heavily on the accuracy of the specific surface measurement [31].

Existing studies largely focus on conventional clay liners, bentonite-modified liners, or geosynthetic materials, with little emphasis on engineered blends of laterite and clay. Furthermore, although the influence of particle size on hydraulic conductivity is well established, there is a lack of quantitative guidance on the optimal clay-laterite blending ratios required to meet international liner performance criteria. In addition, relatively few studies have examined predictive relationships between hydraulic conductivity and fundamental soil properties.

This study addresses these gaps by systematically evaluating the hydraulic properties of laterite, clay, and laterite–clay blends, and establishing practical design thresholds (clay: laterite ratio) required to achieve hydraulic conductivity values consistent with international standards ($\leq 1 \times 10^{-9}$ m/s) based on the particle gradation of the laterite soil. Importantly, the study develops an empirical predictive model linking hydraulic conductivity to basic soil properties, providing a rapid screening tool for identifying suitable liner materials. The findings contribute to the development of affordable, locally sourced liner solutions tailored to ASM contexts, thereby advancing both scientific understanding and practical application in sustainable tailings management.

2. Materials and Methods

2.1. Sample collection and preparation

The study was conducted in Zambia from March 2024 to November 2025. Two clay soil samples (CL_1 and CL_2) and three laterite soil samples (LS_1, LS_2, and LS_3) were collected from geographically distinct locations across the country to capture representative soil variability. Clay soil sample CL_1 was collected from the Goma Fields within the UNZA campus, while clay sample CL_2 was sourced from Kaumbwe in the Petauke District. LS_1 and LS_2 were obtained from Lusaka South (Shantumbu area) and Katenda in Chongwe District, respectively. LS_3 was collected from within the University of Zambia (UNZA) campus, as shown in **Figure 1**.

The soil samples were excavated from pits at depths ranging from 1.0 m to 1.5 m to avoid the influence of topsoil and organic matter. After excavation, all soil samples were sealed in labelled bags and transported to the Geotechnical Engineering Laboratory at the University of Zambia, where they were air-dried before laboratory testing. The geographical distribution of the soil sampling locations is illustrated in **Figure 1**.

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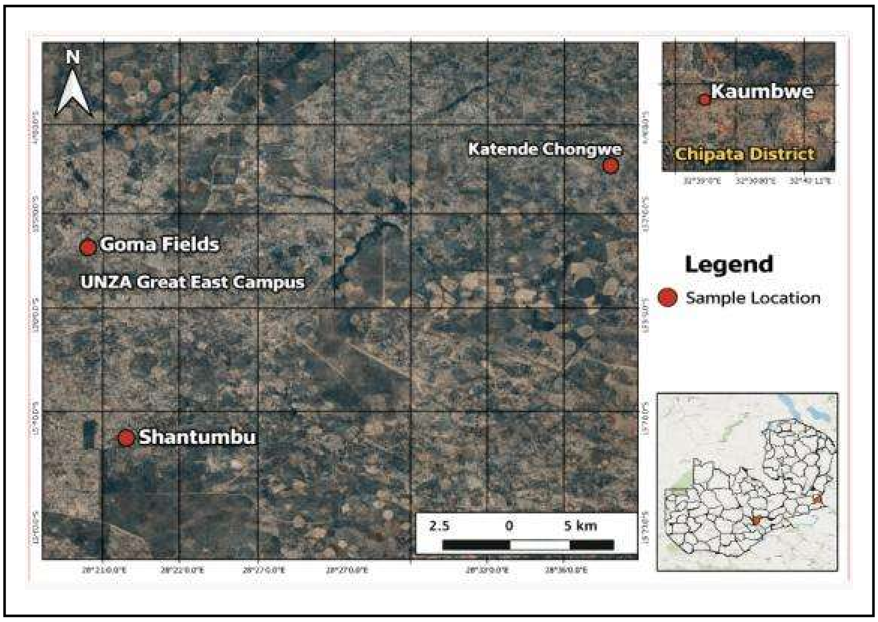

Figure 1. Geographical distribution of soil sampling locations

All collected soil samples were air-dried in the laboratory for 7 days, after which they were sealed in airtight bags and stored before testing. The dried clay soils, which formed hard lumps, were mechanically crushed and then sieved through a 6.7 mm sieve to produce a uniform material for laboratory analysis. The processed clay materials were designated as clay sample 1 (CL_1) and clay sample 2 (CL_2).

Each lateritic soil sample was further subdivided into three subgroups based on particle-size distribution to investigate the influence of gradation on hydraulic performance. Portions of each laterite sample were sieved through 19.1 mm, 13.2 mm, and 6.7 mm sieves, resulting in three distinct gradation classes. Accordingly, laterite sample 1 was classified as LS_1-19.1, LS_1-13.2, and LS_1-6.7 based on the respective sieve sizes. The same sieving procedure and classification were applied to laterite samples 2 (LS2) and 3 (LS_3). These gradation-controlled laterite soils and the clay soils are termed as untreated samples.

The gradation-controlled laterite samples were subsequently blended with varying percentages of clay (expressed as a percentage of the laterite dry mass) to evaluate the influence of clay content on the key performance indicators of compacted soil liners, particularly hydraulic conductivity. For instance, 50% Laterite sample 1 passed through the 19.1mm sieve, and the 50% clay sample 1 blend is represented as 50%LS1/50%CL1-19.1, while 80% Laterite sample 1 passed through the 6.7mm sieve, and the 20% clay sample 2 blend is represented as 80%LS_1/20%CL_2-6.7. These designations were assigned to the clay-modified laterite specimens and were subsequently referred to as such. The clay-modified laterite specimens are referred to as treated samples.

Before compaction and Atterberg limit testing, all soil specimens were hydrated and allowed to cure for 24 hours to facilitate moisture equilibration and allow any physicochemical interactions between the laterite and clay fractions.

2.2. Laboratory Testing and Analytical Methods

Soil consistency characteristics were evaluated using Atterberg limit tests in accordance with British Standard Method of Test for Soils for Civil Engineering Purposes, part 2, classification tests [31]. The liquid limit was determined using the cone penetrometer method, and the hand-rolling technique was used to obtain the plastic limit. Particle size distribution was determined by combining wet sieving and hydrometer analysis, following the procedures outlined in [32].

Compaction characteristics were determined using the standard Proctor test in accordance with British Standard Method of Test for Soils for Civil Engineering Purposes, part 4, compaction tests

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[33]. A 2.5 kg rammer dropped freely from a height of 305 mm was used, with 25 blows per layer across three layers. The free swell index of the soils was determined in accordance with IS 2720 [34]. Organic matter content was determined using the loss on ignition (LOI) method.

For hydraulic conductivity testing, specimens were compacted to 99 mm in diameter and 77 mm in height at a dry density 2% above the optimum moisture content. Previous studies have shown that soils compacted on the wet side of the optimum moisture content generally exhibit lower hydraulic conductivity than those compacted on the dry side [35]. The specimens were saturated until steady-state flow was observed at the permeameter outflow. The duration of saturation varied with the specimen's hydraulic conductivity, with samples containing higher clay content requiring longer saturation periods than those composed predominantly of natural laterite with lower clay content. Permeation was continued until constant flow conditions were achieved over at least 5 consecutive readings. Hydraulic conductivity was evaluated at hydraulic gradients (j) of 18 and 29 using tap water as the permeating fluid. Testing was conducted in accordance with ASTM D5856 [36] using a rigid-wall permeameter operated under constant tailwater elevation conditions.

Mineralogical characterisation of the soil samples was performed using X-ray diffraction (XRD). Approximately 5–10 mg of air-dried material passing through a 75 µm sieve was mounted on an XRD sample holder and analysed using an Olympus TERRA-538 portable X-ray diffractometer. The instrument was operated at 30 kV and 30 mA. Diffraction scans were collected over a 2θ range of 2° to 60°, with a step size of 0.02° 2θ and a counting time of 2 s per step. Mineral phases were identified using X'PERT HighScore Plus software.

Chemical analysis was conducted on 1.5 g of air-dried soil that passed through a 75 µm sieve. The aqua regia method was used for sample digestion, after which the digest was diluted to a final volume of 250 mL with distilled water. The prepared solutions were filtered and stored in sample containers before analysis. Elemental and heavy metal concentrations in the filtrates were quantified using a Vista-MPX dual-view Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) manufactured by Varian Inc. The severity of heavy-metal contamination in the soil samples was compared with internationally recognised FAO/WHO guidelines. These limits are derived from the Codex Alimentarius standards, FAO guidance on soil quality, and WHO environmental safety criteria, which are commonly used to assess soils intended for food production and agricultural use [37]. Major oxide compositions were subsequently calculated by applying appropriate conversion factors to the elemental concentrations obtained from the ICP-OES analysis.

3. Results and Discussions

3.1 Physical Properties of Untreated Soil Samples

Consistency and Swelling Characteristics of Clay and Untreated Laterite Soils

The results of laboratory tests on clay samples and untreated laterite soils show that the free swell index (FSI) values for clay samples CL_1 and CL_2 were 25.7% and 73%, respectively. The substantially higher FSI for CL_2 indicates greater swelling potential, likely due to the presence of highly expansive clay minerals. In contrast, the lateritic soils LS_1, LS_2, and LS_3 exhibited lower FSI values of 21.1%, 15%, and 22%, respectively. Based on established swell classification criteria [20], CL_2 can be classified as having very high swelling potential, whereas all other samples fall within the low swelling category. Linear shrinkage results further highlighted the expansive nature of CL_2, which recorded a shrinkage value of 18%. The remaining soil samples exhibited lower linear shrinkage values, ranging from 5% to 12.5%.

Atterberg limit testing indicated plasticity indices (PI) of 27% and 44% for CL1 and CL2, respectively, while the laterite soils LS1, LS2, and LS3 exhibited PI values of 17%, 9%, and 13%, respectively. When plotted on the Casagrande plasticity chart as shown in Figure 2), CL_2 clearly falls within the high-plasticity clay (CH) region above the A-line, indicating a soil dominated by active clay minerals with a high capacity for water adsorption and volume change. In contrast, CL_1, LS_2, and LS_3 plot within the low-plasticity clay (CL) region, while LS_1 lies close to the A-line, suggesting intermediate plasticity.

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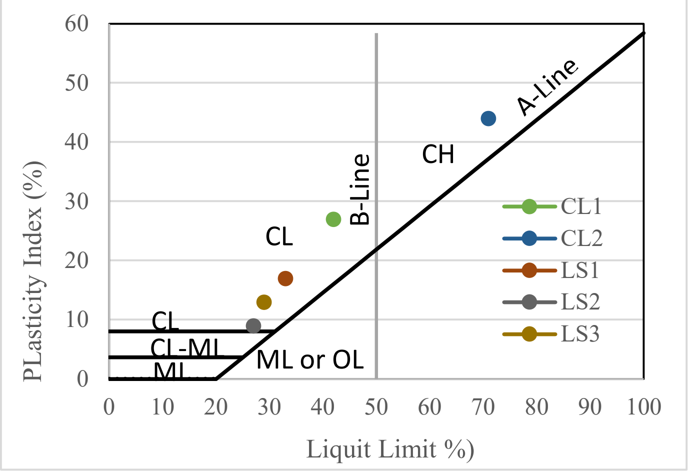

Figure 2. Plasticity chart for the untreated soil samples

The position of CL_2 on **Figure 2,** well above the A-line and at a high liquid limit (71%) reflects a greater thickness of the diffuse double layer, which enhances its swelling potential upon hydration. This explains the high FSI (73%) and linear shrinkage (18%) values observed earlier. Conversely, the laterite soils, which plot at lower liquid limits and are below or near the A-line, are likely dominated by less active clay minerals that exhibit limited swelling and shrinkage with changes in moisture. These characteristics are critical in soil liner applications.

Particle Size Distribution and Soil Classification of Untreated Samples

The particle size distribution (PSD) results for the various soil samples reveal distinct differences between the clay and laterite soils, as shown in **Figure 3**. The summary of the PSD results is provided in **Table 1**.

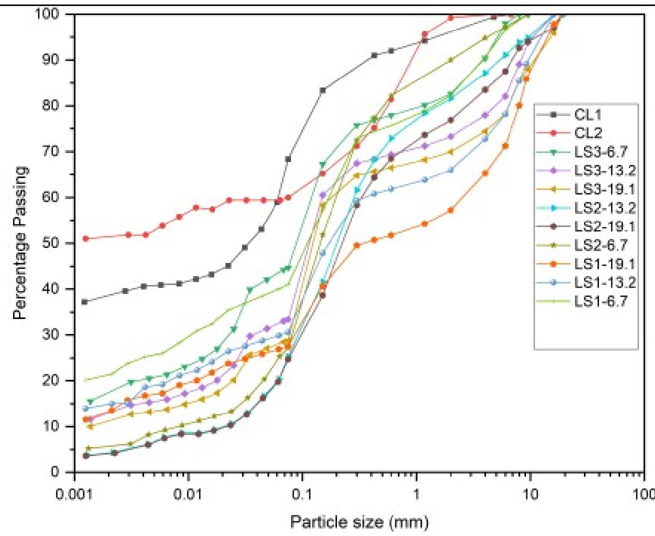

Figure 3. Particle size distribution curve for untreated soil samples

CL_1 contained 0.6% gravel, 31.0% sand, and 68.4% fines, with the fines fraction comprising 38.0% clay and 30.4% silt. In contrast, clay sample CL_2 contained no gravel, 40.0% sand, and 60.0% fines, of which 51.5% was clay and 8.5% was silt. Although CL_1 and CL_2 had comparable proportions of coarse (gravel and sand) and fine fractions, the distribution of silt and clay differed markedly. Specifically, CL_2 had a high clay content and low silt content, whereas CL_1 had relatively balanced proportions of silt and clay, as demonstrated in **Figure 3**.

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Among the laterite soils, LS_2 had relatively low gravel and clay contents but a very high sand fraction, indicating a coarser overall texture. For laterite samples passed through the 19.1 mm sieve, the gravel fractions in LS_1 and LS_3 exceeded the 30% maximum allowable limit recommended by the UK Environmental Agency for soil liner materials [22]. From **Figure 3**, it is observed that as the sieve size decreased, the coarse fractions decreased, and the fines increased across all laterite soils. Samples passed through the 6.7 mm sieve exhibited substantially reduced gravel contents and higher proportions of fine material.

Samples from LS_1 and LS_3 that passed through the 13.2 mm and 6.7 mm sieves met the particle gradation requirements for use as compacted soil liners in accordance with UK Environmental Agency guidelines [22]. Overall, the natural clay soils met both the particle size distribution and plasticity index criteria typically required for soil liner applications. According to the Unified Soil Classification System (USCS), CL1 and CL2 are classified as low-plasticity clay (CL) and high-plasticity clay (CH), respectively. In contrast, all gradation groups derived from LS_1, LS_2, and LS_3 can be classified as clayey sand (SC).

Compaction Characteristics of Clay and Laterite Soil Samples

The dry density–moisture content relationships of the soil samples were determined through standard compaction testing as illustrated in **Figure 4**.

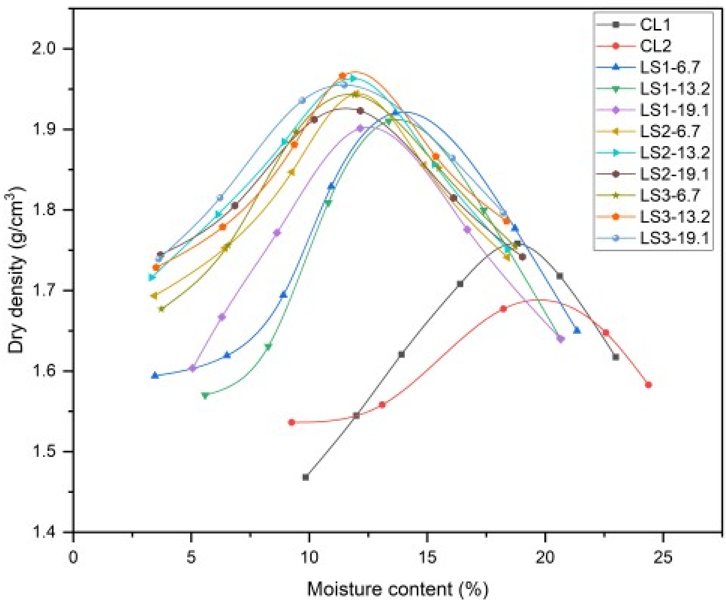

Figure 4: Compaction curve for untreated soil samples.

The results from **Figure 4** indicate that the clay soils exhibited relatively high optimum moisture contents (OMC) and low maximum dry densities (MDD), as demonstrated by the outward and downward positions of the curves compared with those of the laterite soils. CL_1 and CL_2 both recorded an OMC of 19%, with corresponding MDD values of 1.74 g/cm³ and 1.68 g/cm³, respectively. The comparatively low MDD and high OMC observed for the clay soils can be attributed to their high fines content and the presence of clay minerals with high water-absorptive capacity, which require greater moisture to achieve effective particle rearrangement during compaction.

Among the laterite soils, LS_1 exhibited a slightly lower MDD and a higher OMC than LS_2 and LS_3. Analysis of specimens derived from varying particle-size gradations indicated that gradation changes had minimal influence on MDD and OMC. For LS_1, a slight increase in MDD and OMC was observed as particle size decreased. In contrast, LS_2 and LS_3 showed a marginal increase in MDD with decreasing particle size, while OMC values remained largely unchanged. This behaviour is likely associated with the low plasticity of the fine fractions in LS_2 and LS_3, which limits moisture demand during compaction.

Overall, the results show that variations in particle-size distribution achieved by passing each laterite soil through three different sieve sizes had only a minor effect on the dry density–moisture content relationship for a given laterite source, as shown in **Figure 4**.

The summary of the physical and compaction properties of the untreated soil samples is presented in Table 1 below.

Table 1. Summary of physical properties of untreated soil samples

Sample ID	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	LL (%)	PI (%)	USC	MDD (g/cm³)	OMC (%)	FSI (%)
$LS_{1-19.1}$	35	38	14	13	33	17	SC	1.90	12	21
$LS_{1-13.2}$	27	42	16	15				1.91	13	
$LS_{1-6.7}$	9	50	20	21				1.92	13.5	
$LS_{2-19.1}$	10	65	20	5	27	9	SM	1.93	11.5	15
$LS_{2-13.2}$	7	68	20	5				1.94	11.8	
$LS_{2-6.7}$	6	68	16	10				1.95	12	
$LS_{3-19.1}$	30	41	18	11	29	11	SC	1.96	11	22
$LS_{3-13.2}$	22	45	20	13				1.97	11.4	
$LS_{3-6.7}$	10	46	22	18				1.94	11.5	
CL_1	0.6	31	30	38	42	27	CL	1.74	19	26
CL_2	0	40	8.5	51.5	71	44	CH	1.68	19	73

3.2. Chemical Properties of Untreated Soil Samples

Results of heavy metal concentrations in the soil samples are presented in **Table 2**.

Table 2. Elemental concentrations in mg/kg of soil samples and WHO/FAO thresholds

Heavy metal concentrations (mg/kg)						
Heavy metal	**CL_1**	**CL_2**	**LS_1**	**LS_2**	**LS_3**	**WHO/FAO**
As	27.5	31.2	19.1	-	14.3	20
Cd	13.6	5.9	8.0	13.9	9.5	3
Co	35.5	38.6	40.4	28.4	45.7	50
Cr	119.3	49.7	237.0	106.9	341.3	100
Cu	97.5	71.5	119.1	33.9	90.1	100
Li	208.1	88.2	117.9	24.6	88.5	-
Mn	153.2	126.9	261.6	335.8	357.8	2000
Ni	211.4	289.0	219.4	53.1	162.9	50
Pb	24.1	46.2	14.5	0.0	29.4	100
Zn	239.8	295.8	379.1	103.5	349.6	300

Heavy metals tested include Cu, As, Mn, Zn, Co, Ni, Cd, Cr, and Pb. The results indicate that, except for LS_3, all soil samples have elevated As concentrations above the WHO/FAO [38] threshold. The results in **Table 2** indicate that the Zn concentrations in CL_1, CL_2, and LS_2 are within the acceptable range, whereas those in LS_1 and LS_3 exceed the threshold. Ni and Cd show significant exceedances in all soil samples, indicating possible anthropogenic activities. Pb, Cu, Co, and Mn concentrations are within acceptable ranges and do not pose an immediate risk based on the

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WHO/FAO [38] guideline thresholds.

The oxide compositions of the soil samples are presented in **Table 3**. The samples contained high percentages of SiO_2, Al_2O_3, and Fe_2O_3, characteristics of tropically weathered soils that give rise to laterite and lateritic soils, as indicated by Gidigasu [18]. The sesquioxide ratio determined by Equation 1 has served as a basis for classifying residual soils.

$$\frac{SiO_2}{R_2O_3} = \frac{SiO_2}{Fe_2O_3 + Al_2O_3} \tag{1}$$

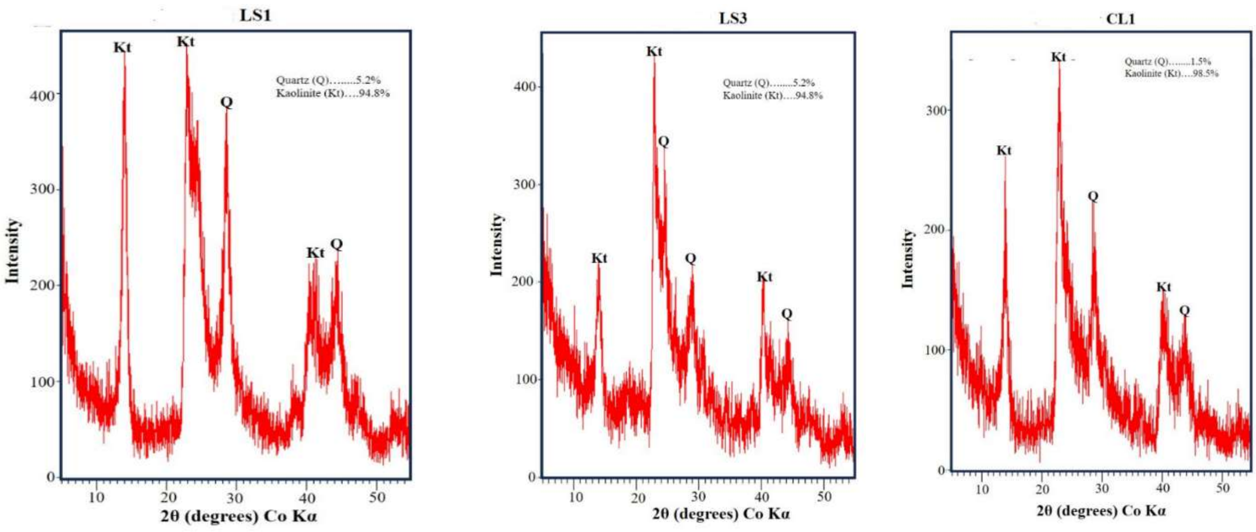
Table 3. Percentage oxide compositions and sesquioxide ratios of soil samples

	CL_1	CL_2	LS_1	LS_2	LS_3
Al_2O_3	28.7	20.2	29.8	18.7	30.1
CaO	10.0	11.7	4.9	15.8	2.9
Fe_2O_3	5.0	9.5	13.9	7.1	15.8
K_2O	3.1	3.3	1.1	0.5	3.8
MgO	9.7	8.0	5.2	5.9	5.4
SiO_2	33.0	33.5	37.4	44.9	30.5
Na_2O	7.2	8.1	4.3	2.2	7.6
P_2O_5	3.0	3.5	2.7	3.5	2.8
TiO_2	0.8	2.3	1.0		1.0
$\frac{SiO_2}{R_2O_3}$	0.979	1.128	0.856	1.740	0.664

Ratios less than 1.33 indicate true laterites; those between 1.33 and 2.00 are termed lateritic soils; and those greater than 2.0 are non-lateritic, tropically weathered soils [18]. Results from the sesquioxide ratio presented in **Table 3** indicate that all samples, except LS_2, could be referred to as laterite soils, while LS_2 could be termed a lateritic soil.

3.3. Mineralogical Properties of Untreated Soil Samples

The X-ray diffractogram shows pronounced peaks corresponding to the dominant mineral phases, as shown in **Figure 5(a)-(e)**.



(a) (b) (c)

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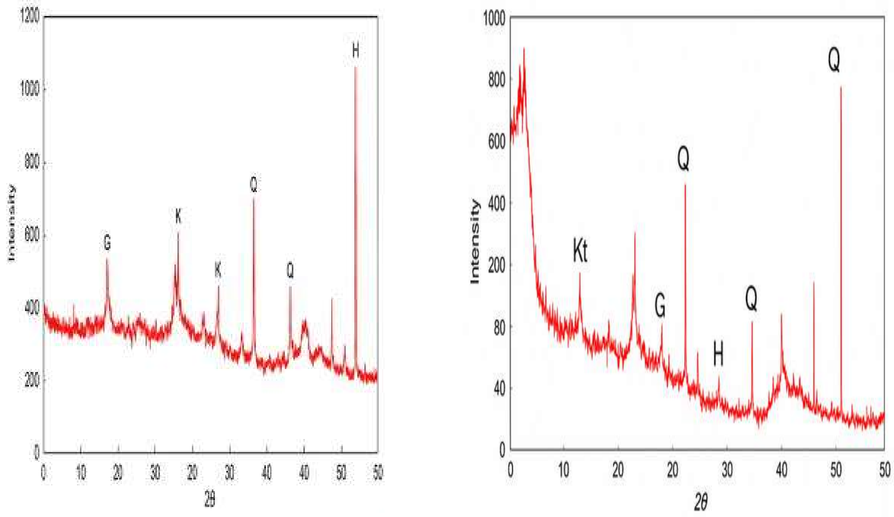

(d) (e)

Figure 1. X-ray diffractogram of (a) LS_1, (b) LS_3, (c) CL_1, (d) LS_2, (e) C L_2

The XRD analysis of LS_1 and LS_3 indicates a highly tropical environment, leading to the formation of a kaolinite-rich regolith profile as shown in **Figure 5(a)** and **Figure 5(b),** a typical mineralogical composition of a tropically weathered soil under distinct dry and wet seasons, and the formation of laterite soils, as indicated by Gadigasu [18]. This agrees with the soil descriptions derived from the sesquioxide ratios.

LS_2 reveals a mineralogical assemblage dominated by hematite, with significant amounts of goethite and kaolinite, and lesser amounts of quartz, as shown in **Figure 5(d)**. This assemblage is characteristic of deep tropical chemical weathering, the formation of lateritic soils, and derivation from feldspar-rich parent rocks. The implied geology is of mature, heavily weathered terrain, typical of basement complex regions subjected to long-term leaching and oxidation.

The XRD analysis of CL_1 indicates a nearly monomineralic kaolinite composition (≈98.5%), with only minor quartz (≈1.5%) as demonstrated in **Figure 5(c)**. This mineral assemblage reflects advanced chemical weathering under tropical conditions, the formation of kaolinitic saprolite or high-grade kaolin deposits, and derivation from feldspar-rich parent rocks that have undergone prolonged hydrolysis. Geologically, CL_1 represents a mature, stable, deeply weathered regolith typical of tropical terrains, such as those found in southern and central Africa.

Figure 5(e) shows the XRD analysis of $CL_{2,}$ the X-ray diffractogram reveals smectite-like features and the presence of quartz. The broad, high-intensity hump at the start of the X-ray diffractogram corresponds to amorphous material, typically amorphous silica or poorly crystalline aluminosilicate phases.

3.4. Hydraulic Conductivity of the Untreated Soil Samples

The hydraulic conductivity tests indicate that clay samples CL_1 and CL_2 exhibit very low permeability, with hydraulic conductivities of 10^{-10} m/s and 10^{-11} m/s, respectively. In contrast, laterite sample LS_2 exhibited relatively high hydraulic conductivity values on the order of 10^{-8} m/s across all particle size ranges and hydraulic gradients tested. Laterite samples LS_1 and LS_3 exhibited hydraulic conductivities ranging from approximately 10^{-8} m/s to 10^{-9} m/s, depending on particle size range and applied hydraulic gradient.

The high hydraulic conductivity behaviour of the laterite samples is attributed to the high coarse fraction, low clay content, and the predominance of less active minerals, particularly hematite, as reported in [30]. Although LS_1 and LS_3 contained kaolinitic clay minerals, their relatively low fines content and high coarse fractions resulted in larger voids, leading to higher hydraulic conductivity than observed in CL_1.

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The low hydraulic conductivity values of the CL samples can be attributed to the relatively low coarse fractions, high proportions of fine particles, and the presence of active clay minerals with high water affinity and a double diffuse layer. The mineralogical analysis of CL_2 showed smectite-like characteristics, as evidenced by its high liquid limit (71%) and free swell index (73%), which contributed to its extremely low hydraulic conductivity. These findings are consistent with previous studies [18, 23, 25], which have demonstrated the strong influence of clay mineralogy on the hydraulic conductivity of compacted soils. Both CL_1 and CL_2 satisfy the maximum hydraulic conductivity criterion (1 x 10-9 m/s) recommended by the UK Environmental Agency for use as compacted soil liners [22].

None of the untreated lateritic soil samples met the hydraulic conductivity requirement typically specified for soil liner applications. This observation aligns with the findings of [26], who reported that while natural clay soils in Zambia may meet liner permeability requirements, untreated laterite soils generally do not.

Although gravel and fines significantly influence the hydraulic conductivity of compacted soils, the mineralogical composition of the clay fraction plays a critical role, as demonstrated by the contrasting permeability behaviour of CL_1 and CL_2. Overall, the results indicate that hydraulic conductivity increased with a higher coarse fraction and a higher applied hydraulic gradient. The test results indicate that the higher hydraulic gradient (j = 29) consistently produced higher hydraulic conductivity values than the lower hydraulic gradient (j = 18) for all specimens, as shown in **Table 4**. This trend is attributed to the increased seepage forces associated with higher hydraulic gradients, which enhance fluid flow through compacted soil matrices, as also reported by [23].

A summary of the hydraulic conductivity results for the clay and lateritic soils tested under different hydraulic gradients is presented in **Table 4**.

Table 4. Permeability data for untreated soil samples

Sample ID	Permeability (K) (m/s)	
	j=18	j=29
LS_1-19.1	8.031×10^{-9}	1.024×10^{-8}
LS_1-13.2	7.727×10^{-9}	1.316×10^{-8}
LS_1-6.7	3.436×10^{-9}	5.484×10^{-9}
LS_2-19.1	5.06×10^{-8}	6.43×10^{-8}
LS_2-13.2	2.85×10^{-8}	3.92×10^{-8}
LS_2-6.7	2.88×10^{-8}	3.84×10^{-8}
LS_3-19.1	9.79×10^{-9}	1.207×10^{-8}
LS_3-13.2	8.39×10^{-9}	9.99×10^{-9}
LS_3-6.7	7.81×10^{-9}	8.918×10^{-9}
CL_1	5.24×10^{-10}	6.06×10^{-10}
CL_2	-	6.53×10^{-11}

3.5. Effect of Clay Addition on Physical and Index Properties of Laterite Samples

Effect of Clay Addition on the Plasticity Characteristics of Laterite Samples

Atterberg limit test results indicate a systematic increase in plasticity index (PI) with increasing clay content for all treated laterite specimens. The magnitude of this increase depends on the initial plasticity of the lateritic soil, the intrinsic plasticity of the added clay, and the proportion of clay incorporated into the mixture, as illustrated in **Figure 6**.

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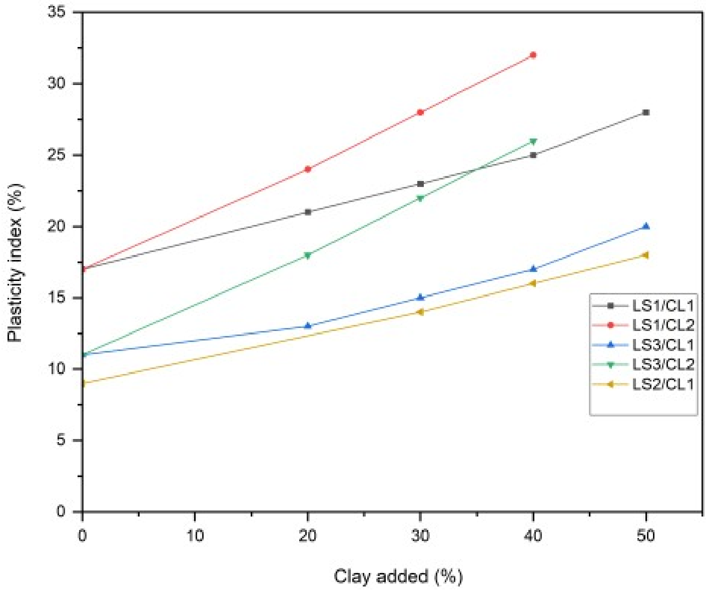

Figure 6. Effect of clay content on plasticity index of laterite soils

The influence of CL_2 on the plasticity characteristics of the treated specimens was more pronounced than that of CL_1, as presented in **Figure 6**, owing to its higher inherent plasticity index (47%) compared with CL_1 (27%). For instance, the liquid limit of LS_1 increased from 33% to 49% after adding 40% CL_2, resulting in a PI increase from 17% to 33%, corresponding to approximately a 94% increase in PI. In contrast, adding 50% CL_1 to LS_1 increased the PI to 28%, representing an approximate 64% increase. However, when the same proportion (50%) of CL_1 was added to LS_2, the resulting PI was only 18%, reflecting LS_2's lower initial plasticity.

Similar trends were observed for the laterite sample LS_3, where adding varying proportions of CL_1 and CL_2 produced progressive increases in the plasticity index, as shown in **Figure 6**. Overall, adding 40% CL_2 to the laterite soils produced nearly a 100% increase in the plasticity index, whereas laterite specimens treated with 40% CL_1 exhibited an average increase of approximately 50%. These findings highlight the critical role of the consistency and mineralogical properties of both the base laterite soils and the clay additives in determining the extent of plasticity enhancement in clay-modified laterite mixtures.

It was further observed that, for a given laterite soil, variations in particle-size gradation had a comparatively minor effect on the plasticity response of the treated specimens. For example, adding 30% CL_1 to LS_1 samples that passed through the 19.1 mm, 13.2 mm, and 6.7 mm sieves produced similar plasticity index values, indicating limited sensitivity of PI to gradation at a constant clay content. The increase in plasticity index with clay addition is primarily due to the higher proportion of active clay minerals, which have large specific surface areas and a strong affinity for water, leading to increased water adsorption and, consequently, higher PI values. This behaviour indicates a transition from a less active, less plastic laterite soil to a more active, highly plastic clay. This change in the modified soils enhances a reduction in hydraulic conductivity.

According to the UK Environmental Agency guidelines [22], all clay-treated laterite specimens satisfied the recommended plasticity index range (10%–65%) for use as compacted soil liner materials.

Effect of Clay Addition on Particle Size Distribution of Laterite Samples

Incorporating varying proportions of clay into lateritic soils produced measurable changes in the particle-size distribution of the blended samples. Increasing the clay fraction in laterite–clay mixtures progressively altered the grain-size distribution, reducing the coarse fractions (gravel and sand) and increasing the fine fractions (silt and clay), as shown in **Figure 7(a)-(e)**.

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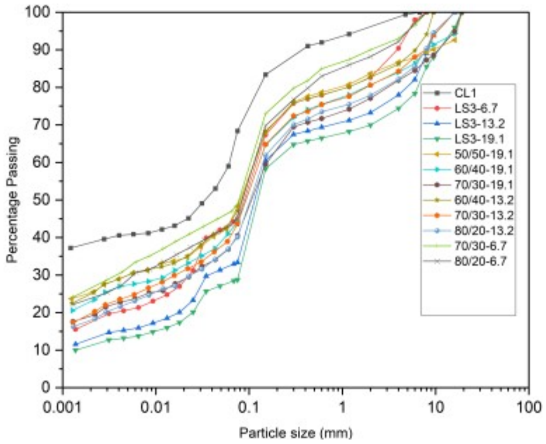
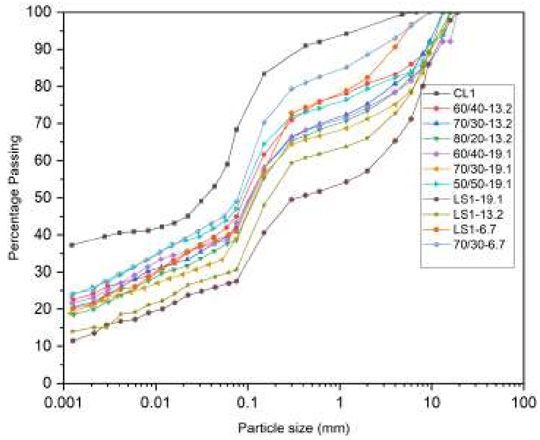
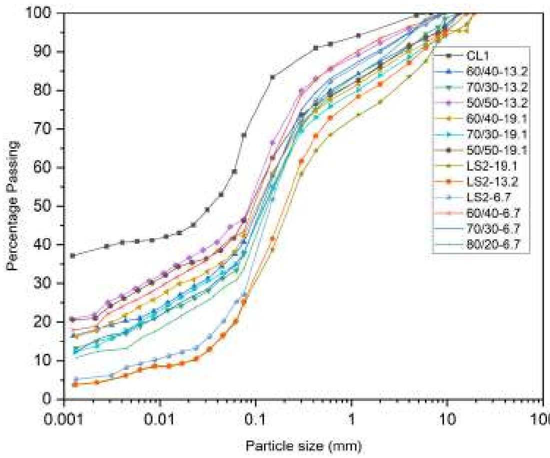


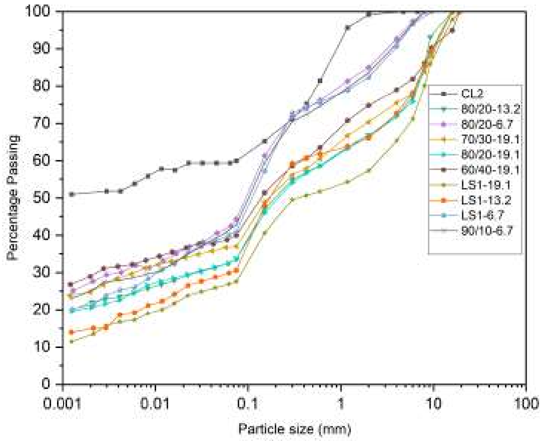
(a)



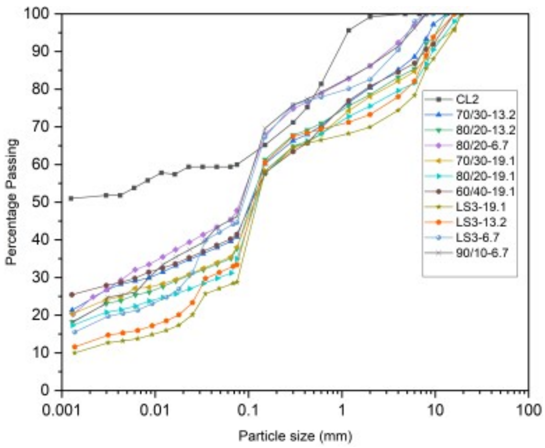
(b)



(c)



(d)



(e)

Figure 2. Effect of CL_1 on particle size distribution of (a) LS_3, (b) LS_2, (c) LS_1. Effect of CL_2 on particle size distribution of (d) LS_1, (e) LS_3

The addition of clay to the laterite samples results in a translational upwards shift of the particle-size distribution curves as presented in **Figure 7(a)-(e)**, indicating an increase in fine particles of the modified samples. This is attributed to the replacement of coarser laterite soil particles with finer

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clay particles.

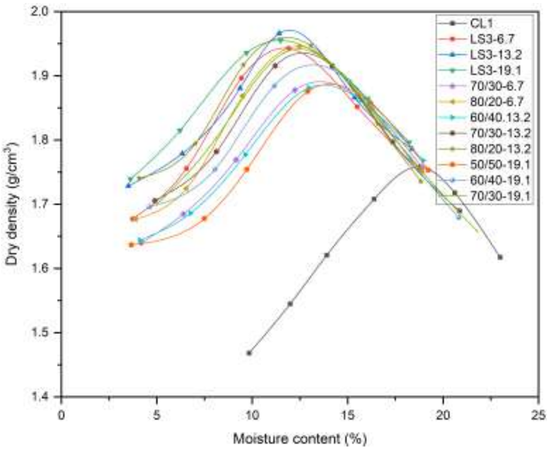
For example, the untreated laterite sample LS_1-19.1 (100% laterite) contained 35% gravel. Adding 30% CL_1 reduced the gravel content to 25%, and adding 50% CL_1 further reduced it to 18%. This represents an overall reduction in gravel content of approximately 30%–50% with increasing clay addition. A similar trend was observed in the sand fraction across all laterite–clay blends. Consequently, blending laterite soils with clay progressively transformed the soil matrix from a sand-dominated to a fine-dominated texture as demonstrated in **Figure 7(a)-(e)**.

The response of the fine fractions varied with the type of clay added. Adding CL_1 increased both silt and clay contents, whereas incorporating CL_2 produced a pronounced increase in the clay fraction, accompanied by a reduction in silt. For instance, in LS_3-19.1, the silt and clay contents increased from 18% and 11%, respectively, to 24% and 25% after adding 50% CL_1. In contrast, adding 40% CL_2 to LS_3-19.1 increased the clay content to 27%, while the silt fraction decreased to 14%. This behaviour reflects the higher clay content in the particle-size distribution of CL2 relative to CL1, and the higher silt fraction in CL1 relative to CL_2.

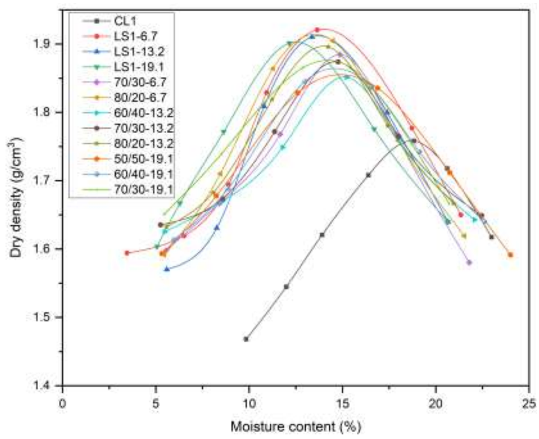
Generally, the results show that adding clay significantly alters the gradation characteristics of laterite soils, with the magnitude and nature of the changes governed by both the proportion and the particle-size distribution of the added clay.

Effect of Clay Addition on the Density–Moisture Relationship of Laterite Samples

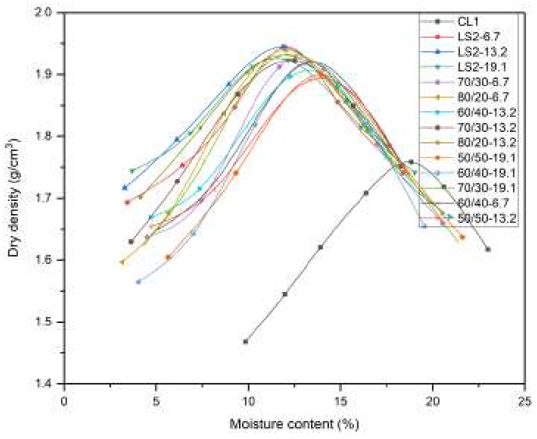
The compaction test results show a systematic decrease in maximum dry density (MDD) and a corresponding increase in optimum moisture content (OMC) with increasing clay content across all laterite–clay blends. The density–moisture content relationships of the clay-treated laterite specimens across the different particle size gradations are illustrated in **Figure 8(a)–(e)**.



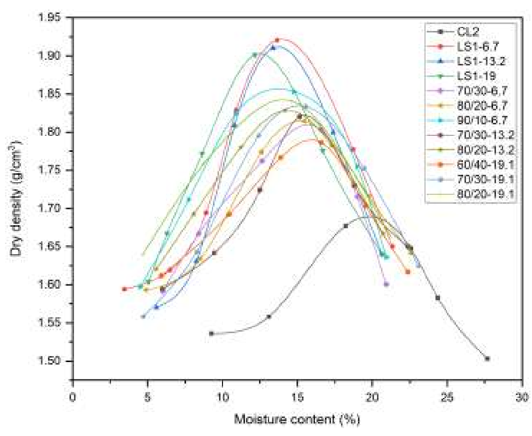
(a)



(b)



(c)



(d)

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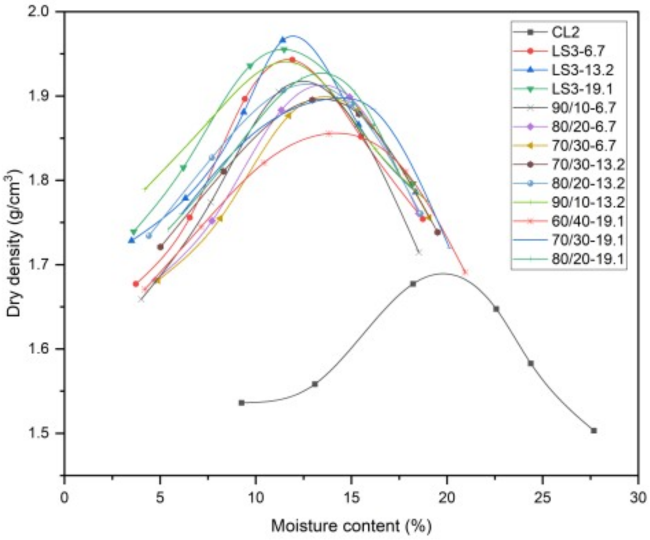

(e)

Figure 8. Effect of CL_1 on the density-moisture content relation of (a) LS_3, (b) LS_1, (c) LS_2. Effect of CL_2 on the density-moisture content relation of (d) LS_1, (e) LS_3

Laterite soils treated with CL_2 showed a more pronounced reduction in MDD and higher OMC values than those treated with CL_1, as indicated in **Figure 8(b)** and **Figure 8(d)**. For example, the untreated laterite LS_1-19.1 recorded an MDD of 1.90 g/cm³ and an OMC of 12%. After adding 40% CL_1, the MDD decreased to 1.86 g/cm³, while the OMC increased to 14.5%. In contrast, incorporating 40% CL_2 reduced the MDD to 1.79 g/cm³ and increased the OMC to 16%.

The reduction in maximum dry density MDD with increasing clay content is associated with the flocculated structure and lower specific gravity of clay minerals, which hinder dense packing compared to coarse-dominated laterite soils. Additionally, increased water demand for lubrication during compaction (higher OMC) results in a more open structure, resulting in lower MDD.

The more substantial changes in compaction properties observed in CL_2-treated specimens as compared to CL_1-treated specimens are attributed to the higher clay content and the presence of highly expansive clay minerals in CL_2, which have a greater affinity for water within their lattice structure.

Overall, the results demonstrate that the type and proportion of clay added are critical to controlling the compaction behaviour of laterite soils.

3.6. Effect of Clay Addition on Hydraulic Conductivity of Laterite Samples

The results from hydraulic conductivity tests on clay-modified laterite soil specimens, shown in **Figure 9**, indicate that adding 30% clay to laterite soils sharply reduces hydraulic conductivity, after which the rate of reduction becomes less pronounced. This trend is particularly evident in lateritic soils with larger maximum particle sizes (<19.1 mm). For example, the untreated LS_1-19.1 specimen exhibited a hydraulic conductivity of 1.024×10^{-8} m/s. Adding 30% CL_1 reduced hydraulic conductivity by nearly one order of magnitude to 1.496×10^{-9} m/s, and further increasing the clay content to 50% reduced it to 8.22×10^{-10} m/s. The introduction of plastic clays to the laterite altered the grain-size distribution. A reduced coarse fraction and increased fine fraction were recorded as shown in **Figure 7(a)-(e).** This increase in fine resulted in progressive filling of intergranular voids, thereby driving an exponential reduction in hydraulic conductivity [30]. The reduced hydraulic conductivity of the clay-modified laterite samples could also be attributed to the introduction of active clay minerals from the clay samples.

The magnitude of hydraulic conductivity reduction depended on several interacting factors,

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including particle-size distribution, the baseline hydraulic conductivity of the untreated laterite, the hydraulic conductivity of the clay additive, and the percentage of clay added. For instance, adding 30% CL_2 to LS_1 and LS_3 specimens that passed through the 19.1 mm sieve reduced hydraulic conductivity from approximately 10^{-8} m/s to 10^{-9} m/s. In contrast, adding the same clay content to LS_1 and LS_3 specimens that passed through the 13.2 mm and 6.7 mm sieves resulted in hydraulic conductivities of the order of 10^{-10} m/s. This clearly demonstrates the influence of particle gradation on hydraulic conductivity, as illustrated in **Figure 9**.

Differences in the baseline permeability of the laterite soils also influenced the performance of the clay-modified specimens. For example, adding 40% CL_1 to LS_2, which passed through the 13.2 mm sieve, produced a higher hydraulic conductivity than adding the same percentage of CL_1 to LS_1 of identical gradation. This behaviour is attributed to LS_2's inherently higher hydraulic conductivity compared to LS_1, highlighting the importance of the parent laterite's initial permeability in controlling the effectiveness of clay modification.

Furthermore, adding equal percentages of CL_1 and CL_2 to the same laterite soil and gradation produced markedly different hydraulic conductivity values. This difference is attributed to the contrasting mineralogies of the two clays. CL_2 exhibits smectite-like mineralogy, whereas CL_1 is predominantly kaolinitic. The higher swelling capacity and finer pore structure of smectitic clays result in lower hydraulic conductivities in CL_2-modified laterite specimens. These observations are consistent with previous studies by [23, 25], who emphasised the dominant role of clay mineralogy in controlling the hydraulic conductivity of compacted soil liners. **Figure 9,** therefore, summarises the combined influence of clay addition and particle gradation on the hydraulic conductivity of clay-modified laterite soils.

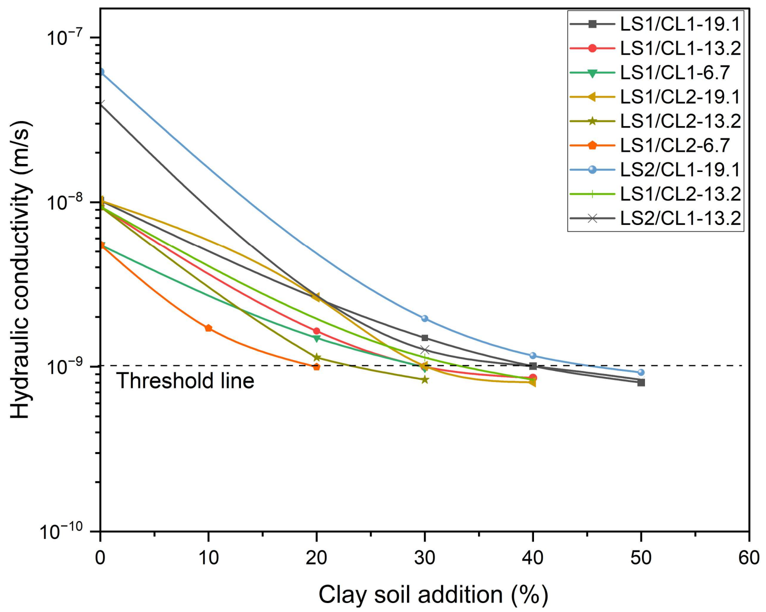

Figure 9: Influence of clay addition on the hydraulic conductivity of laterite samples.

Regardless of maximum particle size (6.7 mm, 13.2 mm, or 19.1 mm) or laterite source (LS_1, LS_2, or LS_3), clay additions of 40%–50% produced hydraulic conductivity values of approximately 1×10^{-9} m/s, representing a reduction of about 1-2 orders of magnitude. However, laterite soils passing through the 6.7 mm sieve required lower clay additions (30%–40%) to achieve the same target hydraulic conductivity, as shown in **Figure 9**. Plasticity index and PSD were found to influence hydraulic conductivity significantly.

The observed reduction in hydraulic conductivity with increasing clay content can be attributed to both microstructural and physicochemical mechanisms. The addition of clay increases the proportion of fine particles, which progressively fill intergranular voids within the laterite soil matrix,

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resulting in reduced effective pore size and lower void connectivity. In addition, clay minerals exhibit double-layer effects, which promote water adsorption and further restrict flow paths. As clay addition increases from 30% to 50%, the laterite soil transitions from a coarse-grained, mechanically controlled system to a fine-grained, physico-chemically controlled system, leading to the observed 1–2 order reduction in hydraulic conductivity.

A summary of the effect of the two clay soil samples on the geotechnical properties of the various laterite soil samples is presented in **Table 5**.

Table 5. Summary of clay-laterite samples test results

Specimen ID	LL (%)	PI (%)	MDD (g/cm^3)	OMC (%)	G (%)	S (%)	M (%)	C (%)	K at j=18 (m/s)	K at j=29 (m/s)
50%LS$_1$/50%CL$_1$-19.1	42	28	1.85	15.0	18	35	22	26	7.635x10^{-10}	8.220x10^{-10}
60%LS$_1$/40%CL$_1$-19.1	41	25	1.86	14.5	21.4	35.2	20.4	23	8.71x10^{-10}	1.061x10^{-9}
70%LS$_1$/30%CL$_1$-19.1	38	23	1.88	14.0	24.8	35.9	18.8	20.5	9.553x10^{-10}	1.496x10^{-9}
60%LS$_1$/40%CL$_2$-19.1	49	32	1.79	16.0	21	38.8	11.8	28.4	7.988x10^{-10}	8.05x10^{-10}
70%LS$_1$/30%CL$_2$-19.1	44	28	1.83	15.0	24.5	38.6	12.4	24.6	8.941x10^{-10}	1.008x10^{-9}
80%LS$_1$/20%CL$_2$-19.1	41	24	1.84	14.5	28	38.4	12.9	20.7	9.483x10^{-10}	2.632x10^{-9}
50%LS$_2$/50%CL$_1$-19.1	33	18	1.9	14.4	8.5	45	25.5	21	8.464x10^{-10}	9.239x10^{-10}
60%LS$_2$/40%CL$_1$-19.1	30	16	1.91	13.5	10	47.8	24.6	17.6	8.693x10^{-10}	1.166x10^{-9}
70%LS$_2$/30%CL$_1$-19.1	29	14	1.92	13.0	11.5	50.6	23.7	14.2	9.778x10^{-10}	1.555x10^{-9}
50%LS$_3$/50%CL$_1$-19.1	36	20	1.88	14.0	13.3	38.3	23.9	24.5	7.406x10^{-10}	8.342x10^{-10}
60%LS$_3$/40%CL$_1$-19.1	35	18	1.91	13.5	15.8	39.8	22.6	21.8	8.335x10^{-10}	1.005x10^{-9}
70%LS$_3$/30%CL$_1$-19.1	33	15	1.94	13.0	18.2	41.3	21.4	19.1	1.767x10^{-9}	1.266x10^{-9}
60%LS$_3$/40%CL$_2$-19.1	44	26	1.86	15.0	15.4	43.4	14.2	27.2	7.727x10^{-10}	8.96x10^{-10}
70%LS$_3$/30%CL$_2$-19.1	40	22	1.90	14.5	17.9	44	15.2	23.2	8.978x10^{-10}	1.031x10^{-9}
80%LS$_3$/20%CL$_2$-19.1	36	18	1.93	13.5	20.5	44.5	16.1	19.1	1.814x10^{-9}	2.733x10^{-9}
60%LS$_1$/40%CL$_1$-13.2	41	24	1.85	15.0	16.6	37.6	21.6	24.2	7.345x10^{-10}	8.546x10^{-10}
70%LS$_1$/30%CL$_1$-13.2	39	22	1.87	14.8	19.2	38.7	20.2	21.9	8.08x10^{-10}	9.993x10^{-10}
80%LS$_1$/20%CL$_1$-13.2	38	21	1.90	14.5	21.8	39.8	18.8	19.6	1.145x10^{-9}	1.645x10^{-9}
70%LS$_1$/30%CL$_2$-13.2	41	25	1.82	15.0	18.9	41.4	13.8	26	6.60x10^{-10}	8.338x10^{-10}
80%LS$_1$/20%CL$_2$-13.2	39	23	1.83	14.0	21.6	41.6	14.5	22.3	8.403x10^{-10}	1.138.x10^{-9}
50%LS$_2$/50%CL$_1$-13.2	33	18	1.90	14.5	7.0	46.5	25.5	21	9.103x10^{-10}	8.342x10^{-10}
60%LS$_2$/40%CL$_1$-13.2	30	16	1.91	13.5	8.2	49.6	24.6	17.6	7.777x10^{-10}	1.005x10^{-9}
70%LS$_2$/30%CL$_1$-13.2	28	13	1.92	12.5	9.4	52.7	23.7	14.2	8.725x10^{-10}	1.266x10^{-9}
60%LS$_3$/40%CL$_1$-13.2	34	17	1.89	13.5	13.6	39.4	24	23	1.2183x10^{-9}	9.049x10^{-10}
70%LS$_3$/30%CL$_1$-13.2	32	15	1.93	13.0	15.7	40.8	23	20.5	6.418x10^{-10}	1.068x10^{-9}
80%LS$_3$/20%CL$_1$-13.2	30	13	1.95	12.5	17.8	42.2	22	18	9.152x10^{-10}	1.628x10^{-9}
70%LS$_3$/30%CL$_2$-13.2	38	21	1.90	14.0	15.4	43.5	16.6	24.6	6.527x10^{-10}	8.591x10^{-10}
80%LS$_3$/20%CL$_2$-13.2	35	17	1.91	13.0	17.6	44.0	17.7	20.7	9.512x10^{-10}	1.263.x10^{-9}
70%LS$_1$/30%CL$_1$-6.7	37	21	1.89	15.0	6.9	44.0	23	26.1	7.928x10^{-10}	9.914x10^{-10}
80%LS$_1$/20%CL$_1$-6.7	35	19	1.91	14.0	7.7	45.9	22	24.4	1.032x10^{-9}	1.496x10^{-9}
80%LS$_1$/20%CL$_2$-6.7	39	23	1.82	16.0	7.5	47.7	17.7	27.1	7.323x10^{-10}	9.971x10^{-10}
90%LS$_1$/10%CL$_2$-6.7	37	18	1.85	15.0	8.4	48.7	18.9	24.1	8.819x10^{-10}	1.709x10^{-9}
60%LS$_2$/40%CL$_1$-6.7	30	16	1.92	14.5	3.52	52.96	24.6	18.8	1.361x10^{-9}	8.816x10^{-10}
70%LS$_2$/30%CL$_1$-6.7	29	14	1.93	13.5	3.94	56.62	23.7	15.6	8.08x10^{-10}	1.1654x10^{-9}

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Specimen ID	LL (%)	PI (%)	MDD (g/cm³)	OMC (%)	G (%)	S (%)	M (%)	C (%)	K at j=18 (m/s)	K at j=29 (m/s)
80%LS2/20%CL1-6.7	28	12	1.94	12.5	4.36	60.28	22.8	12.4	1.187×10^{-9}	1.999×10^{-9}
70%LS3/30%CL1-6.7	33	15	1.88	13.0	7.0	41.3	27.7	24.0	8.567×10^{-10}	9.771×10^{-10}
80%LS3/20%CL1-6.7	31	14	1.95	12.5	7.9	42.8	27.3	22.0	1.168×10^{-9}	1.557×10^{-9}
80%LS3/20%CL2-6.7	34	16	1.91	14.0	7.7	44.6	23.0	24.7	8.859×10^{-10}	1.047×10^{-9}
90%LS3/10%CL2-6.7	32	14	1.92	12.5	8.6	45.2	24.8	21.4	1.204×10^{-9}	1.864×10^{-9}

As shown in **Table 5**, specimens with plasticity index values exceeding 25% and fine contents greater than 40% consistently exhibited hydraulic conductivity values $< 1 \times 10^{-9}$ m/s.The effective liner performance of clay-modified laterite soil depends not only on clay content addition but also on the mineralogical characteristics of the added clay, the mineralogical properties of the base laterite, and the gradation of the soil mixture.

3.7. Modelling Hydraulic Conductivity

Laboratory hydraulic conductivity tests on compacted samples are time-consuming, especially for highly plastic soils. To enable fast screening and prediction of hydraulic conductivity for such soils, an empirical correlation between hydraulic conductivity and key parameters that are easier to determine must be established. This section presents a multiple linear regression analysis to predict hydraulic conductivity (K) using easily measurable soil parameters. The analysis uses measured data for laterite, clay, and clay-modified laterite samples at a hydraulic gradient of 29. 50 datasets (n) were used for the multiple regression analysis. The dependent variable is log10 (K), and the independent variables are Fractal Dimension (D), Plasticity Index (PI, %), Fine content (F, %), and Dry density (MDD, g/cm³).

The fractal dimension model assumes that the cumulative mass of soil particles smaller than a given size follows a power-law relationship. Tyler & Wheatcraft [39] proposed a normalised equation for determining fractal dimensions, as shown in **Equation 2**.

$$\frac{M(<d)}{M_t} = \left(\frac{d}{d_{\max}}\right)^{3-D} \quad (2)$$

where: $M(< d)$: mass of particles smaller than the diameter d, M_t: total sample mass, $d_{\max}$: maximum particle diameter. Taking the logarithm of both sides gives:

$$\log\left(\frac{M(<d)}{M_t}\right) = (3 - D)\log\left(\frac{d}{d_{\max}}\right) \quad (3)$$

Thus, the slope (3-D) of the regression line between the logarithms of normalised cumulative mass ($\log(M(< d)/M_t)$) and normalised particle size ($\log(d/d_{\max})$) provides the fractal dimension as shown in **Figure 10**. Figure 10 shows that the linear fit produced an excellent fit with an R^2 of 0.98.

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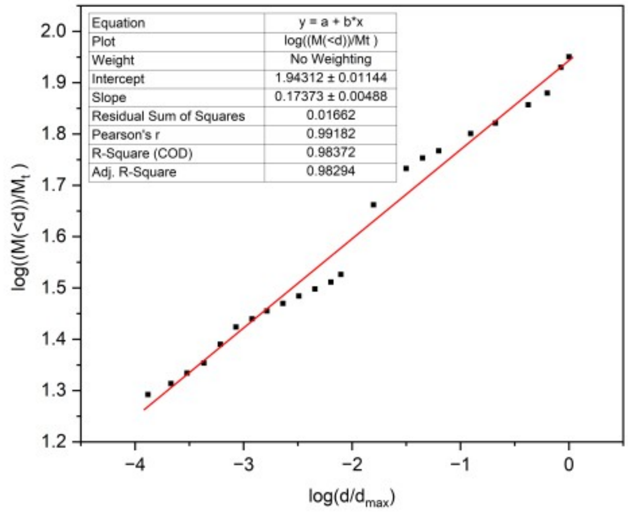

Figure 10. A plot of normalised cumulative mass against normalised particle size.

A sample plot used to determine fractal dimensions from the particle-size distribution of the soil samples is shown in **Figure 10**. By equating the slope of the linear curve to 3-D, the fractal dimension (D) is 2.826. The dependent variable K is related to the predictor variables as;

$$Log_{10}K = 4.11 - 2.93D - 0.0229PI - 0.0234\text{F} - 1.735MDD \quad (4)$$

where D is the fractal dimension, F is the fine content (%), PI is the plasticity index (%), and MDD is the dry density (g/cm³).

An increase in gravel and sand decreases the fractal dimension, increasing hydraulic conductivity, and vice versa. Permeability decreases as fines increase, with the reduction accelerating at higher fines contents. An increase in the plasticity index reduces hydraulic conductivity, consistent with more plastic fines and a tighter pore structure. The degree of compaction influences hydraulic conductivity: a denser sample results in lower hydraulic conductivity. The correlation between measured permeability ($K_{measured}$) and predicted permeability ($K_{predicted}$) was derived from the plot shown in **Figure 11**.

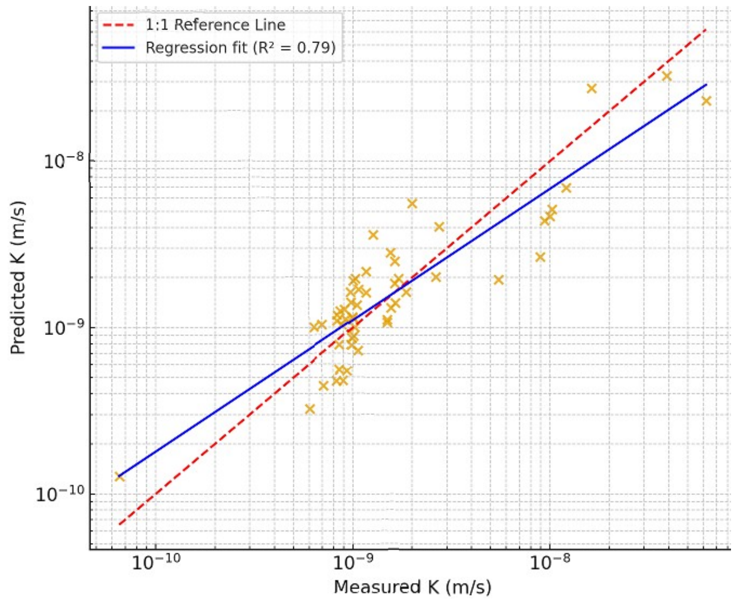

Figure 11: A plot of measured versus predicted hydraulic conductivity

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Figure 11 yielded a correlation coefficient of 0.79 at 95% confidence and a root mean square error of 0.21 log units. This error is relatively low, with 79% of the variance explained by the model. This is a significant statistical parameter that supports the hydraulic conductivity prediction using **Equation 4**.

Discussion

The results demonstrate that soil behaviour is fundamentally governed by clay content, mineralogy, and particle size distribution, which together control swelling, plasticity, compaction, and hydraulic performance. In the untreated state, the clay soil (CL_2) exhibited a high free swell index (FSI) and plasticity, indicating the presence of active clay minerals with high specific surface area and well-developed diffuse double layers. These characteristics promote water adsorption and volumetric expansion. In contrast, the lateritic soils showed low swelling and plasticity reflecting kaolinitic and iron-rich mineralogy, where behaviour is primarily governed by particle arrangement rather than physicochemical interactions. This observation is consistent with established relationships between plasticity and volume change, as indicated by [23], who demonstrated that high active clay mineral content is associated with greater volumetric changes and vice versa.

The Atterberg limits further confirm this distinction. CL_2 plots within the CH region, indicating high plasticity and strong water retention capacity, whereas the laterite soils fall within the CL range, reflecting lower activity. Although laterite soils exhibit greater volumetric stability, their low plasticity limits their sealing capacity, demonstrating that untreated soils may not satisfy the hydraulic requirement. This is in line with previous studies by [28, 29], which reported that high-plasticity soils exhibit lower hydraulic conductivity, while low-plasticity soils mostly exhibit higher hydraulic conductivity.

Particle size distribution (PSD) results reinforce these observations. The high fines content and the dominance of clay-sized particles in the clay samples produce a dense microstructure with reduced pore connectivity, resulting in low hydraulic conductivity. In contrast, laterite soils are characterised by coarse-grained skeletal structures with interconnected macropores that facilitate fluid flow. The introduction of clay with a high fine fraction results in the progressive filling of intergranular voids within the laterite, thereby causing an exponential decrease in hydraulic conductivity in the clay-modified laterite samples. This agrees with studies by [24, 30] on the influence of soil properties on hydraulic conductivity. The authors indicated that the hydraulic conductivity of coarse-grained soil is controlled by the gravel fraction: high pore connectivity yields high hydraulic conductivity, whereas the progressive addition of fine material results in a fine-controlled matrix, leading to low hydraulic conductivity.

Clay-treated soils exhibited increased optimum moisture content (OMC) and reduced maximum dry density (MDD). This transition results in a finer pore structure, which is critical for reducing hydraulic conductivity. Similar trends have been reported in bentonite-modified soils by [28], who attributed the reduced MDD and increased OMC to the introduction of high-active clay (montmorillonite), which increased surface area, enhanced water adsorption, and reduced packing efficiency due to platy particle geometry and flocculated structures.

Consequently, hydraulic conductivity decreased by approximately 1–2 orders of magnitude with increasing clay addition. This reduction is attributed to both void-filling and physicochemical flow-restricting mechanisms, including diffuse double-layer effects that reduce effective pore size and restrict flow. This observation agrees with [27, 30] who indicated that the introduction of plastic clays progressively fills intergranular voids, and shifts flow paths toward micropores, thereby driving an exponential reduction in hydraulic conductivity. The attainment of hydraulic conductivity values on the order of 1×10^{-9} m/s within the 30–40% clay range demonstrates that engineered laterite–clay blends can meet international liner requirements.

From an engineering perspective, the results highlight a balance between hydraulic performance and volumetric changes. Untreated clay soils provide low permeability but are prone to shrink–swell behaviour, while laterite soils offer structural stability but insufficient sealing. Clay treatment of laterite soil enhances hydraulic performance but increases moisture sensitivity and the need for compaction control. The optimal performance observed at 30–40% clay content confirms that

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controlled blending provides a practical compromise, achieving both low hydraulic conductivity and acceptable compaction control.

These findings are particularly relevant for tailings management in artisanal and small-scale mining, where locally available laterite–clay blends offer a sustainable alternative to conventional liner systems. Moreover, the established relationships between basic soil properties and hydraulic conductivity provide a practical framework for rapid material selection in data-scarce environments.

4. Conclusions

4.1. Conclusions

Based on a laboratory study of three different laterite samples, each with three subgroups of different particle sizes, two clay samples, and clay-modified laterite samples, the following conclusions can be drawn.

Particle gradation strongly influences the soil sample's hydraulic conductivity. A high gravel content increases hydraulic conductivity, while a high fine (silt and clay) content reduces it.

The Atterberg limit properties (LL and PI) have a negative correlation with permeability.

The extent of hydraulic conductivity reduction in the clay-modified laterite sample depends strongly on the baseline hydraulic conductivities of both the laterite and clay samples, as well as on the percentage of clay added.

As clay content increases during compaction, MDD tends to decrease slightly, while OMC increases. This promotes a flocculated-to-dispersed microstructure, further encouraging a tighter microstructure and lower hydraulic conductivity through lengthened flow paths. Clay addition reduced MDD by 5–8% and increased OMC by 8–14%, consistent with greater surface hydration demand.

Clay addition reduced hydraulic conductivity by 1-2 orders of magnitude. Mixtures containing 30–40% clay achieved permeability $\leq 1 \times 10^{-9}$ m/s with finer gradation laterites (≤13.2 mm). Coarser gradations (≤19.1 mm) required 40–50% clay to achieve permeability $\leq 1 \times 10^{-9}$ m/s.

A hydraulic conductivity model incorporating fractal dimension, fine content, plasticity index, and maximum dry density exhibits strong generalisation, with a root mean square of approximately 0.80. This is a significant statistical parameter that supports hydraulic conductivity prediction using **Equation 4**. This makes it suitable for practical screening when full permeability testing is not feasible.

The hydraulic conductivity of a compacted soil liner depends on several factors, including physical properties, hydraulic gradient, compaction properties, and mineralogy.

4.2. Recommendations

The results of this study indicated that the investigated clay soil is suitable for use as a compacted soil liner for seepage control.

For small dams, a laterite–clay mixture containing 30–40% clay is recommended because it yields hydraulic conductivity values on the order of 1×10^{-9} m/s, which are commonly considered acceptable for such structures.

For dams subjected to high hydraulic gradients, increasing the clay content to above 40% is recommended because it reduces hydraulic conductivity to 10^{-10} m/s, providing enhanced seepage resistance.

Although increasing the proportion of clay sample enhances seepage resistance, practitioners should consider potential impacts on workability, shrinkage behaviour, and cracking susceptibility, particularly at higher modified-clay contents.

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