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ORIGINAL RESEARCH PAPER

Geotechnical Properties of Surfactant Modified Lateritic Soils

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Abstract
Surfactants may exist in soils as contaminants or as additives for soil remediation and stabilization. The effect of different types of surfactants containing soaps on important geotechnical properties of lateritic soil samples from Oro and Ajase Southwestern Nigeria was investigated here. The soils in their natural state were characterized using specified standard geotechnical methods, X-ray Diffractometry (XRD) and X-ray fluorescence respectively (XRF). The soil samples were modified with liquid soap, bar soap and detergent and the effect of this contamination on important geotechnical properties such as Atterberg limits, bulk density, specific gravity, compaction, permeability, California bearing ratio (CBR), matric suction and shear strength parameters of the soils were investigated. Soils from both locations contain kaolinite, quartz and goethite in varying percentages, while silica, aluminium and iron oxide are the dominant oxides. The addition of surfactants in the three soap types resulted in an increased plasticity index of up to 93%, cohesion and optimum moisture content in soils from the locations. Bulk density, maximum dry density, angle of internal friction and permeability are reduced in them. Matric suction increased in all the soils with the greater increase recorded in the ones modified with liquid soap. These changes are attributable to the dispersion of clay minerals in the soils. Oro soil with a higher percentage of kaolinite is more sensitive to surfactants. The effect of surfactant-containing soaps on the geotechnical properties of lateritic soils vary based on mineralogy and surfactants type.

Keywords Dispersion · Remediation · Contaminants · Stabilization · Surfactants

1 Introduction

Lateritic soils are readily available and widely distributed in tropical areas like Nigeria where they form the foundations of most highways and are used as fill materials for embankments and subbases [1–4]. In their natural state, they rarely possess suitable qualities necessary for desired engineering applications [5–7]. This has prompted much research into possible ways of modifying their properties to make them suitable for engineering applications [8–12].

Additives such as lime, fly ash, cement, sawdust, limestone, etc. used in soil stabilization have proven to modify the engineering properties of lateritic soils. Marto et al. [13] reported a fourfold increase in the strength of Malaysian lateritic soil modified with calcium-based stabilizer. Owoyemi [12] reported a decrease in the liquid limit, plasticity index, and maximum dry density, an increase in linear shrinkage and optimum moisture content, California bearing ratio, and unconfined compressive strength of Nigerian lateritic soil stabilized with sawdust. Razali et al. [14] also reported an increase in strength, optimum moisture content, and a decrease in maximum dry density of quicklime-modified lateritic soil. In the same vein, researchers have also attempted the use of surfactant-assisted soil stabilization to improve soil properties [15–20], but such research is still scarce on tropical residual lateritic soils. For example, Jones et al., investigated the possible use of surfactants as an additive to improve some properties of a mixture of sand and

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kaolin. The researchers observed a decrease in suction as the surfactant concentration increased, a reduction in maximum dry density at high surfactant concentration, and an increase in the plastic limit. Sasser et al. [20] reported strength improvement in beech sands stabilized with surfactants. Berney et al. 2003 [21] recommended mixing surfactants with subgrade and subbase soils to mitigate strength loss and volume change due to increased moisture during episodes of water ingress in surfaced and unsurfaced pavement structures. Lateritic soil forms the foundation of most pavements in tropical and subtropical countries of the world [22–24]. There is a need for studies targeted at understanding the response of this class of soil to surfactant modification.

Surfactants are amphiphilic in nature, possessing both hydrophilic and hydrophobic portions [25, 26]. Base on the charge on the hydrophilic end of a surfactant, it can be classified as a cationic (positively charged) or anionic (negatively charged) molecule [27]. This unique physicochemical property of surfactants makes them useful in many domestic and industrial processes. They are also used for oil recovery and mining operations [28]. Due to their numerous applications, they are constantly being discharged into the environment either directly or through wastewater treatment plants. There is need to investigate their effects of their interaction with the soil which mostly serve as their final repository. Recent research has shown that contaminants have negative influence on the geotechnical properties of soils [29–34]. For example, Valencia-González, et al. [29] reported aggravated deformability and erodibility in soap contaminated soil, Irfan, et al., [30] and Khan et al., [32] reported increased plasticity and reduced strength in cohesive soils contaminated with industrial effluents. However, the recent quest for green alternatives for the reclamation of contaminated soils through remediation has made surfactant-enhanced remediation of contaminated soils increasingly popular because it offers an environmentally friendly and cheap alternative for reclaiming contaminated soils [25, 35–37]. It has been found to have high compatibility with other methods and its versatilile in combating a broad spectrum of pollutants including hydrocarbons, heavy metals, and pesticides [38, 39]. For example, surfactants have been widely used for the remediation of hydrocarbon-contaminated soils because they can displace hydrocarbon through mechanisms such as surface tension reduction and formation of micelles that increase the solubilization of non-aqueous liquids [40–42] Limited work has been done on the influence of surfactants either as additives/enhancements or contaminants on the geotechnical properties of lateritic soils, especially in Nigeria.

Table 1 Physical properties of the studied soils

S/*N*	Oro	Ajase
Natural moisture content (%)	7.3	4.52
% Gravel	1	6
% Sand	57	39
% Fines (> 0.075 mm)	42	55
Unified Soil Classification	CL	CL
AASHTO Classification	A6	A4
AASHTO rating	Fair to poor subgrade	Fair to poor subgrade
Group index	3	3
Liquid limit (%)	39	32
Plastic limit (%)	25	22
Plasticity index	14	10
Specific gravity	2.46	2.44
Bulk density (kg/m^3)	1336	1380
The angle of internal friction (°)	19	53
Cohesion (kPa)	30	13
Permeability (m/sec)	2.8E-06	3.2E-06
Unsoaked CBR (%)	50	81
Soaked CBR (%)	14	24
Matric suction (kPa)	2.6	2.6
MDD (kg/m^3)	1745.2	1813.4
OMC (%)	15.3	18.3
Mineral composition	kaolinite (62%), quartz (33%), goethite (5%)	kaolinite (50%), quartz (38%), goethite (12%)

Surfactants are surface active agents which are the major active ingredients in soaps and detergents, responsible for their cleansing ability [43, 44]. Soaps are water-soluble alkali or ammonium salts of fatty acids [45]. They are made from fats and oils, or their fatty acids by treating them chemically with a strong solution of alkali or ammonium salts. Soaps come in various types. Depending on the physical appearance, they are classified as bar, liquid/gel, or powered soaps. In commercial soaps, the surfactant component is between 30% and 70% [46].

This work is designed to experimentally determine the influence of surfactants in different category of soaps (liquid, bar and powdered soap) on important geotechnical properties of two lateritic soil samples from Nigeria. One soil sample was taken from Oro latitude 4 °54'24" N and longitude 8°13'56" E while the other sample was taken from Ajase, latitude 4 °50'10" N and longitude 8°14'58"E.

2 Materials and methods

Bulk samples of the soils were taken from borrow pits using a digger and shovel. The properties of the bulk soil samples are presented in Table 1. The soils are fine-grained in texture having more than 35% clay and silt contents. Both soils are rated as fair to poor subgrade material according to the American Association for State and Highway Transportation Officials (AASHTO) classification. Figure 1 presents the grading curves of the two soils. They are expected to

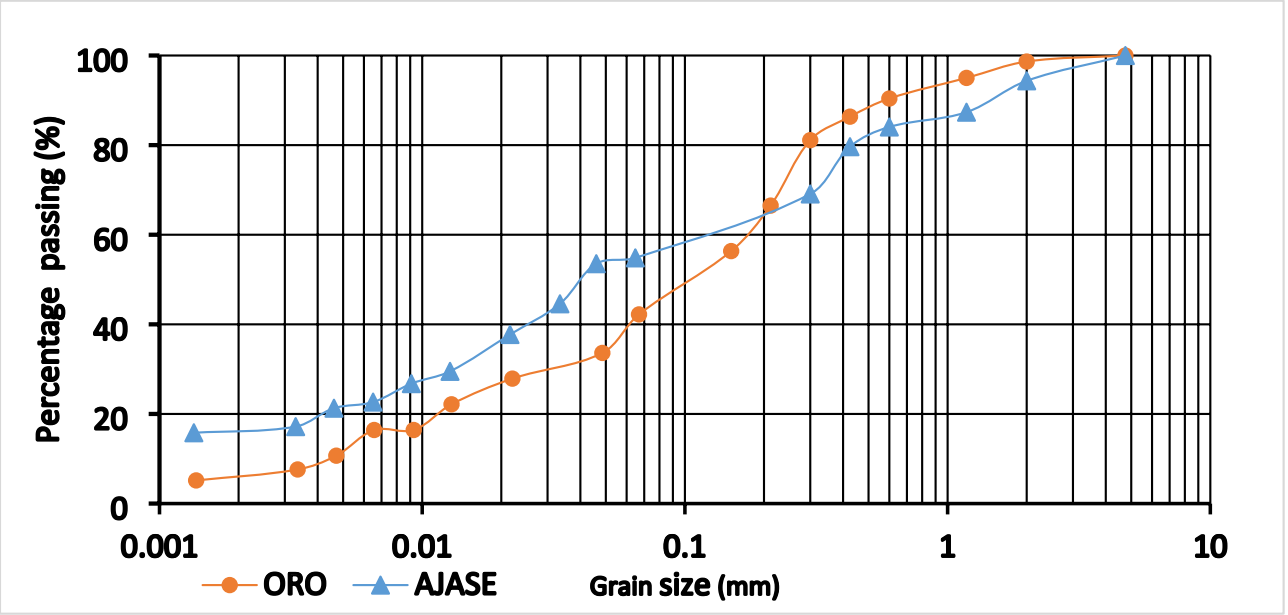


Fig. 1 Grading curves of the studied soils

Table 2 Chemical composition of the soil samples

XRF major elements (wt%)	Oro	Ajase
SiO_2	50.46	46.63
TiO_2	1.41	1.74
Al_2O_3	20.47	23.43
Fe_2O_3	17.28	15.84
MgO	0.09	0.09
MnO	0.15	0.10
CaO	0.10	0.12
Na_2O	0.01	0.01
K_2O	0.37	0.16
P_2O_5	0.07	0.06
LOI	9.12	10.27
Total	99.52	98.46

perform less than optimum as highway subgrade soils if used in their natural state. The soil samples were air-dried to constant weight before subjecting them to the experimental procedures. Their mineralogy composition (Table 1) and geochemistry (Table 2) were determined using X-ray diffractogram (XRD) and X-ray fluorescence (XRF) methods respectively. Figures 2 and 3 show the X-ray diffractograms of the natural soils. A theta-theta goniometer configured diffractometer was used for the XRD analysis while the evaluation of diffractograms was done using the database of the International Centre for Diffraction Data (ICDD PDF −2®).

Grain size distribution was carried out using the ASTM standard [47] standard test method. Specific gravity, Atterberg limits, and bulk density of the natural soils were determined using British standard 1377 [48]. The soil samples were remolded using the Standard Proctor modality. The compacted soil samples at the optimum moisture content (OMC) and maximum dry density (MDD) were used for falling head permeameter following the British Standard method of 1377–7 [48]. Shear strength parameters were determined using a shear box also following British standard 1377–5 [48] California Bearing Ratio (CBR) and matric suction tests were carried out using methods specified in British Standard 1377–4 [48] and ASTM D 5298 [49] method respectively.

Different types of surfactants containing cleaning agents which include liquid soap, powdered soap or detergent, and bar soap are used to modify the air-dried natural soils. 250 g of each soap type was dissolved in two litres of water each. The resulting solution was mixed with 6 kg of soil samples and allowed to soak for 7 days. They were then air dried again to constant weight before re-testing. Atterberg limits, Specific gravity, bulk density, compaction (Standard Proctor), CBR, soaked and unsoaked, shear box, falling head permeability, and matric suction were repeated on the modified samples. The properties of the modified soil samples were compared with those of the unmodified soils in their natural state.

Table 3 presents the contents of the soaps used for contaminating the soil samples. Commercial brand viva® multipurpose bar soap and laundry detergent were used for the bar soap and powdered soap respectively while the commercial morning fresh® dishwashing liquid was used for the liquid soap. According to the soap labels, linear alkyl benzene (LABs), sodium laureth sulphate, sodium palmitate and sodium kernelate are the surfactants in the soaps (Table 3). The surfactants in each soap type are italicized in Table 3. The actual percentage surfactant content in the

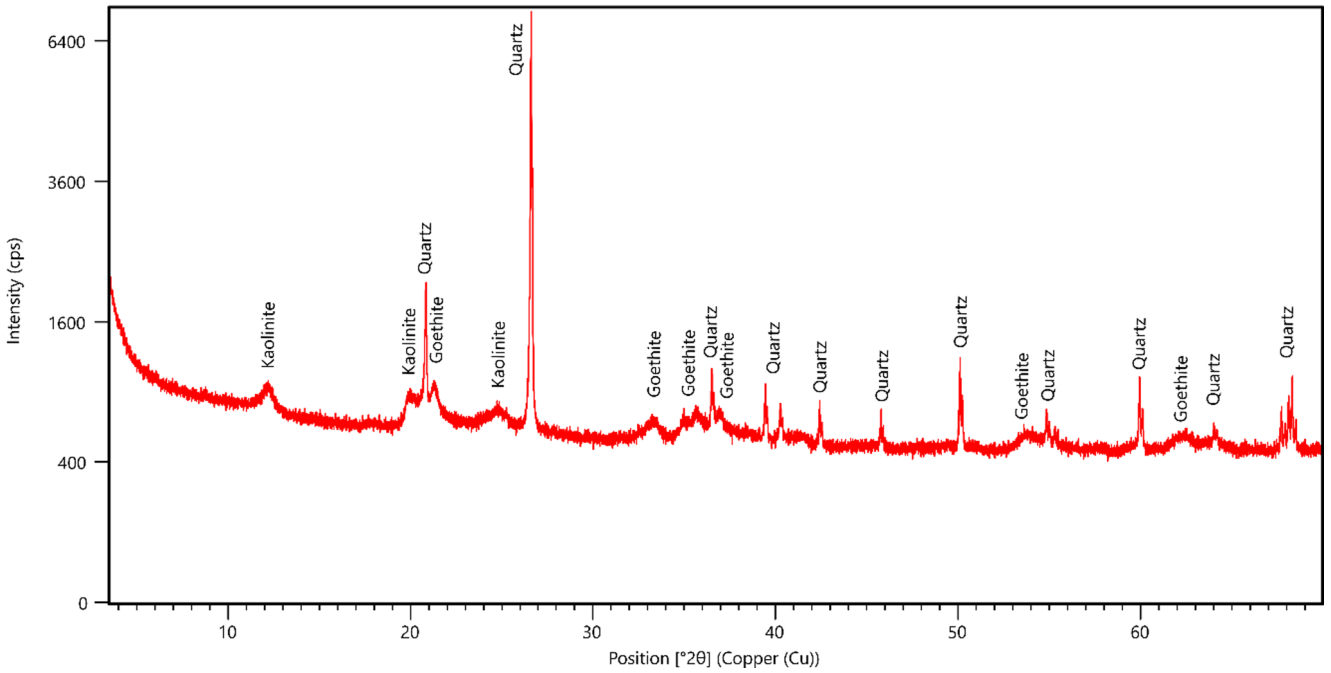


Fig. 2 X-ray diffractograms of Ajase soil

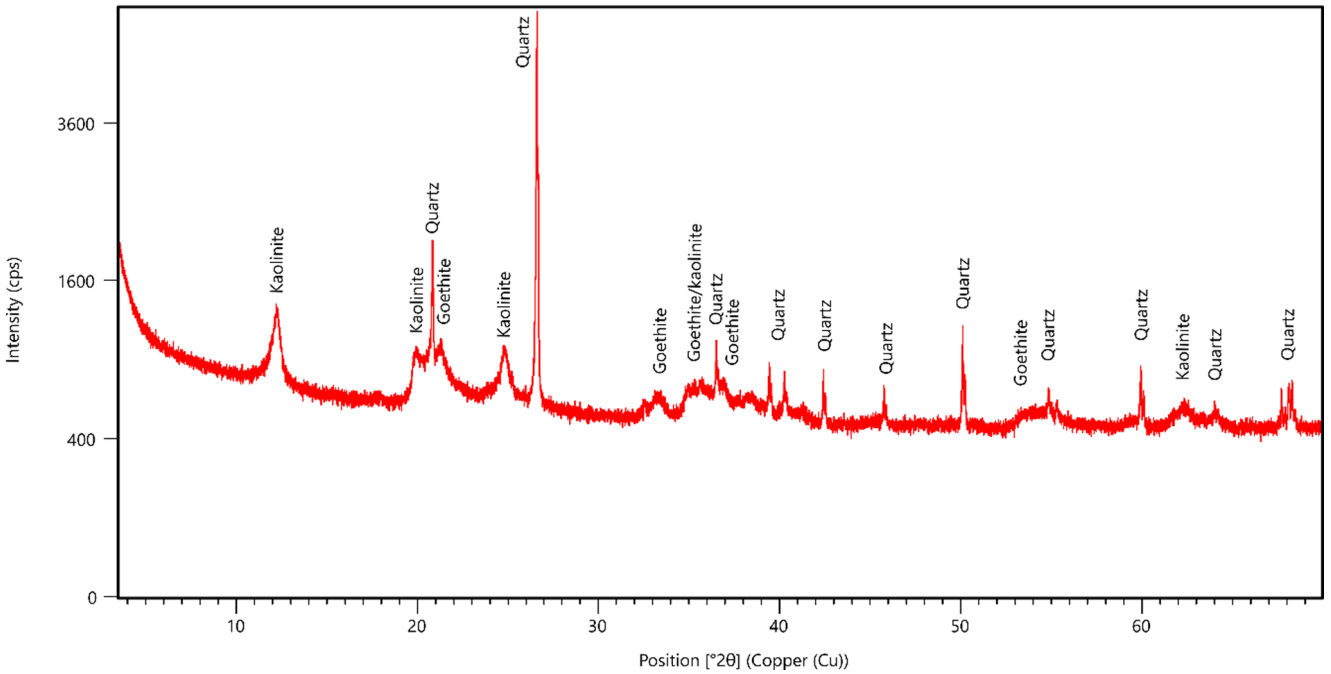


Fig. 3 X-ray diffractograms of Oro soil

soaps is not available in public domain. However, empirically, it is expected that detergents have the highest surfactant concentration while bar soaps are expected to have the least surfactant concentration. The liquid soap is expected to have surfactant concentration in between that of detergents and liquid soaps.

3 Results

3.1 Effect of Surfactants on Index Properties

Variations of the index properties of the soils with surfactant addition are presented in Table 4. Bulk density was reduced with surfactant addition in both soils. Specific gravity was

Table 3 Composition of the categories of soaps used according to the soap labels

Soap type	Detergent	Liquid soap	Bar soap
Content	*Linear alkyl benzene sulphonates (LABs)*, sodium carbonate, sodium silicate, sodium sulfate, polycarboxylate, Benetex OB(brightening agent), vinyl imidazole, Vinylpyrolidane, enzymes, perfume	*Linear alkyl benzene sulphonates (LABs)*, *sodium laureth sulphate*, aqua, magnesium sulphate, glycerine, perfumes, bromonitropropanediol, sodium EDTMP.	*Soap base (Sodium palmitate and sodium kernelate)*, water, glycerin, sodium carbonate, fragrance, sodium chloride, etidronic acid, tetrasodium EDTA. titanium dioxide, butyl phenylmethyl propanal, coumarin, geraniol, hexyl cinnamaldehyde, limonene, linalool, colourant

reduced in the Oro soil but increased average in the Ajase soil. Liquid limit and plasticity index increased in both soils with the addition of all soap types. Liquid soap addition produced the highest increase in plasticity index while bar soap produced a marginal increase in plasticity in both soils. Although there is an increase in plasticity in both soils with surfactant addition, their Unified soil classification on the Casagrande plasticity chart did not change (Fig. 4). The natural soil is classified as low plasticity clay (CL), and the surfactant-modified samples did not cross the boundary between low plasticity clay and high plasticity clay.

This is similar to the result obtained by Akbulut and Kurt [50] and Sharo et al. [31] who reported an increase in the plasticity of cohesive soils and clay respectively due to detergent addition. The increase in plasticity might be due to soil particle dispersion with soap addition. The added soaps reduced the surface tension of the pore water around the soil particles thereby increasing the ability of the porewater to separate coagulated soil solids, hence, dispersion. This is corroborated by SEM images of soap-modified tropical residual soils reported by Valencia-González, et al. [29] showing dispersion. This tends to increase the number of fine particles in the soil. The average increase in plasticity

Table 4 Variation of bulk density, specific gravity, and Atterberg limits of surfactant amended soils

Sample ID	Bulk density(kg/m^3)	GS	LL (%)	PL(%)	PI(%)	% increase in PI
Oro NS	1336	2.46	39	25	14	-
Oro LS	1006	1.8	40	23	17	21
Oro BS	1150	1.9	47	20	27	93
Oro DT	958	1.4	41	22	19	36
Ajase NS	1380	2.44	32	22	10	-
Ajase Ls	1304	2.6	38	22	16	60
Ajase Bs	1376	2.7	37	25	12	20
Ajase Dt	1378	2.6	40	24	16	60

*LL (liquid limit), PL (plastic limit), PI (plasticity index), Gs (Specific gravity), LS (Liguid soap), BS (bar soap), DT (detergent), BS (bar soa), NS (Natural soil)

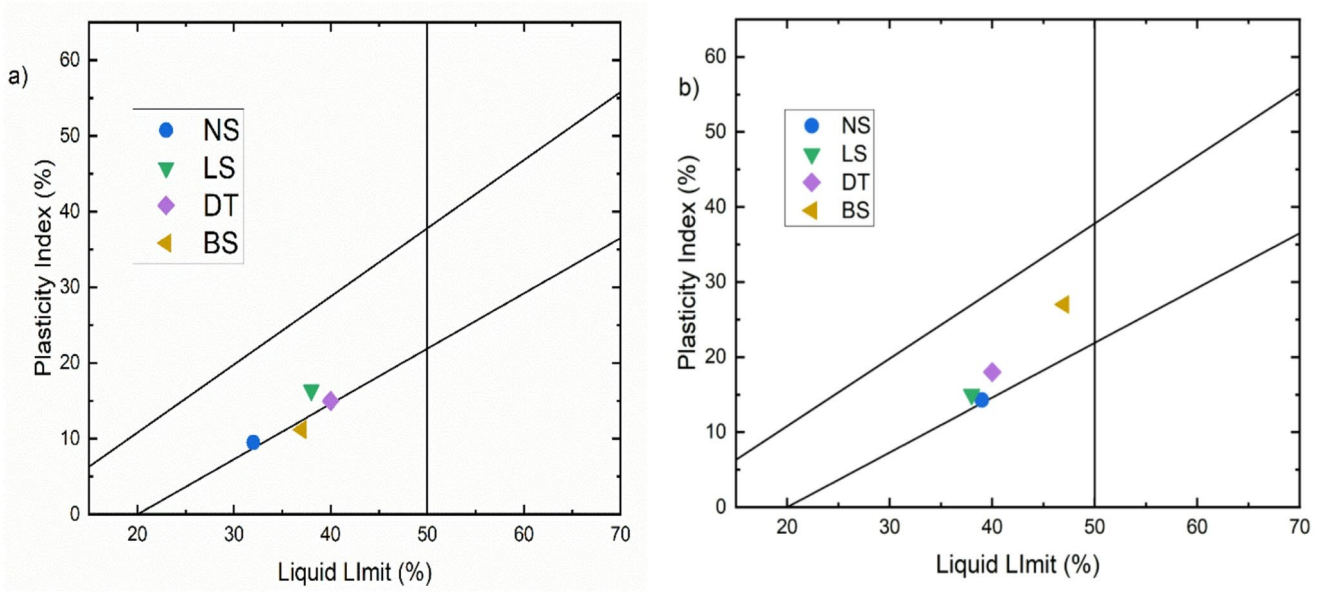


Fig. 4 Casagrande plasticity charts showing the classification of the natural and modified samples. (a) Ajase soil (b) Oro soil

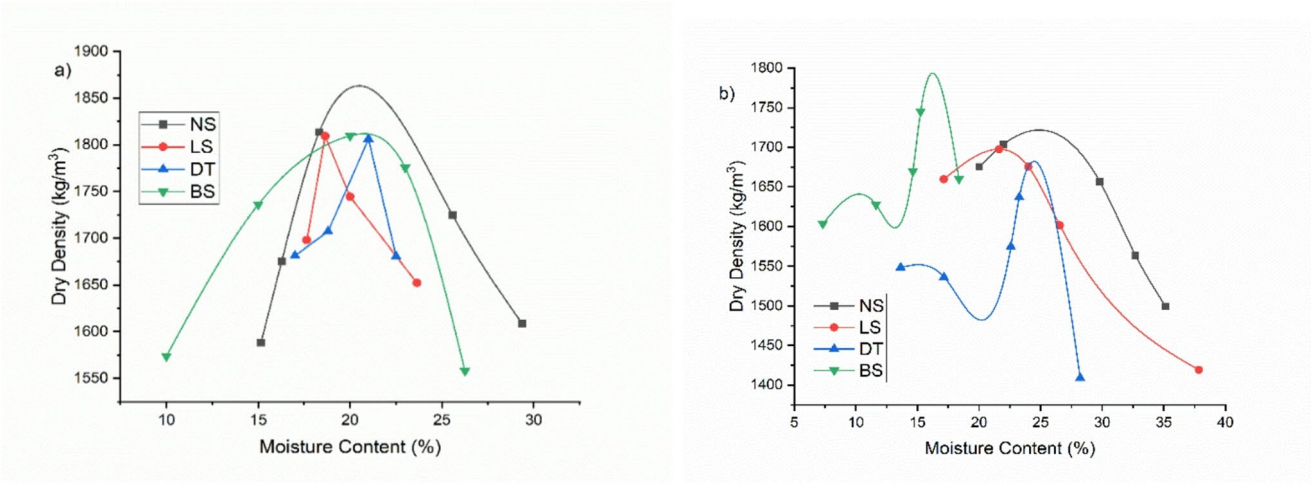


Fig. 5 Moisture dry density relationships of the studied soils (a) Ajase soil (b) Oro soil

Table 5 Effect of surfactant addition on the California bearing ratio of the studied soil

Oro	U- CBR	% decrease	S-CBR	% decrease	Ajase	U - CBR	% increase	S - CBR	% increase
NS	81	-	24	-	NS	50	-	14	-
LS	62	23	19	21	LS	60	20	19	36
DT	35	57	9	63	DT	53	6	17	21
Bs	66	19	20	17	Bs	60	20	20	43

*U- CBR(unsoaked CBR), S- CBR (Soaked CBR)

index and an apparent increase in plasticity as shown in Fig. 3 is higher in Oro soil than in Ajase soil. This is a reflection of the higher kaolinite content in Oro soil. The clay particles are more sensitive to surfactant contamination.

3.2 Moisture Dry Density Relationship

The moisture dry density curves of the soils shifted downwards and towards the right with the addition of surfactants in both soils (Fig. 5). This indicates a decrease in maximum dry density and an increase in optimum moisture content. Moisture dry density relationship curves of soap-modified Ajase soil did not show much deviation from that of the natural soil, the decrease in MDD and increase in OMC being marginal. This might be due to the presence of a greater amount of kaolinite in the Oro soil. This makes it more sensitive to modification than the Ajase soil with a lower amount of kaolinite. This implies that the addition of surfactant to clay-rich soil reduces the achievable density during compaction. This result is like that of [51] who reported a decrease in MDD of surfactant-modified sandy soils, however, there was a corresponding reduction in OMC in the work. This is due to differences in the mineralogy of the investigated soils. Johnson and Sallberg [52] cited in [53] submitted that clayey soils modified with surfactants tend to have decreased MDD and increased OMC at higher plasticity.

3.3 California Bearing Ratio

The addition of the three kinds of soaps leads to up to a 43% increase in both soaked and unsoaked CBR in the soil samples prepared from the Ajase soil. For the Oro soil, up to 63% decrease in soaked and unsoaked CBR was recorded with soap modification (Table 5). Detergent-modified samples experienced a greater decrease in both soaked and unsoaked CBR. The reduction in CBR of the Oro soil samples is expected because of the reduction in maximum dry density with surfactant addition as shown in Fig. 2 since CBR was carried out on samples at maximum dry density. The percentage change in CBR for the soaked CBR is greater than the values obtained for the unsoaked CBR. This might be due to the greater amount of kaolinite in the Oro soil. This finding is similar to that of Jones et al., [16] who submitted that contrary to the suggestion Berney et al., [21] that surfactants should be added to soils in other to improve their maximum dry density does not hold for all soils and conditions. However more research is needed to elucidate the factors affecting subgrade soil response to surfactant modification.

3.4 Shear Strength Parameters

Cohesion (C) increased while the angle of internal friction (δ)reduced for both Oro and Ajase soils with the addition

Table 6 Shear strength parameters of the studied soils

Ajase	C (kPa)	% increase	δ (°)	% decrease	Oro	C (kPa)	% increase	δ (°)	% decrease
NS	13	-	53	-	NS	30	-	19	-
Ls	55	323	14	74	Ls	39	30	8	58
Dt	18	38	10	81	Dt	31	3	5	74
Bs	32	146	15	72	Bs	32	7	6	68

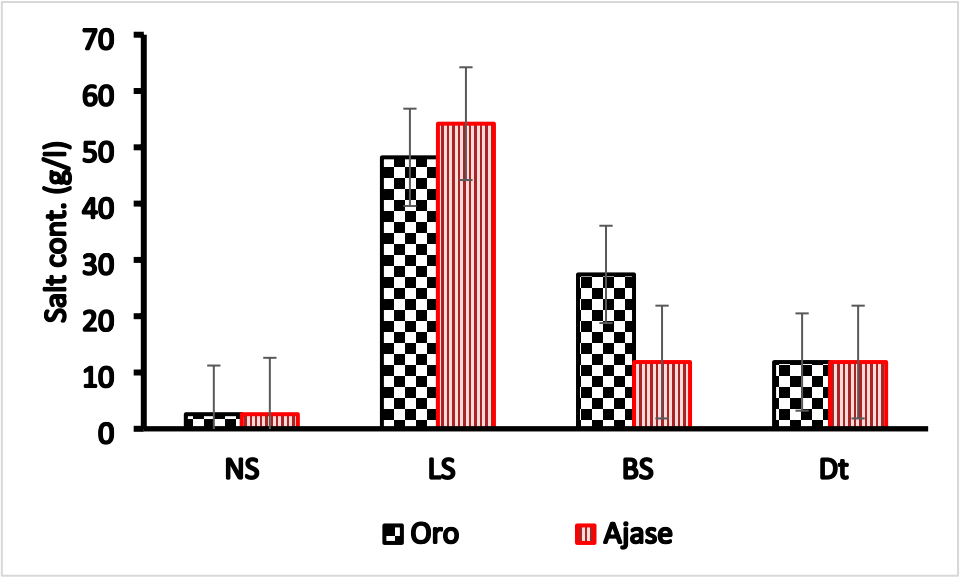


Fig. 6 Variation in Matric suction of soils with soap addition

of soap (Table 6). Since clay minerals have a high specific surface, their structure is significantly influenced by surface forces such as surface tension. Surfactants in the soaps reduced surface tension around the soil particles and enhanced the dispersion of larger particles to smaller ones. Finer soil particles have a larger surface area and exhibit more cohesion. This accounts for the increase in cohesion and reduction in the angle of internal friction of the soils. This is different from the findings of [51], which reported a decrease in both friction angle and cohesion of sandy soils.

3.5 Matric Suction

One important determinant of the stength of highway subgrade soils is matric suction and it has direct relationship with pavement performance due to seasonal variations [54, 55]. It is the presure a dry soil exerts on the surrunding soils to equalize the moisture content of the overall soil block. It is refererred to as negative porewater presure [56, 57]. Figure 6 presents the variation of matric suction of the soils. Natural soil from Ajase same matric suction than Oro natural soil but with the addition of soap, the difference in their matric suctions appeared. The moisture contents of the filter paper reduced in the soils modified with surfactants while their matric suction increased. The increase in matric suction was greater in the liquid soap modified soils than in the bar soap and detergent modified soils. This implies that soap type, rather than soil mineralogy determined the amount of change in matric suction of the soils in response to surfactant addition. Increased matric suction in the soils can be attributed to dispersion due to increase in finer particles and reduced pore space in the soil paricles thereby increasing water retension in the soil rather than relaesing it to the filter paper.

3.6 Permeability

The ease of flow of water through soil measured by permeability can be influenced by several factors including size and configuration of soil pores spaces and temperature. The result of the falling head permeability test carried out on the natural and soap-modified soils showed a reduction in permeability coefficient with the addition of the three types of soap as shown in Fig. 7. This can be attributed to the reduction in pore space in the soap-modified soil samples as a result of dispersion which increases the number of fine-grained particles in the soils. The fine-grained particles tend to clog the available pore spaces thereby, reducing permeability Anaionic surfactants like like linear alkyl benzene sulfonate has been found to cause dispersion of soil particles rather than floculation as expected [27].

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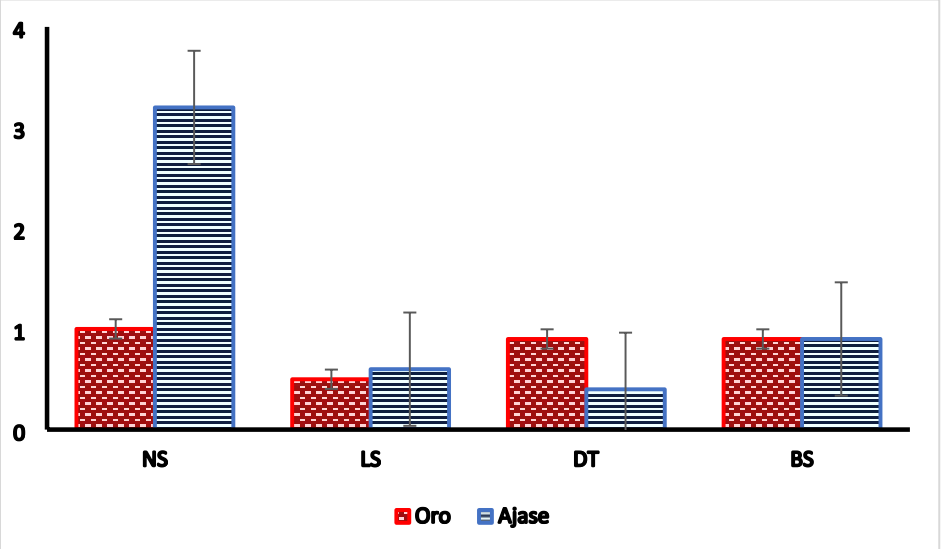


Fig. 7 Variation in permeability coefficients of the modified soil samples

4 Conclusion

Lateritic residual soils with similar grading characteristics but varying amounts of kaolinite, quartz and iron oxide were modified with three types of surfactant-containing soaps namely liquid, detergent and bar soap. The interactions of these soils with the surface active ingredients in the soaps increased plasticity, optimum moisture content and cohesion. Bulk density was reduced, maximum dry density achievable during compaction and permeability was also reduced. Soaked and soaked CBR reduced Ajase soil, while remarkeable reduction was recorded in the Oro soil with the detergent-modified samples experiencing the greater decrease, This might be due to the greater amount of kaolinite in the Oro soil. More research is needed to elucidate the factors affecting subgrade soil response to surfactants. The changes in the geotechnical properties of the soils can be attributed mainly to dispersions. The soil with a higher percentage of kaolinite (Oro soil) showed more sensitivity to surfactants because most of the changes in properties are more pronounced in it than in the Ajase soil with lower kaolinite content. The three types of soap produced the same effect in unequal proportions on the modified soils. The effect of surfactant-containing soaps on the geotechnical properties of lateritic soils cannot be predicted but vary based on soil peculiarities in terms of mineralogical content, percentage abundance of the minerals and types of surfactants. This study has increased our understanding of effect of additives such as surfactants in soaps on soil properties especially residual lateritic soils. However, we intend to study the changes in the microstructural behaviour of lateritic soils under the influence of surfactants in future research.

Author Contributions Research was conceptualized by Owoyemi O.O., laboratory analysis was carried out by all authors, Afolagboye L.O interpreted the results, Egbeyale G. B, analyzed the results. First draft was prepared by Owoyemi O.O. All authors edited and approved the final draft.

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Availability of Data and Material All data that support the findings of this work are available from the corresponding author upon request.

Code Availability Not Applicable.

Declarations

Conflict of interest The authors declare that there are no conflict of interests.

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

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