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Assessment of some selected laterite deposits in southwest Nigeria for various engineering application and post-mining land use

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Abstract Geotechnical characteristics of seven laterite deposits in southwest Nigeria were investigated. The obtained laterite samples from the selected locations with acronym Loc.1 to Loc.7 were subjected to various laboratory tests including specific gravity, linear shrinkage, Atterberg limits, grain size analysis, California bearing ratio, compaction, and permeability. The results of the laboratory analyses showed that the specific gravity of the soils samples ranged from 2.639 to 2.768; liquid limit ranged from 28.1% to 65.8%; plasticity limit ranged from 19.2% to 27.4%; fines content ranged from 17.4% to 71.7%; clay content ranged from 8% to 56.1%, optimum moisture content ranged from 11.3% to 28.7%; maximum dry density ranged from 1462 kg/m^3 to 2065 kg/m^3; unsoaked California bearing ratio ranged from 7% to 82%, soaked California bearing ratio ranged from 2% to 75%, and coefficient of permeability ranged from 5.59e-08 cm/s to 4.81e-04 cm/s. The soils plasticity index were plotted against the liquid limit values on Casagrande plasticity chart to identify their clay mineral and it was revealed that sample Loc.1, Loc.2 and Loc.3 soils are made up of kaolinite; Loc.4 soil clay mineral is montmorillonite while Loc.5, Loc.6, and Loc.7 soils clay minerals are illites and montmorillonite. The soils were classified using AASHTO classification system and based on this, the soil from Loc.1 fall under group A-4 and A-5, indicating that it is silty soil; soils from Loc.2, Loc.4, Loc.5, Loc.6, and Loc.7 fall under group A-6 and A-7, respectively, indicating that they are clayey soil; and soil from Loc.3 fall under group A-1, indicating that it is gravel sandy soil. Geomaterial engineering application identification chart was design in this study to identify the engineering application appropriate for the studied soils. Based on this, Loc.1 soil can be used as road sub-grade, foundation fill, dam core, and dam impervious; Loc.2, Loc.5, Loc.6 and Loc.7 soils can be used as road sub-grade, foundation fill, landfill liners, dam core, and dam impervious; Loc.3 soil can be used as road sub-grade, sub-base and base, structure foundation fill, and dam pervious; and Loc.4 soil can be used as landfill liner; dam core, and dam impervious. The post-mining land use, appropriate for the selected laterite deposits, after the completion of the mining activities, was also suggested in this study using the soils geotechnical properties, clay mineral and classification. Based on this, Loc.1 deposit can be converted to housing estate, industrial park, tourism, and public pack; Loc.2, Loc.6 and Loc.7 deposits can be converted to housing estate and industrial park with light structures, public park, and tourism; Loc.3 can be converted to housing estate, industrial park, tourism; and public park, while Loc.4 and Loc.5 can be converted to public park, tourism, and sanitary landfill**.** The information provided in this study will save cost and time of contractors and field geotechnical engineers in selecting suitable laterite for their project.
Keywords Laterite · Geotechnical properties · Clay mineralogy · Engineering application · Post-mining land use

I. Introduction

Laterite covers a wide area in Southwest Nigeria where it is being used as the major construction material because it is cheap and environmental friendly. However, there is variability in the geotechnical properties of laterites (Adeyemi and Wahab, 2008), and mineralogical composition (Aleva, 1994, Adebisi *et al*., 2013) from one location to another depending on the parent rock in which they are formed from (Aleva, 1994; Adeyemi and Wahab, 2008; Adebisi *et al*., 2013), and this is responsible for differences in their engineering application (Ige, 2010; Ige *et al*, 2010; Ogundipe, 2012 and Adeoye *et al*., 2013, Okewale and Grobler, 2022). Past researchers such as (Odunfa *et al.* 2018; Ogunribido and Fadairo, 2020; Owoyemi *et al*., 2022, among others) have investigated the competency of laterite in Southwest Nigeria for road construction as sub-grade, sub-base and base, and they concluded that laterite in Southwest Nigeria, which meet the specifications suggested by FMWH (1997), can be used for road construction. Also, Ige (2010), Adeoye *et al*. (2013) and

Daramola and Ilasanmi (2018) assessed lateritic soils from Southwest Nigeria and they concluded that the soils that meet the requirements suggested by Daniel (1993), Benson *et al*. 1994, and Rowe *et al.* (1995) among others are suitable for landfill liners. Additionally, laterite can be used for dam construction as core, impervious blanket, pervious, and backfill (Zoorasna *et al.,* 2008).

However, the appropriateness of laterite for the aforementioned engineering construction depends on the geotechnical properties, which include optimum moisture content, maximum dry density, unsoaked California bearing ratio, soaked California bearing ratio and permeability, specific gravity, liquid limit, plastic limit, linear shrinkage and fines content among others. There is a relationship between geotechnical properties and mineralogy of soil (Reeves *et al*., 2006). For example, particle size distribution is an indicator of the mineralogy of the soil (Mitchell, 1993) and on the other hand, geotechnical properties of soil are strongly influenced by the amount, and type of minerals present in it (Reeves *et al*., 2006). In general, laterite contains sand minerals, silt minerals, and clay minerals. Sand particles are generally primary minerals that have not undergone much weathering; it is made up of mineral such as quartz. Silt is the inert by-product of rock weathering; it composed of finer particles of quartz and silica**.** Clay comprises mainly of secondary minerals; they are produced mainly from the chemical weathering and decomposition of feldspers such as orthoclase and plagioclase (Aleva, 1994). For easy identification of the engineering application of the selected laterite, this study design geomaterial engineering application chart based on permeability, maximum dry density and California bearing ratio (soaked and unsoaked) using Federal Ministry of Works and Housing, FMWH (1997) and prominent past researchers specifications.

There is always need to plan for post-mining land use, during the feasibility stage of the mining development project. This seems to be lacking in today Nigeria. Post mining land use, is the used of mined land after completion of active mining. Post mining land uses, of the selected laterite deposits, were suggested in this study. There are different post-mining land uses, including regenerative cropping, protective horticulture, intensive livestock, renewable energy, and adventure tourism facility (Limpitlaw and Briel, 2014). However, this study focuses on the area of converting the post-mining land to housing estate, industrial park, sanitary landfill site, tourism and public park. For effective selection of post-mining land use, there is always need to investigate the geotechnical condition of the land/subsoil before converting it to housing estate, industrial park among others. For example, there are failures of infrastructures around Yelwa North Central part of Nigeria and the cause of the infrastructural failures was investigated by Vincent and Mallo (2023). The results of the various laboratory tests conducted by the authors on the soil samples showed that most of the soils are not fairly within the specifications required for the constructions of infrastructures. Hence, in this study, the geotechnical properties, clay mineral and the classification of the selected laterite deposits were used to suggest their appropriate post-mining land use.

II. Materials and methods

2.1 Sample collection and laboratory analysis

Disturbed soil samples were obtained from seven different laterite deposits in Ondo, Osun and Ekiti States in Southwest Nigeria (Fig. 1, Table 1). Approximately 15–20 kg of each sample was collected at depth of 1 meter.

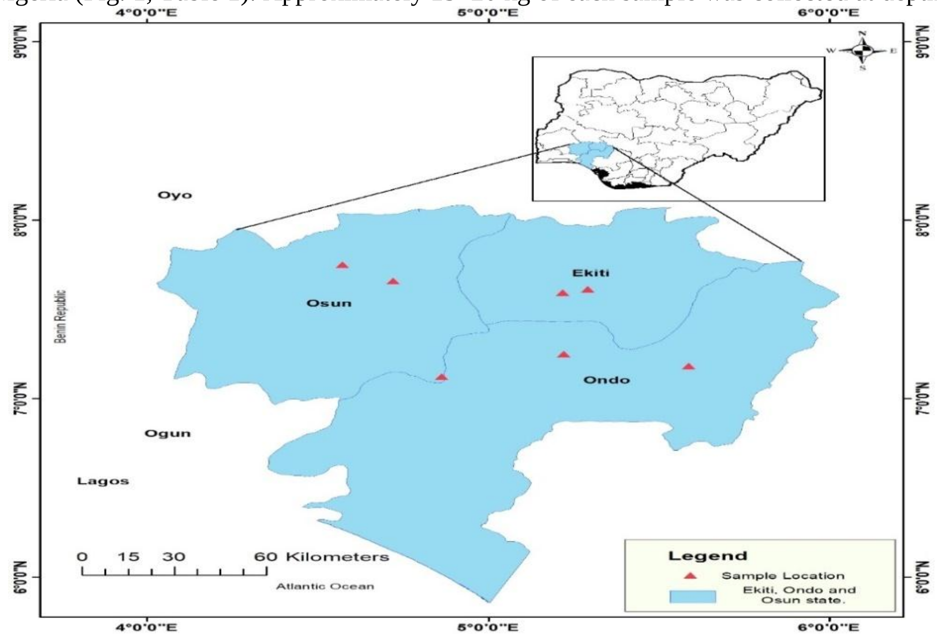

Fig. 1 Map of Nigeria showing the sample locations

Table 1 GPS reading of the sample locations

S/N	Location	Location code	Latitude (N)	Longitude (E)
1.	Akure	Loc.1	07°14.94'	5°13.32'
2.	Ondo	Loc.2	07°7.38'	04°51.9'
3.	Owo	Loc.3	07°10.85'	05°35.32'
4.	Oshogbo	Loc.4	07°44.99'	04°34.42'
5.	Ilesha	Loc.5	07°39.45'	04°43.29'
6.	Ado-Ekiti	Loc.6	07°35.50'	05°13.13'
7.	Ijan-Ekiti	Loc.7	07°36.67'	05°17.58'

Source Fieldwork 2020

The samples extracted were put in nylon, sealed and taken to the laboratory for analysis. The obtained samples were subjected to various laboratory tests including specific gravity, Atterberg limits, grain size analysis, permeability, compaction, and California bearing ratio using ASTM standard procedures. The specific gravity test was conducted according to the ASTM (2002) D 854-02 standard procedure. The Atterberg limits (liquid limit and plastic limit) test was performed according to the ASTM (2018) D4318-17e1 standard procedure. The plasticity index was computed by subtracting the plastic limit from the liquid limit. The grain size analysis test was conducted in accordance with ASTM (2002) D422-63. The permeability test was conducted according to ASTM (2022) D2434-22. The California bearing ratio (soaked and unsoaked) was conducted in accordance with ASTM (2021) D1883-21, and compaction test was carried out in accordance with ASTM (2021) D698-12 standard procedures.

III. Result and discussion

3.1 Specific Gravity

The results of the specific test conducted on the soils samples are summarized in Table 2. The specific gravity of the samples ranged from 2.639 to 2.768. Specific gravity is a very important property of soil that dictates soil engineering application (Ogunribido and Fadairo, 2020).

Table 2 The specific gravity of the studied soils

Locations	Specific gravity
Loc.1	2.639
Loc.2	2.659
Loc.3	2.652
Loc.4	2.768
Loc.5	2.710
Loc.6	2.681
Loc.7	2.670

According to the FMWH (1997) specification, material for road construction should have specific gravity ranging from 2.5 to 2.75. Based on this, all the soils can be used for road construction except Loc.4 with specific gravity of 2.768, but can be used as liners in solid waste landfill according to ONORM S (1990) that recommended a minimum specific gravity value of 2.22.

3.2 Soil Particle Size Distribution

The grain size analysis test results conducted on the soils samples are summarized in Table 3. Grain size analysis is one of the geotechnical properties of soil that dictate its suitability for different engineering construction and it is use for soil classification (AASHTO 1986). The grain size distribution of road subgrade and subbase material must have ≤ 35% of fine content according to FMHW (1997). Based on this, none of the studied soils, except that of Loc.3 conform to the recommendation for both subgrade,and subbase. Furthermore, for soil to be considered as liners, the gravels content must be < 30%, the fines content must be > 30% (Daniel, 1993; Rowe et al., 1995), and the clay content must be ≥20% (Oeltzschner, 1992). The entire soils except Loc.3 did meet the specifications for landfill liners.

Table 3 Summary of the grain-size analysis of the studied soils

Location	% GC	% SC	% FC	% SiC	% CC
Loc.1	10.6	47.2	42.1	26.6	15.6
Loc.2	3.7	48	48.3	26.8	21.5
Loc.3	34.0	48.7	17.4	9.4	8.0
Loc.4	4.6	23.6	71.7	15.7	56.1
Loc.5	8.6	39.0	52.4	14.4	38.0
Loc.6	10.6	41.2	48.2	16.1	32.1
Loc.7	6.7	46.4	46.9	14.5	32.4

GC gravel content (%), SC sand content (%), FC fine content (%), SiC silt content (%), and CC clay content (%)

3.3 Atterberg limits

The results of Atterberg limits test conducted on the soils samples are summarized in Table 4. Atterberg limit is another very important soil index property that is used for soil classification (AASHTO 1986). According to FMWH (1997), subgrade and foundation fill material should have ≤ 50% liquid limit and ≤ 20% plasticity index, while subbase material should have ≤ 30% liquid limit and ≤ 12 % plasticity index. All the soils except that of Loc.4 satisfy the recommendation to be used as road subgrade and foundation fill while Loc.3 soil meets the requirement for road subbase. For soil to be considered as landfill liners, its plasticity index value must be ≥ 15% (Daniel, 1993; Rowe *et al*., 1995) and liquid limit must be ≥ 30% (Benson *et al*., 1994).

Table 4 Summary of Atterberg limits of the studied soils

Location	LL (%)	PL (%)	SL (%)	PI (%)	CI (%)
Loc.1	34.3	27.4	12.5	6.95	3.73
Loc.2	39.6	27.4	12.0	12.20	2.25
Loc.3	28.1	24.2	14.4	3.95	5.28
Loc.4	65.8	20.3	6.3	45.53	1.04
Loc.5	48.3	19.5	8.7	28.85	1.19
Loc.6	44.0	19.2	9.1	24.80	1.12
Loc.7	41.8	22.2	9.6	19.60	1.5

LL liquid limit (%), PL plastic limit (%), SL shrinkage limit (%), PI plasticity index (%), and CI consistency index (%)

Loc.3 soil has liquid limit lesser than 30%, while Loc.1, Loc.2 and Loc.3 soils have plasticity index values lesser than 15%. Based on this, Loc.1, Loc.2 and Loc.3 soils cannot be used as liners in landfill system.

3.4 Maximum dry density and optimum moisture content

The summary of the results of the compaction test conducted on the soils samples are shown in Table 5. The results showed that the soils OMC ranged from 11.3% to 18.4% while the MDD ranged from 1462 kg/m^3 to 2065 kg/m^3.

Table 5 Summary of compaction parameters of the studied soils

Location	OMC (%)	(MDD) (kg/m^3)
Loc.1	14.3	1963
Loc.2	16.4	1890
Loc.3	11.3	2065
Loc.4	28.7	1462
Loc.5	21.4	1714
Loc.6	18.4	1819
Loc.7	17.5	1851

OMC optimum moisture content, MDD maximum dry density

According to the FMWH (1997), the least MDD value recommended for soil to be used as sub-grade and subbase is 1700 kg/m^3. All the studied soils meet the requirement to be used as subgrade and subbase except that of Loc.4 with MDD value lesser than the requirement.

3.5 California Bearing Ratio

The results of California bearing ratio (CBR) test conducted on the soils samples are presented in Table 6. From Table 6, it can be observed that the unsoaked CBR values varied between 7% and 85% while the soaked CBR value varied between 2% and 75%. According to the FMWH (1997), the value of the unsoaked CBR of soil to be used as subgrade must be ≥ 10%. Furthermore, FMWH (1997) specified that the value of the soaked CBR of subbase material must be ≥ 30%, while the base course material soaked and unsoaked CBR value must be ≥ 80%.

Table 6 Summary of the CBR of the studied soils

Location	CBR_U (%)	CBR_S (%)	WDBS (kg/m^3)	WDAS (kg/m^3)	Swell (%)
Loc.1	33	21	2267	2278	0.5
Loc.2	27	17	2231	2246	0.7
Loc.3	82	75	2329	2329	0.0
Loc.4	7	2	1941	2010	3.6
Loc.5	14	3	2120	2148	1.3
Loc.6	24	15	2189	2204	0.7
Loc.7	17	8	2202	2223	1.0

CBR_U un-soaked California bearing ratio, %; CBR_S soaked California bearing ratio, %; WDBS wet density before soaking, kg/m^3; WDAS wet density before soaking, kg/m^3

Based on FMWH (1997) specification, only Loc.4 soil did not conform to the recommendation for road subgrade and this was also revealed in its swell percentage value (Table 6), which is extremely high compared to others. Furthermore, only Loc.3 soil meets the requirement to be used as both sub-base and base course material.

3.6 Permeability coefficient

The summary of the results of permeability test conducted on the soils samples are shown in Table 7. Permeability of soil is it capacity to allow water to pass through it. The coefficient of permeability of the studied soils standardized at 20ºC ranged from 5.59e-08 cm/s to 4.81e-04 cm/s. For soil to be used as liners in landfill, it must have a low hydraulic conductivity to control leachate from the waste (Mitchell et al., 1995). Various authors have suggested a maximum coefficient of permeability value of 1×10^{-7} cm/sec for landfill liners (Daniel, 1993; Rowe et al., 1995). Based on this specification, Loc.1 and Loc.3 soils did not conform to the requirement for landfill liners. Also according Lambe and Withman (1969), the permeability value of Loc.3 soil falls within the range termed low permeability (between 10^{-5} and 10^{-3} cm/sec); Loc.1, Loc.2, Loc.5, Loc.6 and Loc.7 fall within the range termed very low permeability (between 10^{-7} and 10^{-5} cm/sec); Loc.4 soil falls within the range termed practical impermeable (<10^{-7} cm/sec). According to Lambe and Withman (1969), Loc.3 soil can be used as borderline between pervious and impervious soils while the rest soils can be considered as dam core or impervious blanket.

Table 7 Summary of the permeability in the study

Sample	$\alpha(\eta_T/\eta_{20})$	k_T (cm/sec)	k_{20} (cm/sec)
Loc.1	0.8287	$8.79e^{-6}$	$7.28e^{-6}$
Loc.2	0.8287	$4.25e^{-7}$	$3.53e^{-7}$
Loc.3	0.8287	$5.80e^{-4}$	$4.81e^{-4}$
Loc.4	0.8287	$6.75e^{-8}$	$5.59e^{-8}$
Loc.5	0.8287	$2.95e^{-7}$	$2.44e^{-7}$
Loc.6	0.8287	$4.25e^{-7}$	$3.52e^{-7}$
Loc.7	0.8287	$4.68e^{-7}$	$3.88e^{-7}$

ηT viscosity at any temperature, $\eta 20$ viscosity at 20^0C; k_T permeability coefficient at any temperature, k_{20} coefficient of permeability standardized at 20^0C.

Also, Aysen (2002) specified that soils with coefficient of permeability ranging from 1 to 10^{-6} m/sec (1 - 10^{-4} cm/sec) are well drained soils while those with coefficient of permeability ranging from 10^{-8} to 10^{-11} m/sec (10^{-6} - 10^{-9} cm/sec) are practically impervious soils. Based on this, Loc.3 is a well-drained soil and can be used as dam pervious fill, while soil from other locations are practically impervious soils, thus, they can be used as dam impervious. Zoorasna *et al.* (2008) recommended 5×10^{-7} m/sec (5×10^{-5} cm/sec) permeability coefficient value for dam core and 5×10^{-8} m/sec (5×10^{-6} cm/sec) for dam core wall. Based on Zoorasna *et al.* (2008) specifications, all the studied soils can be used as dam core and wall, except that of Loc.3.

3.7 Clay mineralogy of the studied soils

Clay mineral present in a soil can be revealed by plotting the plasticity index (PI) of the soil against its liquid limit on Casagrande's plasticity chart (Amadi *et al*., 2015). Thus, in this study, the clay minerals in each of the selected soils were identified using the Casagrande's plasticity chart as shown in Fig. 2. Based on the plots of the liquid limit against the plasticity index values, Loc.1, Loc.2 and Loc.3 soils fell in the zone of kaolinite, meaning that the soil clay content is composed of kaolinite; Loc.4 soil was plotted in the zone of montmorillonite, indicating that the soil clay content is made of montmorillonite; meanwhile, Loc.5, Loc.6 and Loc.7 soils plots fell in between illites and montimorinollites (Fig. 2), indicating that the soils have two clay minerals.

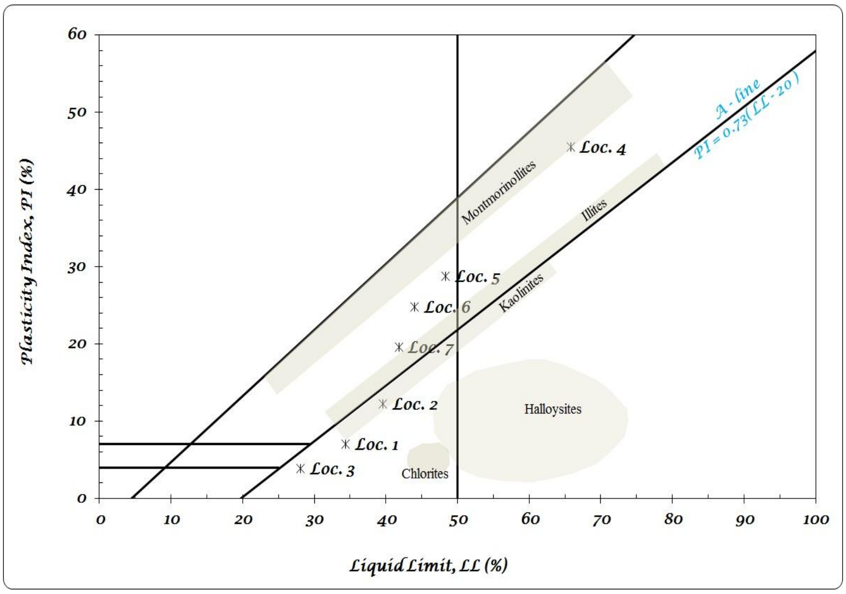

Fig. 2 Plots of the studied soils' plasticity index against liquid limit on Casagrande chart

The geotechnical properties of laterite are strongly influenced by the amount, and type of minerals present in it (Reeves *et al*., 2006). Kaolinite has strong binding forces between its structure layers and this make it to exhibits very little plasticity cohesion, shrinkage, and swelling. On the other hand, montmorillonite is noted for inter layer expansion, which occurs by swelling when the minerals are wetted and shrink when dried (Reeves *et al*., 2006). Thus, Loc.1, Loc.2, and Loc.3 soils will not swell when wetted and this is being justified by their low consistency index values shown in Table 4 and low swell percent values shown in Table 6. As a result of this, Loc.1, 2, and 3 soils are suitable for engineering constructions. Meanwhile, Loc.5, Loc.6, and Loc.7 soils contain montmorillonite and illites, indicating that they have tendency of swelling when wetted, and shrink when dried. However, the soils can be stabilized with cement, lime, or firing to high temperature. Loc.4 sample contains high percentage of clay (56.1%) which is purely montimorinollites, meaning that, it will excessively swell when wetted and shrink when dried, thus, the soil cannot be used for engineering construction such as road sub-base, subgrade and foundation fill where high strength is required from the soils.

3.8 Classification of the studied soils

The studied soils were classified using AASHTO classification system and the results are summarized in Table 8. In AASHTO classification system (AASHTO 1986), soil with 35% or lesser of total sample passing No. 200 is classified as granular materials while soil having more than 35% of the total sample passing sieve No. 200 is classified as silt-clay materials. Liquid limit and plasticity index of the soil were determined to further classify the soil into group and sub-group. Based on the AASHTO classification, the soil from Loc.1 fall under group A-4 and A-5; Loc.2, Loc.4, Loc.5, Loc.6, and Loc.7 fall under group A-6 and A-7, respectively, and soil from Loc.3 fall under group A-1, indicating that the soil of Loc.1 is silty soil; Loc.2, Loc.4, Loc.5, Loc.6, and Loc.7 are clayey soil; and Loc.3 is gravel sandy soil. The rating of the soils as subgrade material indicated fair to poor sub-grade materials except soil of Loc.3 which is rated as excellent to good sub-grade material. Furthermore, various earth-fill dam sections presented in USACE (2004) comprises of pervious fill/compacted earth fill, transition fill and impervious zone/dam core. The pervious fill/compacted fill were made up of gravelly sand; transition fill between the impervious and pervious material were made up of silty sand while the impervious zone/ dam core were made up of clay/sandy clay. Based on the results of AASHTO classification system (Table 8), Loc.1 can be used as transition fill between the impervious and pervious material; Loc.3 can be used as pervious fill/compacted earth fill; while Loc.2, Loc.4. Loc.5, Loc.6 and Loc.7 can be used as dam core.

Table 8 Classification of the studied soils using AASHTO Classification System

Index properties	Studied laterite						
	Loc.1	Loc.2	Loc.3	Loc.4	Loc.5	Loc.6	Loc.7
Percent passing sieve No. 10	89.4	96.3	66.0	95.4	91.4	89.4	93.3
Percent passing sieve No. 40	65.7	69.6	36.1	81.8	67.7	66.1	63.6
Percent passing sieve No.200	42.1	48.3	17.4	71.7	52.4	48.2	46.9
Liquid Limit (%)	34.3	39.6	28.1	65.8	48.3	44.0	41.8
Plasticity Index (%)	6.90	12.2	3.9	45.5	28.9	24.8	19.6
Clay (%)	15.6	21.5	8	56.1	38.0	32.1	32.4
AASHTO Classification	A-4(0)	A-6(3)	A-1-6(3)	A-7(20)	A-7(20)	A-7(20)	A-7(20)
Type of material	Silty soil	Clayed soil	Gravel sand	Clayed soil	Clayed soil	Clayed soil	Clayed soil

3.9 Geomaterial engineering application identification chart

The application of geomaterial such as laterite, clay, and sand, among others for different engineering construction depends majorly on the geotechnical properties (Okewale and Grobler, 2022).

Table 9: Engineering Construction Material Requirement

Engineering application	Geotechnical properties requirement								References
	SG	FC	LL	PI	MDD	CBR_S	CBR_U	PERM	
Road sub-grade	2.5 – 2.75	≤ 35%	≤ 50%	≤ 20%	>1700 kg/m^3	-	≥ 10%		FMWH (1997)
Road sub-base	2.5 – 2.75	≤ 35%	≤ 35%	≤ 12%	>1700 kg/m^3	≥ 30%	-		FMWH (1997)
Road base	2.5 – 2.75	≤ 35%	≤ 35%	≤ 12%	>1700 kg/m^3	≥ 80%	≥ 80%		FMWH (1997)
Landfill Liner	≥ 2.22	≥ 30%	≥30%	≥ 15%				≤1 x 10^{-7} cm/sec	ONORM S, (1990) Daniel (1993); Rowe *et al.* (1995)
Dam core								5×10^{-7} cm/sec	Zoorasna *et al.* (2008)
Dam Impervious								5×10^{-8} cm/sec	Zoorasna *et al.* (2008)
Foundation fill	2.5 – 2.75	≤ 35%	≤ 50%	≤ 20%	>1700 kg/m^3	-	≥ 10%		FMWH (1997)

CBR_U unsoaked California bearing ratio, CBR_S soaked California bearing ratio, %; PERM = permeability, cm/sec; MDD = maximum dry density, kg/m^3; and OMC = optimum moisture content, %.

The summary of the geotechnical properties specifications for materiel recommended by the Federal Ministry of Works and Housing, FMWH (1997) and some of the prominent past researchers for different engineering construction are presented in Table 9. As shown in Table 9, the Federal Ministry of Works and Housing, FMWH (1997), suggested specifications for the geotechnical properties for material for foundation fill, road subgrade, subbase and base course; ONORM S (1990), Daniel (1993) and Rowe *et al.* (1995) suggested specification for the geotechnical properties for material to be used for landfill liners; and Zoorasna *et al*. (2008) suggested specification for soil to be used as dam core and dam impervious. For easy identification of the engineering application of laterite and other geomaterial, this study design geomaterial engineering application identification chart shown in Fig. 3 based on FMWH (1997) and past researchers' (ONORM S (1990), Daniel (1993); Rowe *et al.* (1995), Zoorasna *et al.,* 2008) specifications as presented in Table 9. The chart comprises of the major engineering properties, which are permeability, maximum dry density and California bearing ratio (soaked and unsoaked), whose values will be plotted on the chart and the zone of their interception will indicate the engineering application of the geomaterial. To identify the engineering application of the studied soils, their permeability, maximum dry density and California bearing ratio values were plotted on the geomaterial engineering application identification chart as presented in Fig.4.

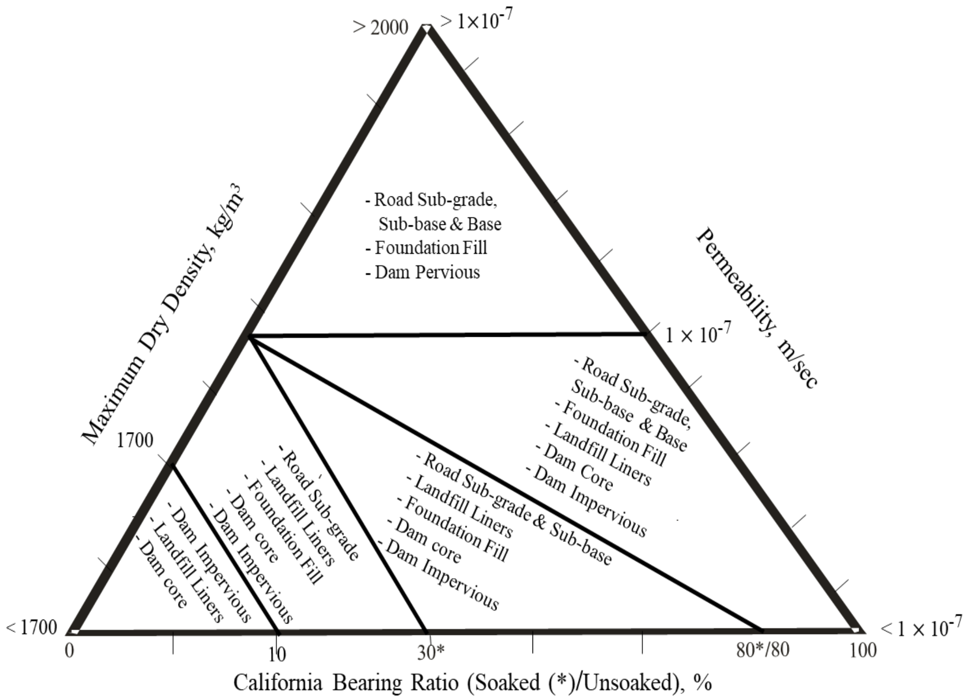

Fig. 3 Geomaterial engineering application identification chart (Source: Authors design)

Based on the chart (Fig.4), Loc.1, Loc.2, Loc.5, Loc.6 and Loc.7 soils can be used as road sub-grade, foundation fill, landfill liners, dam core and dam impervious. Loc.3 soil can be used as road sub-grade, sub-base and base, foundation fill, and dam pervious. Loc.4 soil can be used as landfill liners, dam core, and dam impervious. Identification of the laterite engineering application in this study is very important as this will assist geotechnical engineers in the quick selection of appropriate soil from the studied ones, and this will help in preventing frequent failure of engineering construction and loss of life.

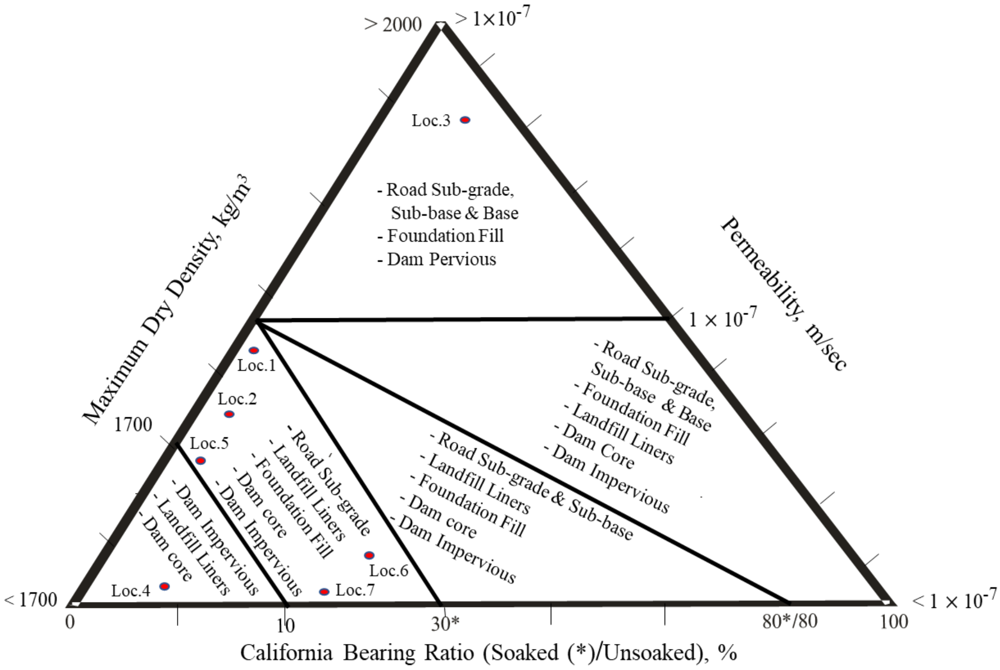

Fig. 4 Studied soils Engineering application

3.10 Post mining land use of the studied laterite deposits

In this study, the post-mining land uses for the studied laterite deposits after completion of the active mining was suggested. The post-mining land uses considered for the selected laterite deposit were limited to housing estate, industrial park, sanitary landfill site, tourism, and public park using the soils geotechnical properties, clay mineralogy and classification, and they were summarized as follow:

1) Loc.1 soil has low gravel content (10.6%), high fine content (42.1%) and low clay content (15.6%) with kaolinite as the major clay mineral. It has a high maximum dry density (1963 kg/m^3), moderate un-soaked California bearing ratio (33%), moderate soaked California bearing ratio (21%), low swell percent (0.5) and very low permeability coefficient (8.79e-6 cm/sec), and it is classified as silt soil. With all indication, the soil exhibits a very good quality. Thus, after the completion of the mining activity, the land can be converted to housing estate, industrial park, sanitary landfill site, tourism and public park.
2) Loc.2, Loc.6, and Loc.7 soils exhibit similar characteristics, which are: high fine content (ranged from 46.9% to 48.3%), moderate clay content (ranged from 21.5% to 38%), fair maximum dry density (ranged from 1819 kg/m^3 to 1890 kg/m^3), low unsoaked California bearing ratio (ranged from 17% to 27%); and low soaked California bearing ratio (ranged from 8% to 17%); very low permeability coefficient which ranged from 4.68e-7 cm/sec to 4.25e-7 cm/sec; and moderate swell percent, which ranged from 0.7% to 1.0%; and they are classified as clayed soil. Thus, after the completion of the mining activity, the land can be converted to sanitary landfill site; housing estate and industrial park with light structures due to low strength properties of the soil; public park, and tourism.
3) Loc.3 soil has high gravel content (34%); very low fine content (17.4%) and very low clay content (8%) with kaolinite as the clay mineral, very high maximum dry density (2065 kg/m^3), very high un-soaked California bearing ratio (82%), very high soaked California bearing ratio (75%), low permeability (5.80e-4 cm/sec), and zero (0) swell percent; and it is classified as gravel sandy soil. Thus, the appropriate post mining land uses are housing estate, industrial park, public park, and tourism. The land cannot be converted to sanitary landfill due to high percentage of gravel, low percentage of clay and not suitable permeability.
4) Loc.4 soil has very low gravel content (4.6%); very high fines content (71.7%); very high clay content (56.1%); which is majorly made up of montmorillonite; has low maximum dry density (1462 kg/m^3), very low un-soaked California bearing ratio (7%); very low soaked California bearing ratio (2%); very high swell factor (3.6%); very low permeability coefficient (6.75e-8 cm/sec); and it is classified as clayed soil. Hence, the land after completion of mining activity can be used as public park, tourism, and sanitary landfill site. However, it cannot be converted to housing estate or industrial park because of its very low strength properties, which can cause collapse/sinking of building within a few years.
5) Loc.5 soil has very low gravel content (8.6%); very high fines content (52.4%); very high clay content (38%) which is majorly made up of kaolinite; low maximum dry density (1714 kg/m^3); low un-soaked California bearing ratio (14%); low soaked California bearing ratio (3%); high swell factor of 1.3%; and

very low permeability coefficient (2.95e-7 cm/sec); and it is classified as clayed soil. Hence, the land after completion of mining activity can be used as public park, tourism, and sanitary landfill site.

IV. Conclusions

The laboratory analyses of seven selected laterite deposits in southwest, Nigeria was carried out to determine their engineering construction appropriateness and post-mining land use. The results of the laboratory analyses showed that the specific gravity of the samples ranged from 2.639 to 2.768; liquid limit ranged from 28.1% to 65.8%. The plasticity limit ranged from 19.2% to 27.4%. The plasticity index ranges from 3.95% to 45.53%. The fines content ranged from 17.4% to 71.7%. The clay content ranged from 8% to 56.1. The optimum moisture content ranged from 11.3% to 28.7%. The maximum dry density ranges from 1462kg/m^3 to 2065 kg/m^3. Unsoaked California bearing ratio ranged from 7% to 82%, the soaked California bearing ratio ranged from 2% to 75%, permeability ranged from 5.59e-08 cm/s to 4.81e-04 cm/s. The plotting of the soils plasticity index against the liquid limit on Casagrande chart revealed that samples of Loc.1, Loc.2 and Loc.3 clay content are made up of kaolinite; Loc.4 clay mineral is montmorillonite while Loc.5, Loc.6, and Loc.7 soils were made up of illites and montmorillonite. The soils were classified using ASHTO classification system and based on this, Loc.1 is classified as A-4(0) (silty soil), Loc.2 is classified as A-6(3) (clayey soil), Loc.3 is classified as A-1-b(3) (gravel and sandy soil), Loc.4 soil is classified as A-7(20) (clayey soil), Loc.5 soil is A-7(11) (clayey soil), Loc.6 soil is classified as A-7(8) (clayey soil) and Loc.7 is classified as A-7(6) (clayey soils). Geomaterial engineering application identification chart was design in this study to identify the engineering application of the studied soils baesd on the geotechnical properties specifications by past resesrchers and FMWH (1997). Based on this, Loc.1 soil can be used as road sub-grade; foundation fill; landfill liner; and dam core; and road/railway embankment. Loc.2, Loc.5, Loc.6 and Loc.7 can be used as road sub-grade, foundation fill, landfill liner, dam core, and road/railway embankment. Loc.3 soil can be used as sub-grade, sub-base and base course material for road construction; structure foundation fill; dam pervious. Loc.4 soil can be used as landfill liner; dam core, dam impervious blanket, and cannot be converted to housing estate or industrial park because of low strength properties. Geotechnical properties, clay mineral and classification of the studied soils were used to suggest the studied soils appropriate post-mining land use after completion of the mining activitie. Based on this, Loc.1 deposit can be converted to housing estate, industrial park, tourism, and public pack; Loc.2, Loc.6 and Loc.7 deposits can be converted to housing estate and industrial park with light structures, public park, and tourism; Loc.3 deposit can be converted to housing estate, industrial park, tourism; and public park, while Loc.4 and Loc.5 deposits can be converted to public park, tourism, and sanitary landfill**.** The acquired information in this study will assist contractors and geotechnical engineers in selecting from the studied laterite for their proposed engineering construction, thereby, will save time and cost of searching for the appropriate laterite.

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