

Hydraulic Performance Evaluation of Clay, Laterite, and Bentonite-Modified Laterite Soils for Use as Liner Materials

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Abstract: Artisanal and small-scale gold mining (ASGM) generates large volumes of tailings that pose serious risks to soil and groundwater due to inadequate containment systems. Developing cost-effective, locally available liner materials is therefore critical to improving environmental protection in resource-constrained settings. This study evaluates the hydraulic conductivity of clays, laterite soils, and bentonite-modified laterites as potential liner materials for tailings storage facilities. Three clay soils (CL1–CL3), three lateritic soils (LS1–LS3), and calcium bentonite were characterised through particle size distribution, Atterberg limits, compaction, free swell index, X-ray diffraction (XRD), chemical analysis, and hydraulic conductivity testing. Untreated clays exhibited moderate to high plasticity (LL = 41–71%; PI = 25–44%) and low hydraulic conductivity (10^{-10} – 10^{-11} m/s), satisfying international liner hydraulic conductivity criteria. In contrast, untreated laterites showed low plasticity (PI = 9–17%) and higher hydraulic conductivity (10^{-8} – 10^{-9} m/s), making them unsuitable as standalone liners. Mineralogical analysis revealed kaolinite and vermiculite dominance in clays; laterites contained quartz, hematite, and kaolinite, while bentonite is montmorillonite-rich. Incremental bentonite contents (1–10%) increased linear shrinkage, liquid limit, plasticity index, and free swell index, while decreasing maximum dry density and increasing optimum moisture content. Hydraulic conductivity decreased by 1–2 orders of magnitude with increased bentonite addition, meeting the adopted hydraulic conductivity criterion of 1×10^{-9} m/s. Depending on the initial gradation, baseline hydraulic conductivity of the laterite soil, and the hydraulic gradients under which the samples were tested, 2–4% bentonite addition resulted in a hydraulic conductivity of $<1 \times 10^{-9}$ m/s. The results indicate that bentonite-modified laterite is promising for liner applications under the tested laboratory conditions.

Keywords: Bentonite-modified laterite, hydraulic conductivity, soil liners, tailings containment, artisanal and small-scale gold mining.

1 INTRODUCTION

Artisanal and small-scale mining (ASM) remains a significant driver of economic development globally, particularly in resource-rich developing regions. In Sub-Saharan Africa, mineral exploitation has historically contributed substantially to national revenues, foreign exchange earnings, and employment creation [1], [2]. ASM provides livelihoods for millions of people in Africa and other developing countries worldwide. Its socio-economic importance is reflected through employment and poverty reduction, particularly in rural and marginalised communities [3]. In Ghana, ASM accounted for approximately 43% of total gold production in 2018. These figures underscore ASM's growing relevance to national economies and the urgent need to integrate the sector into sustainable development frameworks [3]. Despite its economic significance, ASGM is widely associated with severe environmental degradation and public health risks [4], [5]. Gold extraction and processing generate large volumes of waste materials, commonly referred to as tailings, which may contain residual mercury and cyanide associated with amalgamation and cyanidation processes [6].

At ASM sites, tailings are often disposed of indiscriminately because of limited technical capacity, financial constraints, and weak regulatory enforcement [7]. Several documented cases across Africa and other regions have demonstrated the catastrophic consequences of poor tailings management, including mass fish kills, loss of potable water sources, and long-term ecosystem damage. Although international conventions and national regulations call for responsible tailings management, compliance within the ASGM sector remains limited [3]. Mercury use in the amalgamation process remains one of the most critical environmental concerns associated with artisanal and small-scale gold mining (ASGM). During ore processing and amalgam burning, mercury is discharged into the atmosphere, soils, and aquatic environments [8]. In water bodies, mercury may transform into highly toxic methylmercury, which bioaccumulates in aquatic organisms and is subsequently transferred through the food chain to humans [9].

Communities downstream of ASGM operations often rely on contaminated water for drinking, irrigation, and fishing, thereby facing heightened risks of neurological disorders, reproductive health problems, and developmental impairments, particularly among children and pregnant women. Well-designed and properly constructed tailings dams help minimise contaminant transport and safeguard surrounding ecosystems. The liner system is central to the performance of such facilities, acting as a barrier to prevent seepage of contaminated effluents into the subsurface. Common liner materials include high-density polyethylene (HDPE) geomembranes, geosynthetic clay liners (GCLs), and compacted clay liners (CCLs). While HDPE geomembranes and geosynthetic clay liners are effective containment materials, their application can require more material, installation, and quality-control effort than locally available compacted soils [10]-[12].

In Sub-Saharan Africa, ASGM operations need cost-effective, locally sourced, and technically feasible liner solutions. Locally available soils, including laterite and clay-rich materials, are abundant across many mining regions. With appropriate engineering modifications, such as blending, compaction, and chemical stabilisation, these soils can meet the liner requirement for tailings containment. Hydraulic conductivity, shrink-swell characteristics, and chemical attenuation are key soil liner considerations [11]-[13]. Using locally available and modified soils offers an opportunity to reduce construction costs, enhance regulatory compliance, and promote environmentally responsible mining practices in the ASGM sector.

Existing research on ASM has largely focused on socio-economic impacts, environmental impacts, and policy challenges. Compared with other sectors, comparatively little attention has been paid to practical engineering solutions tailored towards sustainable ASGM operations. A clear research gap remains in systematically evaluating alternative liner materials for tailings dams in ASGM operations within the sub-region. Addressing this gap is essential for developing sustainable tailings management strategies that balance environmental protection with economic realities of ASGM. This study, therefore, investigates the suitability of locally available soils and bentonite-modified soils as liner materials for tailings dams in ASGM by focusing on material characterisation and hydraulic performance. This research aims to contribute to affordable, locally appropriate, and environmentally sound tailings management solutions for ASGM operations.

2 MATERIALS AND METHODS

2.1. Material Selection

Sampling locations were chosen based on soil characteristics and geological properties, primarily lateritic soils and natural clays. These locations were selected to capture variability in soil properties. A total of six samples were collected from six locations (three samples each from lateritic and natural clay geologic formations). The laterite soils were sourced from Katenda in Chongwe District (LS1), Lusaka South in the Shantumbu area (LS2), and the University of Zambia campus (LS3). The clay samples were collected from Goma fields at the University of Zambia (CL1), Kaumbwe in Petauke District (CL2), and Matero in Lusaka District (CL3). Soil samples were obtained by manually excavating test pits ranging from 0.5 m to 1.5 m, ensuring sampling below the organic matter zone. Using a hand tool, disturbed samples were obtained from the base of the test pits. The sampling technique was conducted in accordance with ASTM D420 [14] for site investigation and subsurface exploration. The samples were sealed in labelled bags immediately after collection and transported to the Materials Engineering Laboratory at the University of Zambia for testing. In addition, a local drilling services company supplied calcium bentonite. The study selected calcium bentonite because it is locally available and cost-effective.

2.2. Sample Preparation

Soil samples were spread under ambient laboratory conditions and air-dried. Once drying was complete, the clay soils were lightly crushed to break down hardened lumps, then passed through a 6.7 mm sieve to obtain a consistent material suitable for testing. Following drying, the samples were stored in airtight bags to prevent moisture reabsorption. All samples were stored in a temperature-controlled laboratory (20°C–25°C) until testing. To investigate the influence of particle size on hydraulic conductivity, each laterite soil was divided into three gradation classes using 19.1 mm, 13.2 mm, and 6.7 mm sieves. The resulting fractions were treated as separate untreated materials. The gradation-controlled laterite soils, together with the clay soils, were collectively referred to as untreated samples.

Bentonite-modified specimens were subsequently prepared by incorporating 1, 2, 4, 6, 8, and 10% bentonite as a proportion of dry laterite to assess the impact of bentonite content on the hydraulic conductivity of soil liners. The 1–10% bentonite content was selected based on literature and engineering considerations. Previous studies show that bentonite additions within this range significantly reduce hydraulic conductivity [15]. Higher bentonite content usually adversely affects workability, shrink-swell properties, and liner construction cost, while very low bentonite content may not meet the hydraulic conductivity requirement. Dry soil samples were thoroughly mixed with dry bentonite in predetermined proportions using a bench-top soil mixer to ensure laterite-bentonite uniformity. Smaller mixes were manually mixed in a steel tray with a spatula until visual inspection confirmed homogeneity.

Dry mixing was done over 5 minutes. Before Atterberg limit tests, compaction, and hydraulic conductivity testing, distilled water was slowly added to the dry samples, and mixing progressed for about 8 minutes after uniform consistency was obtained. After wet mixing, the mixtures were stored in airtight plastic bags and allowed to equilibrate for 24 hours under controlled laboratory conditions (18°C–20°C) to ensure uniform moisture distribution and adequate hydration of the bentonite-modified laterite samples.

2.3. Testing methodology

Particle-size distribution was determined by combining wet sieve analysis with hydrometer testing in accordance with BS 1377-2 [16]. Liquid and plastic limits were measured using the cone penetrometer and hand-rolling procedures, respectively, while linear shrinkage was evaluated using the same standard. The linear shrinkage test in accordance with BS 1377-2 determined the shrinkage properties of the untreated and bentonite-modified samples. Water equivalent to the liquid limit was added to the dry samples, mixed thoroughly, and hydrated for 24 hours before testing. The Atterberg limit test was conducted in duplicate, and the average values were reported. The free swell index was determined using both distilled water and kerosene according to IS 2720 [17]. Specimens were tested in duplicate, and average values were reported. The difference between duplicate measurements was less than 0.5%, which is acceptable by BS 1377.

Five 3.2 kg specimens from each dry bentonite–laterite mixture and untreated samples were weighed. Predetermined amounts of water (3%, 6%, 9%, 12%, and 15%) were added, and specimens were thoroughly mixed using a bench-top soil mixer to ensure uniform moisture distribution. The uniformly mixed samples were sealed in airtight containers and allowed to equilibrate for 24 hours before compaction. After equilibration, the compaction test was conducted according to the standard Proctor method, corresponding to BS 1377-4 [18], employing a 2.5 kg rammer with 25 blows per layer for 3 layers to produce a reported energy level of 601 kJ/m³, compared with approximately 594 kJ/m³ for the standard Proctor. Hydraulic conductivity testing was carried out in accordance with ASTM D5856 [19] using the falling-head method. The samples were equilibrated at 2 percentage points above the optimum moisture content for 24 hours. Compaction for the hydraulic conductivity test was performed directly inside the rigid-wall permeameter mould in two layers. The variation in specimen height is attributed to differences in the heights of the available permeameter cells.

The surface of the first layer was grooved after compaction to ensure proper bonding with the overlying layer. The second layer was then placed and compacted. Each layer was compacted to approximately 40 mm thick using 25 blows of a 2.5 kg rammer, resulting in a reported energy level of 595 kJ/m³. After compaction, the specimen was carefully trimmed. The mould with the compacted specimen was then weighed, and representative trimmings were collected to determine moisture content. This was used to determine the compaction level. The compaction level for hydraulic conductivity testing was 97%–99%. The rigid wall permeameter was assembled and checked for possible leakage. A water head of 3.0 m was maintained through a reservoir system during specimen saturation. Saturation was considered satisfactory when no further air bubbles were detected in the outlet tube, effluent flow was steady, and hydraulic conductivity readings stabilised. Saturation lasted 12 to 24 hours for untreated laterite samples, while clay- and bentonite-modified samples lasted 48 to 168 hours, depending on particle size and bentonite content. Permeation was performed using tap water at hydraulic gradients of 18 and 29. The hydraulic gradients used in this study were selected to facilitate measurable flow through the low-hydraulic-conductivity clay and laterite–bentonite mixtures, and do not represent field conditions.

At the selected hydraulic gradients, no soil boil, channelling along the permeameter sidewall, or sudden increase in seepage flow through the specimens was observed. The difference in compacted thickness was accounted for by adjusting the water head during permeation to ensure the same hydraulic gradient across all samples. The permeating fluid was water. Hydraulic conductivity under actual tailings effluent may differ because of differences in fluid chemistry and ionic strength. Duplicate tests were performed for each sample to verify result consistency, and the average value was reported. Hydraulic conductivity measurements were determined from five consecutive readings. Effluent temperature was measured and used to correct hydraulic conductivity values to standard values at 20°C. The difference between replicate measurements was minimal, with variation within 10%–15%.

While ASTM D5856 does not specify an allowable percentage difference between duplicate tests, the observed variability is within the range commonly reported for laboratory hydraulic conductivity measurements. The cation exchange capacity (CEC) of the samples was determined using 1N ammonium acetate at a pH of 7.0. The CEC determination followed the ion-displacement principle after washing, as described in the FAO GLOSOLAN standard operating procedure [20]. Mineralogical characterisation was achieved through X-ray diffraction (XRD). Air-dried samples were ground, sieved (<63 µm), and clay-sized particles were obtained through sedimentation and centrifugation. The residue was air-dried under laboratory conditions. The dried sample was subsequently crushed into powder for X-ray testing. XRD analysis was conducted on randomly prepared powdered samples without oriented mounts or glycolation treatment. The analysis was limited to general mineralogical identification rather than detailed clay-mineral characterisation. Semi-quantitative interpretation was done. The Olympus TERRA-538 portable XRD analyser was used to analyse the samples over a 2°–60° 2θ scanning range.

Chemical composition was determined using 0.5 g of air-dried soil ($<63\ \mu\text{m}$). Soil samples were subjected to chemical fusion using ammonium difluoride (NH_4HF_2) to ensure complete breakdown of silicate minerals. The fused samples were subsequently digested using a reverse aqua regia method involving nitric acid (HNO_3), hydrochloric acid (HCl), and hydrofluoric acid (HF). The digestion was conducted by heating the acid mixture on a hot plate at $95 \pm 5\ ^\circ\text{C}$ for 1.5–2 hours, until the soil completely dissolved and the solution became clear. Duplicate digestions were performed to evaluate analytical precision, and the results showed satisfactory agreement between replicates. However, certified reference materials (CRMs) were not analysed. Therefore, analytical accuracy could not be independently verified against certified standards. This represents a limitation of the study. The digestion procedure used ammonium difluoride fusion followed by reverse aqua regia digestion.

After digestion, the solution was allowed to cool, diluted to 100 mL with distilled water, and filtered into acid-washed sample containers. The diluted samples were analysed immediately using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES). ICP-OES calibration was performed using a multi-element calibration approach prepared from standard stock solutions (1000 mg/L). Several calibration standards covering the anticipated concentration range of the samples, along with reagent blanks, were used to determine calibration curves. The calibration was deemed satisfactory when the coefficient of determination surpassed 0.999. The detection limits for the analysed metals were determined from the instrument specifications as $<0.01\text{mg/L}$. Concentrations below the detection limit were reported as not detected. Major oxides were derived from the elemental concentrations determined by ICP analysis.

3 RESULTS AND DISCUSSION

3.1. Properties of Untreated Samples

3.1.1. Particle Size Distribution

The particle gradation for the various soil samples indicates that CL1 contains 1% gravel, 31% sand, and 68% fines (38% clay and 30% silt). CL2 contains no gravel, 40% sand, and 60% fines (51.5% clay and 8.5% silt). CL3 has 12% gravel, 33% sand, 19% silt, and 36% clay. The natural clay soils meet the soil gradation requirements for a typical soil liner, as recommended by the UK Environmental Agency [12]. Different grading groups in each laterite produced different gradations. LS1 and LS3 had high gravel contents of 42% and 30%, respectively, in samples passing a 19.1mm sieve. Passing through the 13.2mm sieve reduced gravel content and increased the sand, silt, and clay fractions. The gravel contents present in LS₁ and LS₃ for samples passing the 19.1mm sieve exceed the 30% maximum liner requirement, as recommended by the UK Environmental Agency [12]. LS₂ produced less gravel and clay fractions but a high sand content for all grading groups.

Samples with maximum sizes of 13.2mm and 6.7mm for both LS₁ and LS₃ met the liner requirement based on particle gradation but failed the liner requirement for a maximum particle size of 19.1mm. With low clay content and high sand fractions across all sample groups under LS₂, the soil does not meet the liner requirement. According to the Unified Soil Classification System (USCS), CL1 could be classified as low-plasticity clay (CL), while CL2 may be classified as high-plasticity clay (CH). All sample groups under LS₁, LS₂ and LS₃ could be classified as clayey sand (SC). Fig. 1 presents the particle gradation curves for the various untreated samples, and Table 1 summarises them.

3.1.2. Soil Plasticity

The laterite soils exhibit relatively low to moderate plasticity. Liquid limit values range from 27% to 33%, with plasticity indices generally between 9% and 17%. For example, LS1 shows LL = 33% and PI = 17%, while LS2 has LL = 27% and PI = 9%, indicating low plasticity and limited clay activity. The clay soils demonstrate significantly higher plasticity than the laterites. Their LL values range from 41% to 71%, while PI values range from 25% to 44%. CL₂ exhibits very high plasticity (LL = 71%, PI = 44%), reflecting the existence of active clay minerals. CL₂ is plotted on the high plasticity clay side of the chart; CL1 and CL3 are plotted on the intermediate plasticity clay side of the chart, while LS1, LS2, and LS3 are plotted on the low plasticity clay side of the chart, as indicated in Fig. 2. Except for LS₂, all samples satisfy the PI requirement for application as soil liner materials [12]. Bentonite represents the end of the plasticity spectrum, with LL = 331% and PI = 281%. The progressive increase in LL and PI from laterite to clay to bentonite reflects increasing clay mineral activity.

3.1.3. Specific Gravity

The samples had specific gravity ranging from 2.41 to 2.71. The laterite soil samples exhibited values of 2.41, 2.68, and 2.54, with an average of 2.54, while the clay samples ranged from 2.65 to 2.71, with an average of 2.67. The clay samples generally exhibited higher specific gravity than the laterite soils, suggesting a relatively greater proportion of denser mineral constituents.

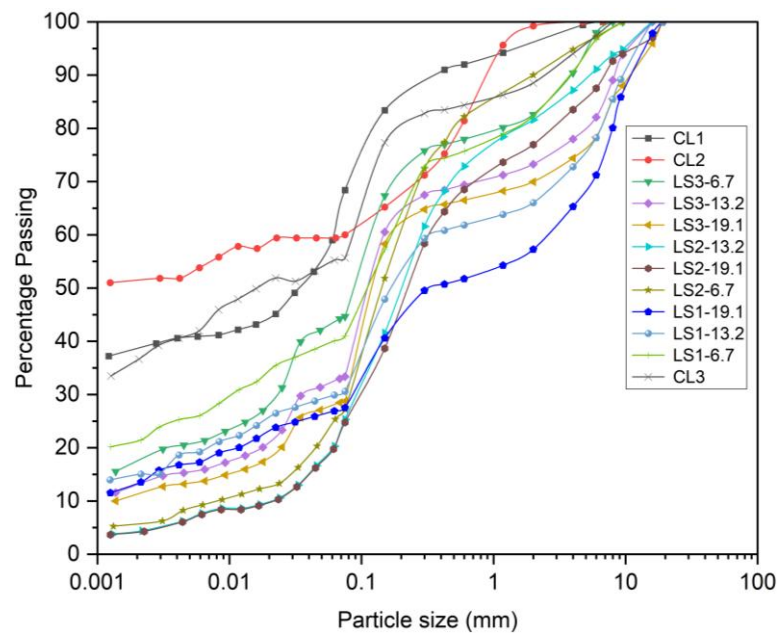


Fig. 1. Particle size distribution of untreated soil samples.

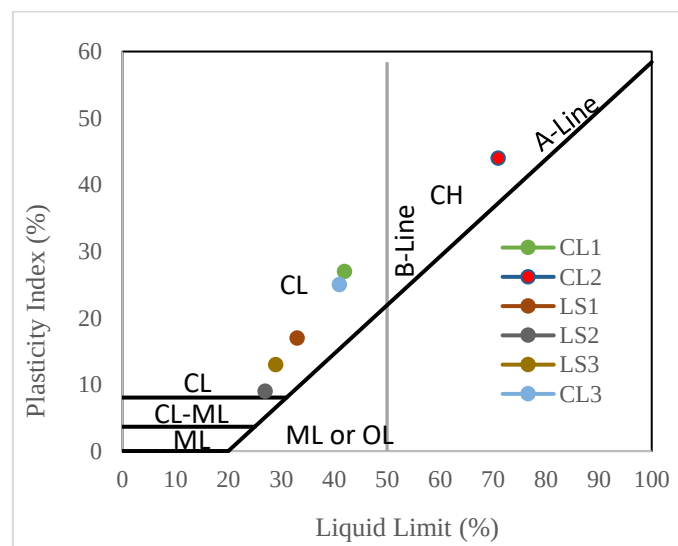


Fig. 2. Casagrande plasticity chart for untreated soil samples.

3.1.4. Compaction

The compaction results indicate distinct differences between the clay and laterite soils. CL1 and CL2 both recorded an OMC of 19%, with corresponding MDD values of 1.74 g/cm³ and 1.68 g/cm³, respectively, whereas CL₃ exhibited a lower OMC of 15.5% and a higher MDD of 1.86 g/cm³. The comparatively high moisture demand and lower dry densities of the clay samples are likely related to their greater proportion of fine particles and the presence of expansive clay minerals, which increase water adsorption during compaction. Among the laterite soils, LS1 exhibited a slightly higher OMC and a lower MDD.

This behaviour is consistent with its relatively higher plasticity index, which increases the amount of water required to achieve maximum compaction while limiting the attainable dry density. In contrast, LS2 and LS3 attained marginally higher MDD values at lower OMC, reflecting the influence of their lower plasticity and comparatively coarser particle composition. Although the laterite soils were prepared using three different particle-size fractions obtained by sieving, the resulting gradation changes had only a minor influence on the moisture–density relationships within each soil type. Fig. 3 illustrates the compaction characteristics, expressed as the relationship between optimum moisture content and maximum dry density, and Table 1 summarises them.

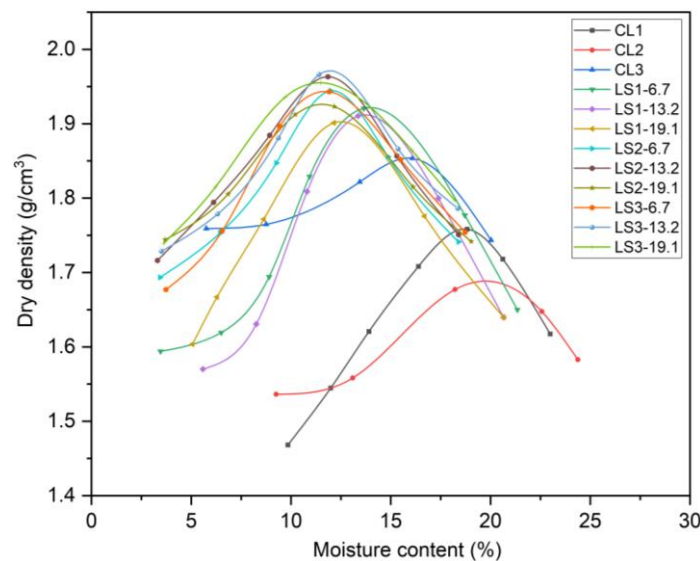


Fig. 3. Compaction curves for untreated samples.

Table 1. Summarised results for untreated samples.

Sample ID	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	LL (%)	PI (%)	USC	GS	MDD (g/cm³)	OMC (%)	FSI (%)
LS1-19.1	35	38	15	13	33	17	SC	2.41	1.9	12	21
LS1-13.2	27	42	16	15					1.91	13	
LS1-6.7	9	50	20	21					1.92	13.5	
LS2-19.1	16	59	21	4	27	9	SC	2.68	1.93	11.5	15
LS2-13.2	13	62	21	4					1.94	11.8	
LS2-6.7	5	68	21	6					1.95	12	
LS3-19.1	26	46	18	11	29	11	SC	2.54	1.95	11	22
LS3-13.2	22	45	20	13					1.97	11.4	
LS3-6.7	10	46	27	18					1.94	11.5	
CL1	1	31	30	38	42	27	CL	2.71	1.74	19	26
CL2	0	40	9	52	71	44	CH	2.65	1.68	19	73
CL3	7	38	19	36	41	25	CL	2.66	1.858	15.5	40
Bent	0	0	2	98	331	281	CH	-	-	-	600

3.1.5. Chemical Properties

All samples were dominated by SiO_2 , with significant amounts of Al_2O_3 , Fe_2O_3 , CaO , MgO , and Na_2O . The sesquioxide ratio ($\text{SiO}_2/(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)$) is commonly used to classify residual soils. Ratios below 1.33 indicate true laterites, values between 1.33 and 2.0 represent lateritic soils, while ratios exceeding 2.0 are classified as non-lateritic soils [21]. Based on this criterion, LS1, LS3, CL1, and CL2 were classified as lateritic soils, LS2 as a lateritic soil, and CL3, together with bentonite, as non-lateritic materials. Table 2 summarises the percentages of oxides available in each sample. The cation exchange capacity was 11 meq/100g for both LS1 and LS2, while LS3 recorded 13 meq/100g. The clay samples recorded CEC of 28 meq/100g, 40 meq/100g, and 31 meq/100g for CL1, CL2, and CL3, respectively, while the bentonite sample had a CEC of 43 meq/100g. The high CEC of the clay and bentonite samples reflects a high specific surface area due to the presence of active clay minerals. The low CEC of the laterite samples indicates the absence of active clay minerals.

3.1.6. Mineralogical Properties

The X-ray diffraction patterns display distinct, well-defined peaks corresponding to the principal mineral phases, as illustrated in Fig. 4. The XRD results for LS1 and LS3 suggest intense tropical weathering conditions that promoted the development of a regolith profile rich in kaolinite. This mineralogical composition is characteristic of soils formed from distinct climatic conditions, as reported by Gadigas [21].

Table 2. Major oxide compositions of the untreated samples.

	CL1	CL2	CL3	LS1	LS2	LS3	Bentonite
Al ₂ O ₃	28.7	20.2	6.5	29.8	18.7	30.1	13.8
CaO	10.0	11.7	15.1	4.9	15.8	2.9	13.3
Fe ₂ O ₃	5.0	9.5	6.2	13.9	7.1	15.8	8.0
K ₂ O	3.1	3.3	0.8	1.1	0.5	3.8	0.5
MgO	9.7	8.0	4.7	5.2	5.9	5.4	9.3
SiO ₂	33.0	33.5	59.0	37.4	44.9	30.5	45.9
Na ₂ O	7.2	8.1	1.9	4.3	2.2	7.6	6.4
P ₂ O ₅	3.0	3.5	3.5	2.7	3.5	2.8	1.9
TiO ₂	0.8	2.3	<LOD	1.0	<LOD	1.0	<LOD
$\frac{\text{SiO}_2}{\text{R}_2\text{O}_3}$	0.979	1.128	4.6	0.856	1.740	0.664	2.106

These findings are consistent with the soil classifications as revealed by $\text{SiO}_2/(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)$. LS2 is primarily composed of quartz and hematite. This mineral assemblage indicates intense tropical weathering, laterite development, and weathering of feldspar-rich parent materials. In contrast, the XRD pattern of CL1 shows kaolinite as the dominant mineral with only a minor quartz component. Such a composition is consistent with extensive chemical weathering in tropical environments and is typical of well-developed kaolin deposits. CL2 is predominantly composed of vermiculite. This dominance of a 2:1 clay mineral is consistent with soils exhibiting high swelling and plasticity behaviour. CL₃ consists of quartz, dolomite, vermiculite and phlogopite. Overall, CL3 reflects a mixed mineralogy. The bentonite sample is predominantly montmorillonite, indicating a montmorillonite-rich smectitic clay. The mineralogical compositions of the various soil samples agree with Mitchell *et al.* [22] on the mineralogical compositions of laterite soils, clay soils, and bentonite. XRD results were sufficient to identify key minerals relevant to the study, and geotechnical and hydraulic conductivity data supported the interpretation.

3.1.7. Swell and Shrinkage Properties

Free swell index (FSI) values of 21%, 15%, and 22% were recorded for LS1, LS2, and LS3, respectively. CL1 and CL3 had free swell indices of 26% and 40%, respectively, while CL2 recorded 73%. According to [13], the FSI values for LS1, LS2, LS3, CL1, and CL3 may be considered low, while CL2 may be considered moderate. The low FSI of LS1, LS2, LS3, and CL1 could be associated with inactive clay minerals (kaolinite, quartz, and hematite) with small surface areas and low water adsorption, which is the primary mechanism responsible for swelling. CL2 recorded moderate FSI due to the dominance of an expansive clay mineral (vermiculite) with a higher surface area and greater water-absorption capacity. The linear shrinkage of the samples was 7.9%, 3.2%, 6%, 13.6%, 18%, and 13.6% for LS1, LS2, LS3, CL1, CL2, and CL3, respectively. Except for CL2, linear shrinkage may be considered acceptable for use as a liner material. The expansive clay mineral (vermiculite) in CL2 results in higher water adsorption during wetting and, subsequently, higher linear shrinkage upon drying, while the low clay content of LS2 contributed to its relatively low linear shrinkage.

3.1.8. Hydraulic Properties

The hydraulic conductivity results show that CL1 and CL3 exhibited values on the order of 10^{-10} m/s, while CL2 recorded values on the order of 10^{-11} m/s. These values satisfy the hydraulic conductivity criterion for soil liners recommended by the UK Environment Agency [12]. Their low hydraulic conductivity likely reflects the low coarse fraction, high clay fraction, and predominance of clay minerals such as kaolinite and vermiculite. In contrast, LS2 exhibited hydraulic conductivity values on the order of 10^{-8} m/s across all particle-size ranges and hydraulic gradients. The hydraulic conductivity of LS1 and LS3 ranged from 10^{-8} to 10^{-9} m/s depending on gradation and hydraulic gradient. The relatively higher hydraulic conductivity of the laterite soils may be attributed to their greater sand content, lower clay fraction, and the dominance of quartz and hematite rather than highly active clay minerals. The gradation-controlled laterite samples showed noticeable differences in hydraulic conductivity. For example, LS1 specimens passing the 19.1 mm and 6.7 mm sieves recorded hydraulic conductivities on the order of 10^{-8} and 10^{-9} m/s, respectively. Comparable trends were observed for LS2 and LS3.

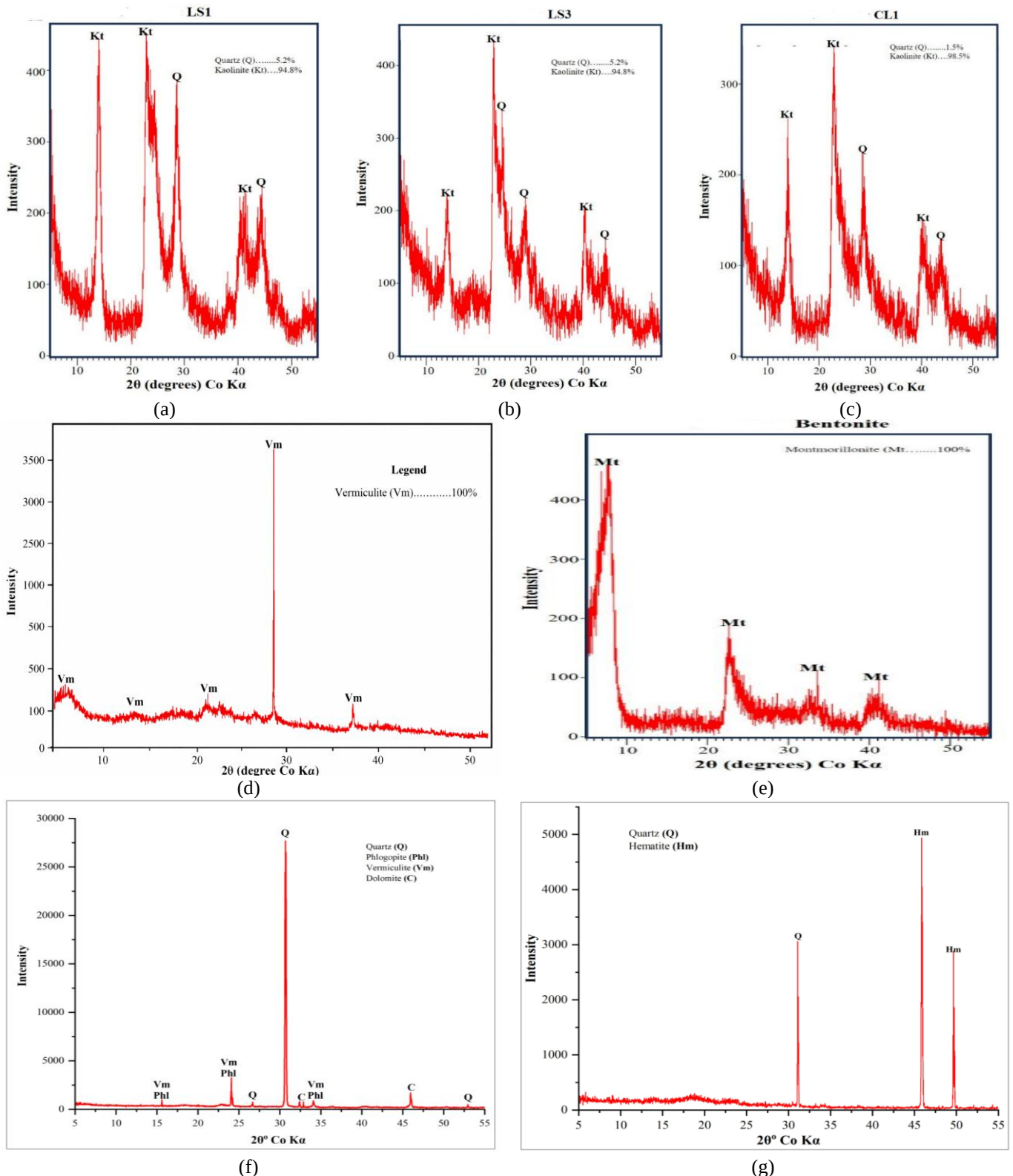


Fig. 4. X-ray diffractogram of soil samples (a) LS₁, (b) LS₃, (c) CL₁, (d) CL₂, (e) Bent, (f) CL₃ and (g) LS₂

Overall, particle-size distribution and mineralogical composition strongly influenced hydraulic conductivity. Samples with higher gravel and sand contents, lower clay fractions, and less active clay minerals exhibited higher hydraulic conductivity. Conversely, the clay soils, which contained abundant fine particles and clay minerals, developed a dense microstructure with small, poorly connected pores that restricted water movement. The laterite soils formed a coarser framework with interconnected macropores, allowing more rapid flow.

These findings agree with Boadu [23], who reported that well-connected gravel-sized pores control hydraulic conductivity in coarse-grained soils. In contrast, the fine matrix in clay-rich soils restricts pore connectivity and reduces hydraulic conductivity. Table 3 summarizes the hydraulic conductivity results for the untreated soil samples under different hydraulic gradients.

Table 3. Hydraulic conductivity results of untreated samples.

Sample ID	LS1-19.1	LS1-13.2	LS1-6.7	LS2-19.1	LS2-13.2	LS2-6.7	LS3-19.1	LS3-13.2	LS3-6.7	CL1	CL2	CL3
Hydraulic conductivity (nm/s)												
j = 18	8.03	7.73	3.44	50.6	28.5	9.78	9.79	8.39	7.81	0.524	-	0.564
j = 29	10.2	9.40	5.48	61.9	39.2	16.3	12.1	9.99	8.92	0.606	0.0653	0.708

j = hydraulic gradient

3.2. Physical Properties of Bentonite-Modified Samples

3.2.1 Soil Plasticity

Adding bentonite consistently increased the PI of the laterite-bentonite mixtures. Even small quantities of bentonite (2–4%) increased PI noticeably, while higher incorporation (6–10%) led to a marked rise in plasticity, as shown in Fig. 5, underscoring the growing influence of bentonite clay mineralogy.

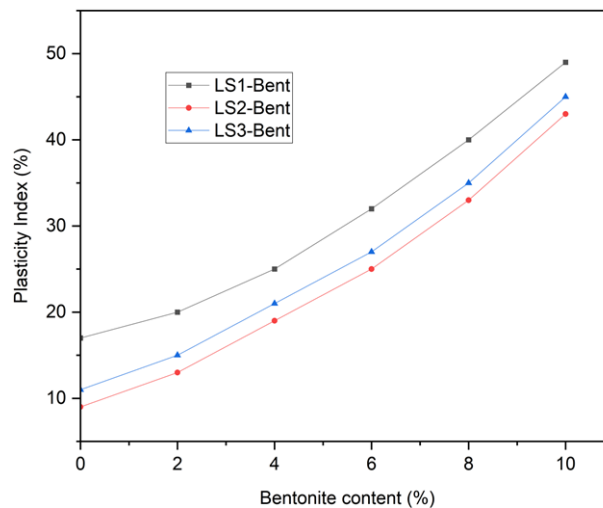


Fig. 5. Influence of Bentonite on plasticity index of laterite sample.

The plasticity index increases more sharply beyond 4% bentonite addition. At 6%, the PI increase becomes more pronounced, reaching approximately 44 – 49% at 10% bentonite for the different laterite samples. This steeper rise beyond 6% bentonite suggests a dosage beyond which bentonite becomes the main factor influencing soil consistency. This trend underscores the importance of bentonite clay minerals in the mixtures' plasticity behaviour. Eyo et al. [24] and Zeng et al. [25] previously reported that the plasticity index increases with increasing bentonite content.

LS₁ consistently records the highest PI values across all bentonite contents. LS2 shows the lowest PI values, with LS3 positioned between LS1 and LS2. The consistent vertical gap between the curves, as shown in Fig. 5, indicates that the base soil's plasticity influences absolute PI values, while bentonite addition determines the overall trend. Notably, the approximately parallel curves suggest that bentonite affects all soils' plasticity proportionally. Differences among individual soil series underscore the need to account for base-soil variability when determining bentonite dosages for liner designs. This behaviour is attributed to physico-chemical mechanisms. The increase in plasticity is associated with the increased surface area and enhanced water adsorption capacity of montmorillonite, the dominant clay mineral in bentonite. As bentonite content increases, more water is required to reach the liquid limit because of the mineral's strong affinity for water, leading to higher plasticity values.

3.2.2. Compaction

The density-moisture content relation for the bentonite-modified laterite soils is represented by Fig. 6. The compaction curves of the bentonite-treated samples shifted rightward (higher OMC) and downward (lower MDD) compared to those of the untreated samples. This inverse OMC–MDD relationship is characteristic of highly active clay minerals.

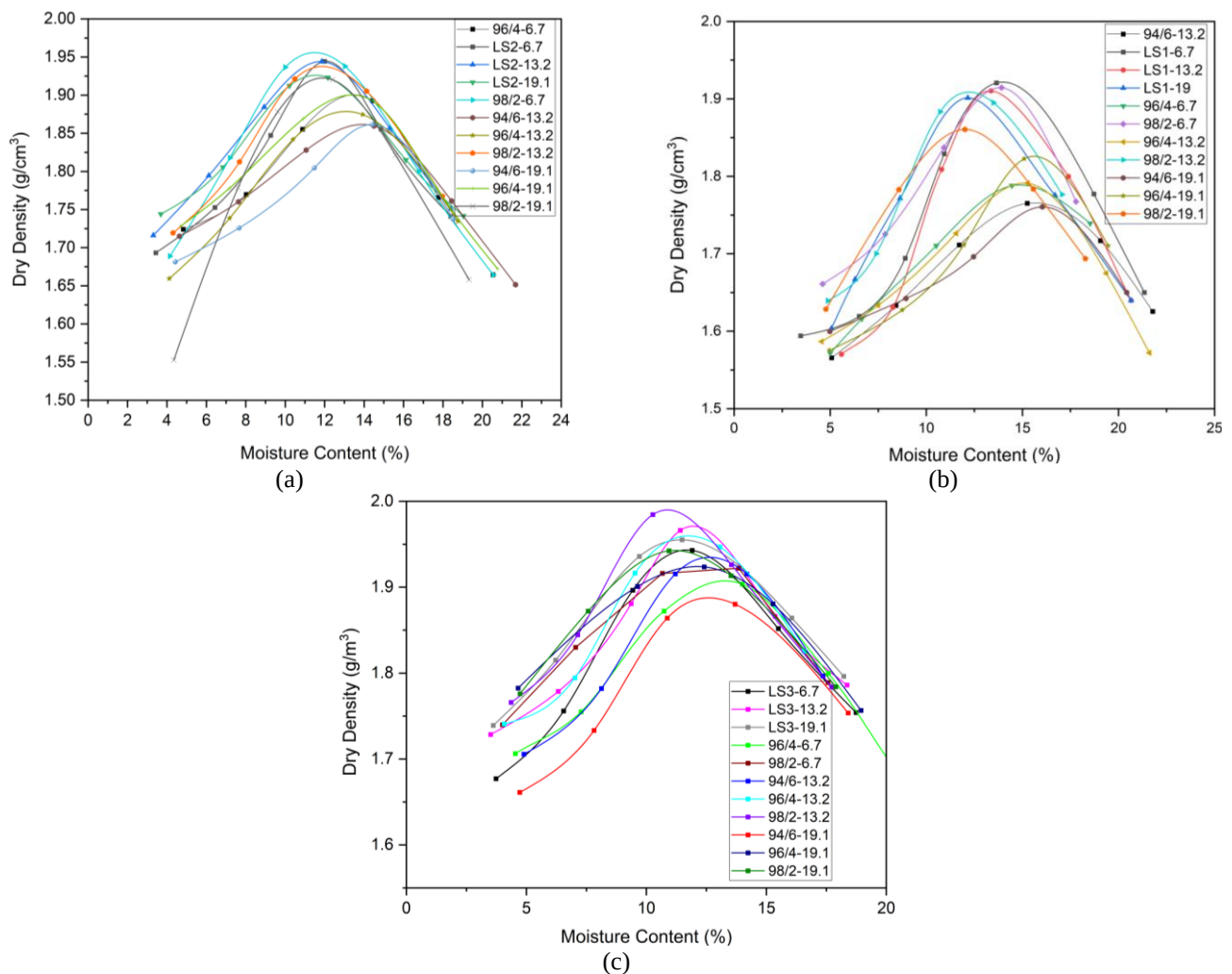


Fig. 6. Influence of bentonite on the compaction properties (a) LS₁, (b) LS₂ and (c) LS₃.

The compaction results clearly indicate that increasing bentonite content (0–10%) consistently reduced the maximum dry density (MDD) while increasing the optimum moisture content (OMC) for all laterite soils. This trend is consistent across the entire bentonite content range, confirming that bentonite addition reduces dry density regardless of the base laterite soil, as shown in Fig. 7.

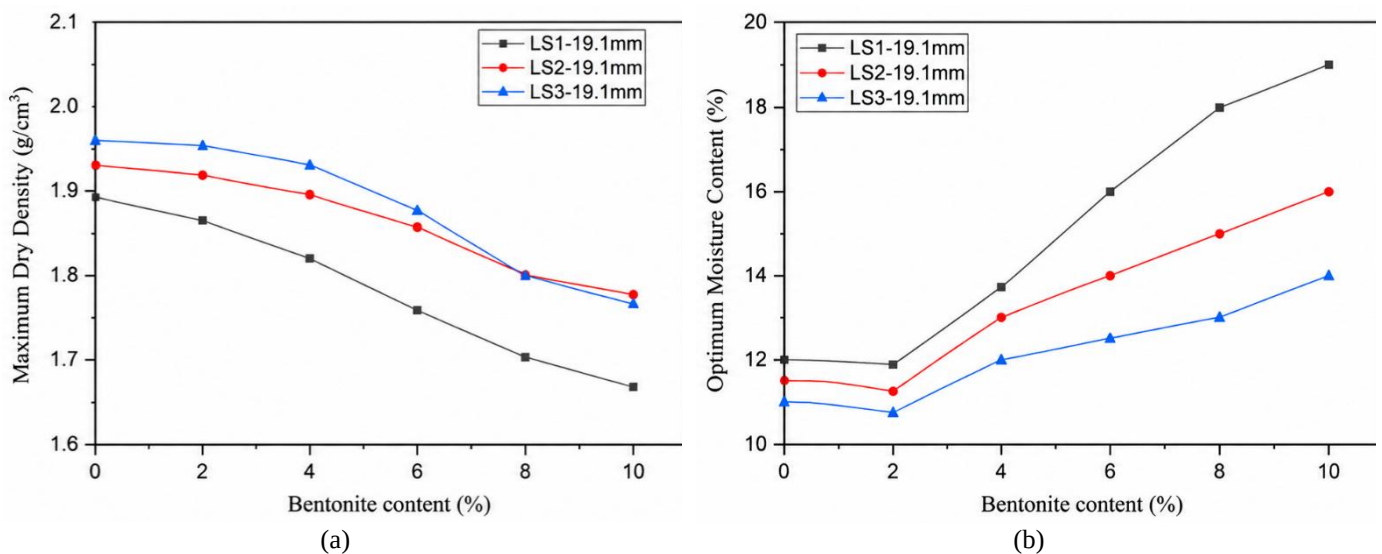


Fig. 7. Effect of bentonite on (a) maximum dry density, (b) optimum moisture content of laterite samples.

The reduction in MDD is gradual at low bentonite contents (0–4%), becomes more pronounced beyond 4–6%, and is most evident at 8–10% bentonite addition. Fig. 7 (a) shows a consistent reduction in MDD across all soil types as bentonite content increased from 0 to 10%. For LS₁, MDD decreased from 1.90 g/cm³ at 0% bentonite to 1.67 g/cm³ at 10% bentonite, representing an overall reduction of about 0.23 g/cm³ (12.1%). Similarly, LS₂ decreased from 1.93 g/cm³ to 1.78 g/cm³ over the same bentonite range, a reduction of about 0.15 g/cm³ (7.8%). LS₃ showed the highest initial density but a comparable decline, with MDD decreasing from 1.95 g/cm³ at 0% bentonite to 1.77 g/cm³ at 10% bentonite, a reduction of about 0.18 g/cm³ (9.2%). Similar trends have been reported by Eyo *et al.* [24] and Nath *et al.* [15] upon addition of different percentages of bentonite to kaolinite clay and other local soils. The observed decrease in MDD with increasing bentonite content agrees with Mitchell *et al.* [22] who attributed the swelling behaviour, which promotes the formation of a more open soil structure during compaction, to a reduced MDD. The authors also indicated that fine bentonite particles tend to coat coarser lateritic grains, reducing interparticle friction and limiting efficient particle rearrangement during compaction.

In contrast to MDD, OMC increased systematically with increasing bentonite content across all soil types, except for a minor reduction at 2% bentonite, as shown in Fig. 7(b). For LS₁, OMC increased from approximately 12.0% at 0% bentonite to 19.0% at 10% bentonite, representing an absolute increase of about 7.0%. LS₂ showed a moderate increase in OMC, rising from about 11.5% to 16.0% over the same bentonite range, an increase of about 4.5%. LS₃ showed the lowest moisture demand, with OMC increasing from about 11.0% at 0% bentonite to 14.0% at 10% bentonite, a 3.0% increase. Eyo *et al.* [24] and Nath *et al.* [15] made similar observations when using various percentages of bentonite with kaolinite clay and other local soils, where an increase in bentonite content resulted in increased OMC.

The initial decrease in OMC at low bentonite content (2%) could be attributed to improved particle packing due to partial void filling by fine bentonite particles, reducing the water required for lubrication during compaction. However, as bentonite content increases further, OMC rises significantly. This increase is associated with bentonite's higher surface area and strong water affinity. As bentonite dosage increases, additional moisture is required to satisfy interlayer hydration and diffuse double-layer expansion, shifting the compaction curves toward higher moisture contents, as reported by [22]. The magnitude of the OMC increase varied among soils, reflecting differences in initial gradation and clay–water interaction behaviour, with LS₁ exhibiting the greatest sensitivity to bentonite addition. The reduction in MDD and increase in OMC as bentonite dosage increases indicate a progressive shift in the soil fabric from a dense, friction-dominated structure to a clay-controlled, moisture-sensitive matrix, as reported by Boadu [23].

3.2.3. Swell and Shrinkage Characteristics

Fig. 8 presents the influence of bentonite on free swell index (FSI) and linear shrinkage. As bentonite content increased, both FSI and linear shrinkage increased consistently, highlighting the strong influence of bentonite-induced volumetric changes associated with its montmorillonite mineralogy.

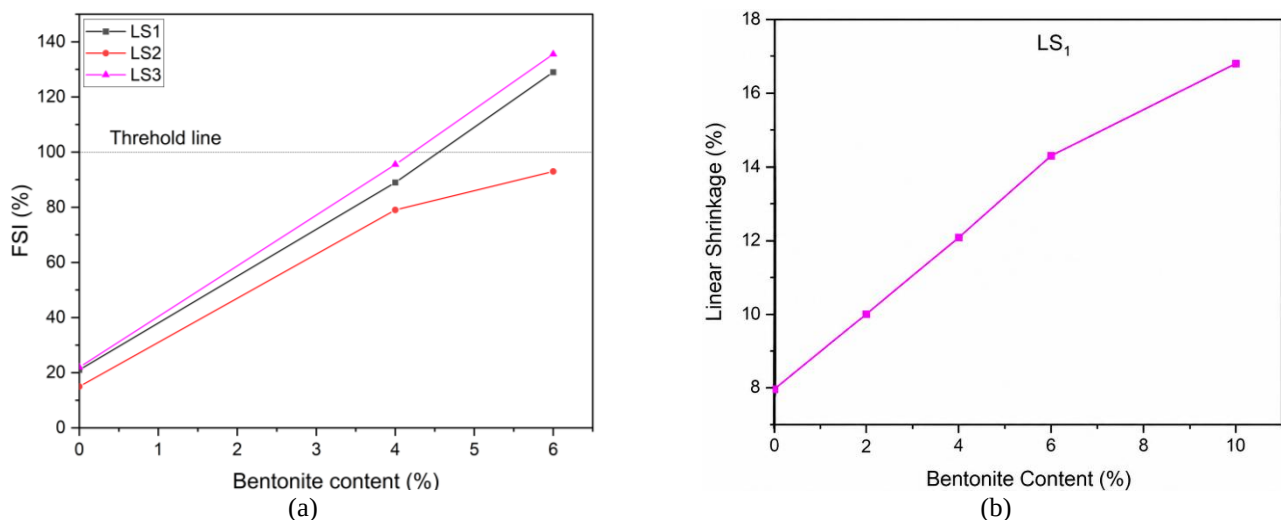


Fig. 8. Effect of bentonite on (a) the free swell index and (b) linear shrinkage of laterite samples

At 0% bentonite, the soils exhibit low potential volume change, with FSI values of 21%, 15%, and 22% for LS₁, LS₂, and LS₃, respectively. Upon addition of 4% bentonite, FSI increased to 89% for LS₁, 79% for LS₂, and 96% for LS₃. These values could be classified as moderate potential for volume change according to [24], [25]. Further increasing bentonite content to 6% continued to increase FSI, reaching 129% for LS₁, 93% for LS₂, and 136% for LS₃. The FSI values for LS₁ and LS₃ indicate high potential volume change, whereas LS₂ remains within the moderate range [13].

While LS1 and LS3 showed much higher swelling between 4% and 6% bentonite, LS2 exhibited a comparatively smaller increase, suggesting reduced swelling efficiency likely linked to differences in initial soil mineralogy. This pronounced increase in FSI reflects enhanced water adsorption and diffuse double-layer swelling resulting from the introduction of expansive montmorillonite minerals (FSI of 600%), as indicated by [22], [26]. Similar observations were made by [15] on the influence of bentonite on soil FSI. From an engineering perspective, enhanced swell is advantageous for self-sealing in liner applications but may cause shrinkage when excessive, leading to high hydraulic conductivity. Beyond 4% bentonite addition, liner-related volume-change problems may occur because the material shifts from moderate to high swell potential [13].

Linear shrinkage in LS1-bentonite-modified samples increased consistently with bentonite addition, rising from 7.9% at 0% bentonite to 10.0%, 12.1%, 14.3%, and 16.8% at 2%, 4%, 6%, and 10%, respectively, as shown in Fig. 8 (b). The increase in linear shrinkage is associated with montmorillonite dominance in bentonite, which has a high affinity for water. Upon saturation, the montmorillonite mineral absorbs and holds more water within diffuse double layers and interlayer spaces. On drying, the loss of this adsorbed water causes greater volume reduction through linear shrinkage. Fig. 8(b) indicates that linear shrinkage increases appreciably beyond 4% bentonite content. Higher bentonite contents may increase the potential for desiccation cracking, which could promote preferential flow and adversely affect hydraulic performance.

3.2.4. Hydraulic Properties of Bentonite-Modified Samples

Incorporating bentonite increased the plasticity index, accompanied by a corresponding reduction in hydraulic conductivity, as shown in Fig. 9 (a). A relationship between plasticity index and hydraulic conductivity, determined at a hydraulic gradient of 29 from 25 observations and presented as a regression model, is given as

$$K = 1.608846 \times 10^{-8} \times PI^{(-1.003029)} \quad (1)$$

A statistically significant inverse relationship was observed between plasticity index and hydraulic conductivity, which was best described by a power function ($R^2 = 0.54$, $P < 0.001$). This indicates a moderate level of explained variation in hydraulic conductivity. This fit is acceptable given the intrinsic variability of compacted soils, where hydraulic behaviour depends not only on plasticity but also on factors such as soil gradation and compaction properties. The plasticity index required to meet the hydraulic conductivity threshold varied with particle gradation. Samples sieved through 19.1 mm required a plasticity index of more than 20%, while those sieved through 13.2mm and 6.7mm required less plasticity to attain a hydraulic conductivity of 1×10^{-9} m/s. This justifies the effect of soil particle size on its hydraulic conductivity. The model therefore captures the general trend rather than serving as a precise hydraulic-conductivity predictive tool for cohesive soils. This agrees with previous studies by Zhixiong *et al.* [25], Benson and Trast [27] and Nath *et al.* [15], who reported an inverse relationship between plasticity index and hydraulic conductivity.

Hydraulic conductivity decreased from 10^{-8} m/s in low-plasticity samples to 10^{-10} m/s in highly plastic mixtures, a reduction of 1–2 orders of magnitude, as shown in Fig. 9(b). Higher plasticity indicates greater clay mineral expansion, reduced pore-throat diameters, and increased tortuosity of flow paths. Hence, flow channels become narrower and more discontinuous, reducing hydraulic conductivity in bentonite-modified laterite samples with higher plasticity. This confirms that plasticity-driven microstructural changes significantly affect hydraulic conductivity, making the plasticity index a practical, performance-based indicator for assessing hydraulic conductivity.

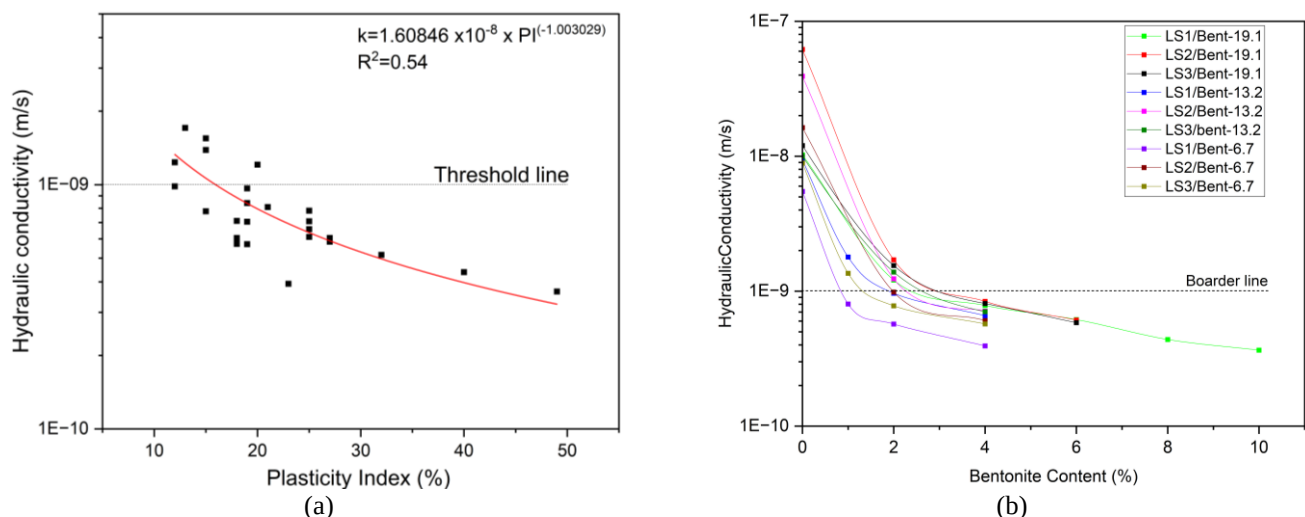


Fig. 9. Effect of plasticity (a) index and (b) bentonite content on hydraulic conductivity.

Hydraulic conductivity declined sharply as bentonite content increased, showing a 1–2 orders-of-magnitude reduction, as indicated in Fig. 9 (b). Bentonite-modified soils achieved hydraulic conductivity levels suitable for use as engineered liners with 2%–4% bentonite, depending on soil type, gradation, and applied hydraulic gradient. Fig. 9(b) illustrates the combined influence of bentonite content and particle size on the hydraulic conductivity of bentonite-treated laterite soils. From Fig. 9(b), unmodified LS₁-19.1 exhibited a hydraulic conductivity of 1.02×10^{-8} m/s. Adding 2% bentonite reduced it by about one order of magnitude to 1.21×10^{-9} m/s, while increasing the bentonite content to 4% further decreased it to 7.83×10^{-10} m/s. A previous study by Nath et al. [15] reported decreased hydraulic conductivity with increasing bentonite content. In this study, 4% bentonite addition was required to attain hydraulic conductivity below 1×10^{-9} m/s for all soil types and gradations. This demonstrates that the required bentonite dosage depends on the initial hydraulic conductivity and particle-size characteristics of the laterite.

The combined effects of soil gradation, the initial hydraulic conductivity of the unmodified laterite, and the bentonite content controlled the reduction in hydraulic conductivity. For example, adding 2% bentonite to specimens passing the 19.1 mm sieve decreased hydraulic conductivity from the order of 10^{-8} m/s to 10^{-9} m/s, whereas the same bentonite dosage reduced specimens passing the 6.7 mm sieve to the order of 10^{-10} m/s. Coarser-grained specimens therefore required higher bentonite contents to attain the liner hydraulic conductivity criterion. Additionally, baseline hydraulic conductivity differences among laterite soils affected the performance of bentonite modification. For instance, incorporating 2% bentonite into LS₂ passing the 13.2 mm sieve produced a higher hydraulic conductivity than LS₁ of comparable gradation. This difference reflects LS₂'s inherently higher initial hydraulic conductivity, indicating that the response to bentonite treatment depends not only on bentonite content but also on the properties of the base laterite soil.

Adding bentonite to laterite significantly alters the soil microstructure, leading to a marked reduction in hydraulic conductivity. Bentonite particles occupy intergranular voids and coat laterite grains. Upon hydration, bentonite swells markedly, narrowing pore throats, blocking flow paths, and reducing pore connectivity. This swelling-induced pore refinement, together with the development of diffuse double layers around clay particles, restricts fluid movement. Consequently, flow paths become increasingly tortuous and discontinuous. Reduced hydraulic conductivity is therefore attributed to microstructural refinement, including smaller pore-throat diameters, thicker adsorbed water layers, and longer flow paths, with swelling and tortuosity as the primary mechanisms governing hydraulic sealing in bentonite-modified laterite soils [22]. If sodium bentonite were used, hydraulic conductivity would decrease further because it has a greater diffuse double-layer thickness and higher swelling potential than calcium bentonite, and it could therefore reduce pore connectivity more effectively [22]. Table 4 summarizes the effects of bentonite addition on the physical and hydraulic properties of the laterite soils.

4 CONCLUSION

Mineralogically, laterite soils are dominated by iron oxides, quartz, hematite, and kaolinite. Clay samples primarily consist of kaolinite and vermiculite, whereas bentonite is rich in montmorillonite. The results demonstrate a clear performance contrast between soil groups. Clay soils and bentonite-modified laterite samples exhibit superior containment characteristics compared to untreated laterites. Natural clays (CL1–CL3) showed moderate to high plasticity ($PI = 25$ – 44%) and hydraulic conductivities of 10^{-10} – 10^{-11} m/s, meeting the adopted hydraulic conductivity criterion for compacted soil liners. In contrast, untreated laterite soils showed relatively low plasticity ($PI = 9$ – 17%) and high hydraulic conductivity (10^{-8} – 10^{-9} m/s), about 10–100 times more permeable than the clay soils, making them unsuitable as soil liners.

Adding bentonite changed the physical and hydraulic behaviour of all laterite types investigated. These changes were accompanied by a systematic shift in compaction characteristics, marked by reduced MDD and increased OMC. Incorporating bentonite increased the plasticity index, reflecting a clay-dominated soil fabric and reduced hydraulic conductivity. While bentonite inclusion reduces hydraulic conductivity through pore filling and swelling-induced sealing, excessive shrinkage and swelling can significantly compromise liner integrity. A bentonite content of 2–4% reduced hydraulic conductivity and controlled shrink-swell behaviour in the tested laterite soils, with the required dosage depending on soil type, gradation, and applied hydraulic gradient. Less plastic and high-sand laterite, such as LS₂, may require a higher bentonite content (4%). In contrast, intermediate-plasticity and low-gravel-content laterite soils may require 2% bentonite to meet the adopted hydraulic conductivity criterion. Table 5 summarises the effect of bentonite addition on LS₁, with hydraulic conductivity tested at a hydraulic gradient of 18. Overall, the results indicate that bentonite-enhanced laterite is promising for liner applications under the tested laboratory conditions. The required bentonite addition to achieve similar performance may be lower if sodium bentonite is used. This study evaluated the hydraulic conductivity of clay, laterite, and bentonite-modified laterite soil using tap water under controlled laboratory conditions. Actual tailings facilities may contain heavy-metal leachates, acidic or alkaline effluents, and high-ionic-strength pore fluids, all of which can influence the hydraulic conductivity and long-term performance of compacted soil liners. Future studies should investigate the compatibility and long-term performance of the proposed liner material under representative tailings leachate chemistries to assess its field applicability.

Table 4. Summarised physical and hydraulic properties of bentonite-modified laterite soils.

Sample ID	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	LL (%)	PI (%)	MDD (g/cm ³)	OMC (%)	K (m/s)	
									j = 18	j = 29
90%LS1/10%B-19.1	31.5	34.2	12.8	21.5	68	49	1.67	19.0	1.03x10 ⁻¹⁰	3.65x10 ⁻¹⁰
92%LS1/8%B-19.1	32.2	35.0	13.0	19.8	58	40	1.71	18.0	1.78x10 ⁻¹⁰	4.38x10 ⁻¹⁰
94%LS1/6%B-19.1	32.9	35.7	13.3	18.1	50	32	1.76	15.0	3.99x10 ⁻¹⁰	5.16x10 ⁻¹⁰
96%LS1/4%B-19.1	33.6	36.5	13.5	16.6	43	25	1.82	15.0	5.91x10 ⁻¹⁰	7.83x10 ⁻¹⁰
98%LS1/2%B-19.1	34.3	37.2	13.8	14.7	38	20	1.86	12.5	9.67x10 ⁻¹⁰	1.21x10 ⁻⁹
96%LS1/4%B-13.2	25.9	40.3	15.4	18.3	42	25	1.80	15.0	4.98x10 ⁻¹⁰	6.58x10 ⁻¹⁰
98%LS1/2%B-13.2	26.5	41.2	15.7	16.7	37	19	1.91	12.4	7.79x10 ⁻¹⁰	9.66x10 ⁻¹⁰
96%LS1/4%B-6.7	9.0	47.6	19.3	24.1	40	23	1.79	14.5	2.11x10 ⁻¹⁰	3.93x10 ⁻¹⁰
98%LS1/2%B-6.7	9.2	48.6	19.6	22.6	37	19	1.92	13.6	4.29x10 ⁻¹⁰	5.71x10 ⁻¹⁰
99%LS1/1%B-6.7	9.3	49.1	19.8	21.8	-	-	2.04	14.4	6.93x10 ⁻¹⁰	8.04x10 ⁻¹⁰
94%LS2/6%B-19.1	15.0	55.5	19.9	9.6	43	25	1.86	14.0	5.04x10 ⁻¹⁰	6.12x10 ⁻¹⁰
96%LS2/4%B-19.1	15.4	56.6	20.2	7.8	37	19	1.89	13.5	7.17x10 ⁻¹⁰	8.41x10 ⁻¹⁰
98%LS2/2%B-19.1	15.7	57.8	20.6	5.9	31	13	1.92	12.0	1.26x10 ⁻⁹	1.71x10 ⁻⁹
96%LS2/4%B-13.2	12.7	60.8	20.6	5.9	36	18	1.88	13.0	6.88x10 ⁻¹⁰	7.11x10 ⁻¹⁰
98%LS2/2%B-13.2	12.9	61.4	20.8	4.9	30	12	1.93	11.6	9.18x10 ⁻¹⁰	1.24x10 ⁻⁹
96%LS2/4%B-6.7	5.1	66.2	20.6	7.8	36	18	1.90	13.5	5.20x10 ⁻¹⁰	6.06x10 ⁻¹⁰
98%LS2/2%B-6.7	5.1	66.9	20.8	6.9	30	12	1.95	11.6	8.37x10 ⁻¹⁰	9.84x10 ⁻¹⁰
94%LS3/6%B-19.1	24.1	42.9	16.8	16.2	45	27	1.88	12.5	5.07x10 ⁻¹⁰	5.84x10 ⁻¹⁰
96%LS3/4%B-19.1	24.6	43.8	17.1	14.5	39	21	1.92	12.0	5.98x10 ⁻¹⁰	8.10x10 ⁻¹⁰
98%LS3/2%B-19.1	25.1	44.7	17.4	12.7	33	15	1.94	11.5	1.16x10 ⁻⁹	1.55x10 ⁻⁹
96%LS3/4%B-13.2	21.1	43.2	19.3	16.4	38	19	1.95	12.5	5.78x10 ⁻¹⁰	7.05x10 ⁻¹⁰
98%LS3/2%B-13.2	21.6	44.1	19.6	14.7	33	15	1.99	10.8	1.05x10 ⁻⁹	1.39x10 ⁻⁹
96%LS3/4%B-6.7	21.8	44.6	19.8	13.9	37	18	1.91	13.0	4.04x10 ⁻¹⁰	5.72x10 ⁻¹⁰
98%LS3/2%B-6.7	9.4	44.8	26.2	19.6	33	15	1.93	12.6	6.55x10 ⁻¹⁰	7.78x10 ⁻¹⁰
99%LS3/1%B-6.7	9.5	45.3	26.4	18.8	-	-	-	-	1.08x10 ⁻⁹	1.36x10 ⁻⁹

Table 5. Effect of bentonite content on hydraulic conductivity, plasticity, and linear shrinkage of LS1.

Bentonite Content (%)	Hydraulic Conductivity (m/s)	Plasticity index (%)	Linear Shrinkage (%)	Engineering Trade-off
0	8.03×10^{-9}	17	7.9	Hydraulic conductivity exceeds the adopted criterion
2	9.67×10^{-10}	20	10	Hydraulic conductivity reduced below the adopted criterion with a moderate increase in plasticity and shrinkage.
4	5.91×10^{-10}	25	12.1	Lower hydraulic conductivity with increased plasticity and shrinkage
6	3.99×10^{-10}	32	14.3	Further reduction in permeability but significantly higher plasticity and shrinkage, increasing cracking risk

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ETHICS STATEMENT

This study did not involve human or animal subjects and, therefore, did not require ethical approval.

STATEMENT OF CONFLICT OF INTERESTS

The authors declare no conflicts of interest related to this study.

LICENSING

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