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COMPACTION BEHAVIOUR OF PERIWINKLE SHELL ASH TREATED LATERITIC SOIL FOR USE AS ROAD SUB-BASE CONSTRUCTION MATERIAL

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ABSTRACT

Lateritic soil treated with up to 12% periwinkle shell ash (PSA) by dry weight of soil was evaluated for use as road pavement material. Three compaction energies were used: British Standard light (BSL), West African Standard (WAS) and British Standard Heavy (BSH). The maximum dry density increased with decrease in optimum moisture content for all compaction efforts. Peak unconfined compression strength (UCS) and California bearing ratio (CBR) were obtained at a threshold of 6% PSA content for all compaction efforts. Durability assessment showed that the resistance to loss in strength increased with increase in PSA content but did not show any consistent trend with increasing compaction effort. Peak resistance to loss in strength of 24.3% was obtained at 8% PSA treatment for British standard heavy compaction effort. Microanalysis studies revealed that improvement in soil properties was due to the formation of cementitious products of calcium silicate hydrate and calcium aluminate hydrate at inter particle contact of soil grains. The study showed that PSA can be used to improve lateritic sub-base of lightly trafficked roads, but would be more effective as admixture in either lime or cement stabilization of lateritic soil.

Key words: Compaction characteristics, lateritic soil, microanalysis, periwinkle shell ash, strength characteristics.

1. INTRODUCTION

The rise in demand for road infrastructures in Nigeria has placed a need on lateritic soils that meet specification requirements for use as road construction material. Some lateritic soils may not be readily suitable in their natural form for use as road construction material (Francis and Vernantus 2013). This has created an urgent need towards increasing effort to improve locally available soils for use within the vicinity for road construction. Lateritic soils are essentially the results of weathering from tropical or sub-tropical origin. They are also the most common reddish and tropically pedogenic surface buildups that are found in Nigeria and other part of the world such as Australia, Asia and South America (Gidigasu 1976). Two groups of tropical soils were chemically identified (Sherman 1952; Maigen 1966): one with iron oxide as predominant (ferruginous laterite) and the other with alumina as predominant (aluminous laterite).

There are cases where a lateritic soil may contain ample amount of clay minerals which undermine its strength and stability as well as the ability to withstand intended traffic load. These categories of laterites are usually known for their behaviours such as swelling or expansion, depressions and lateral movement due to the effect of water even under intermediate wheel loads (Obeahon 1993). Lateritic soils largely form the sub-grades of most tropical roads and are also extensively used as formation materials in sub-bases and or bases of flexible pavement (Gidigasu 1976). Some laterite soils contain swelling clays minerals like illite and montmorillonite which decrease the shear strength of such soils, increase pore pressure and swelling potential compared with the lateritic soil with majorly kaolinite and chlorite minerals (Gidigasu 1976). Also, large amounts of fines and some swelling clay minerals like vermiculite, hydrated halloysite and montmorillonite may exist in some lateritic soils. The presence of such clay minerals made some lateritic soils deficient in their engineering properties for use as sub-base and base materials in road pavements (Francis and Venantus 2013).

New emerged innovations compel the use of waste materials (*i.e.,* agricultural and industrial wastes) for improving deficient soils, which is also a mechanism for achieving sustainable environment. Studies have reported treatment of deficient soils with locally available material from agro-industrial waste such as locust bean waste ash, rice husk ash, fly ash, bagasse ash, coal bottom, crushed concrete powder, quarry dust, cement kiln dust, blast furnace slag, iron ore tailing etc. (Osinubi and Eberemu 2006; Francis and Venantus 2013; Yadu and Tripathi 2013; Salahudeen *et al.* 2014; Osinubi *et al.* 2015; Sharma and Sivapullaiah 2016). Great exploit that has expressed concern in this area had shown that some of these wastes have preferred effect on the geotechnical characteristics of the soils.

Large quantity of periwinkle is being harvested yearly from about thirty-five mangroves and shoreline communities of Niger-delta, Nigeria (Powell *et al.* 1985; Job *et al.* 2009; Jamabo and Chinda 2010; Mmom and Arokoya 2010). The continuous improper disposal of periwinkle shell has generated large heaps of waste to the environment. Periwinkle Shell Ash (PSA) is obtained by calcining periwinkle shell. Recent study has shown that PSA is

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considered a potential stabilizer for soil improvement (Nnochiri and Aderinlewo 2016). However, there are no controlled studies which compare or evaluate the differences in compaction behaviour as well as other qualitative analysis in PSA treated lateritic soil. The need to evaluate the effect of compaction energy on the engineering properties of lateritic soil mixed with PSA becomes necessary. Furthermore, the statistical analysis of variance on the variation of PSA and compaction efforts, the resistance to loss in strength, as well as the microstructural analysis of specimen will address the existing gap of previous studies on the effect of PSA on lateritic soil.

Previous study on chemical analysis of PSA revealed that it is predominantly composed of CaO (Umoh and Olusola 2012), similar to that of lime used for soil stabilization (Spangler and Handy 1982; Amadi and Okeiyi 2017). Periwinkle shell in various forms have been used in concrete based materials (Orangun 1974; Falade 1995; Bamidele 2002; Job *et al.* 2009; Olusola and Umoh 2012; Soneye *et al.* 2016; Etim *et al.* 2017a). Although PSA have shown great potential in geotechnical applications (Nnochiri and Aderinlewo 2016), yet limited studies exist. This study seeks to investigate the effect of PSA on the geotechnical properties of lateritic soil for use as road construction material. It will also be a source of knowledge contribution to the inadequate information on PSA studies as applied in geotechnical engineering. Specific objectives are to evaluate the compaction and strength attributes of the treated soil. It is presumed in this study that PSA will be beneficial and will be an alternative to expensive additives (such as bitumen, cement and lime) for soil stabilization. Hence the dual purpose of soil improvement and safe waste disposal would be achieved.

2. MATERIALS AND METHODS

2.1 Soil Sample

Disturbed sample of lateritic soil was sourced from a borrow area located about 1.5 km away from Akwa Ibom State University main campus, Ikot Akpaden, Nigeria. The soil was excavated prior collection to a depth of around 0.5 to 1.0 m from the natural earth surface to avoid organic matter inclusion. Soil samples were packaged neatly in plastic bags and moved to the laboratory for moisture content test. The clay mineralogy study of the soil specimen was carried out using Empyrean X-ray Diffractometer.

2.2 Periwinkle Shell Ash

The periwinkle shell was obtained from a dumpsite located in Uyo, Akwa Ibom State, Nigeria. It was calcined to a temperature of 1200°C and allowed for about an hour inside the oven. The calcined shell was brought out of the oven, and allowed to cool and further pulverized to powdered form. The pulverized ash was sieved through BS sieve No 200 (0.075 mm aperture) and stored in a sealed polythene bag to be mixed with the soil specimen in appropriate percentage by dry weight of the soil. Oxide composition of the specimens (soil and PSA) were investigated by X-ray fluorescence using Niton^{TM} XL3t XRF analyser.

2.3 Index Tests

Particle size distribution was determined with the use of hydrometer analyses (wet sieving) and mechanical sieve as described in Head (1992). The Atterberg limits test was done on soil passing 0.425 mm opening in accordance with British Standards 1377 and 1924 (BSI 1990).

2.4 Compaction

Compaction tests were conducted following the procedure outlined in BS 1377 (BSI 1990) to determine the compaction characteristics of the natural and the PSA-treated soil. Standard Proctor (BSL), West African standard (WAS) or "intermediate" and modified proctor (BSH) compaction energy were used.

2.5 Unconfined Compression Strength Test

The unconfined compression strength (UCS) was determined following the procedure outlined in British Standards 1377 and 1924 (BSI 1990). The air-dried clayey soil was mixed with different percentages of PSA in stepped concentrations of 0%, 2%, 4%, 6%, 8%, 10%, and 12% by dry weight of soil. The thoroughly mixed air dried soil-PSA mixtures were compacted at predetermined optimum moisture contents (OMC) derived from the moisture density relationship of the preceding section for the various treatment levels and compaction efforts. Steel coring ring with dimensions 76 mm by 38 mm was used to carefully bring out UCS samples from compacted specimen. Specimens were waxed round and wrapped with cellophane to allow for saturation as well as prevent rapid loss of moisture. Specimens were kept in the laboratory under this condition for the period of 7, 14, and 28 days before testing. The minimum of three samples was used and average taken as representative of a data point for the various percentages of PSA. The UCS was evaluated as:

$$\text{UCS} = \frac{\text{Load at failure}}{\text{Cross sectional area}} \tag{1}$$

2.6 California Bearing Ratio

The test was done in accordance with BSI 1377 and 1924 (1990) for the natural and treated soils. The specimens were cured for a period of 6 days and after the sixth day the specimens were submerged in water for 48 hours before testing as specified by Nigeria General specification (1997) for region with high rainfall such as the Niger delta. The CBR was calculated as:

$$\text{CBR} = \frac{\text{Measured load}}{\text{Standard load}} \times 100\% \tag{2}$$

2.7 Durability

The durability is a measure of the resistance to loss in strength. The method adopted to assess durability of PSA treated soils in this study is proposed by Ola (1983) rather than the wet-dry freeze-thaw tests stressed in ASTM (1992). It is the ratio of unconfined compression strength (UCS) of specimen wax-cured for 7 days, and then de-waxed upper and lowest cross section of specimen to allow for water absorption in water tank for another 7 days to the UCS of specimen wax-cured for 14 days (Ola 1983; Osinubi 2006). The resistance to loss in strength was computed as:

$$\text{Resistance to loss in strength} = \frac{\text{UCS (7 days cured + 7 days soaked)}}{\text{UCS (14 days cured)}} \times 100\% \tag{3}$$

2.8 Micro Analysis Using Scanning Electron Microscope

Micro analysis was performed to identify the structural and morphology of the natural and optimally improved lateritic soil at micro level. The test was done with Phenom World scanning electron microscope which has variety of software applications such as fibermetric package used for data gathering and subsequent image interpretation of specimen. The fibermetric application is a statistical tool or adds-ins integrated in SEM that generates data sets interpreting the fabric orientation and pore size distribution within the soil matrix. Such results are produced as histograms called fiber and pore histogram. SEM predicts with high degree of accuracy and precision the morphology and structural orientation of the soil structure. This have been shown to translate to accurate size information that ranged between micro and nano scale of fibermetric analysis. The sequence is that the output is displayed on the desktop monitor, screenshot, exported and reported accordingly.

3. RESULTS AND DISCUSSION

3.1 Material Characterization

Preliminary results of the studied soil are presented in Table 1. The reddish-brown colour shade could to be linked to either the different levels of iron, titanium and manganese present or hydrated iron oxide in the mineral composition form of goethite ($Fe_2O_3.H_2O$). Percentage passing of 0.075 mm sieve size is 52.4% and is grouped by the American Association of State Highway and Transportation Officials (AASHTO 1986), and the Unified Soil Classification System (USCS) (ASTM 1992) as A-7-5(4) and CL, respectively. Mineralogical characteristic of the natural soil specimen as obtained from the X-ray diffraction analysis confirms kaolinite and mixed layer kaolinite/quartz and goethite minerals. Table 2 shows the oxide composition of soil and PSA specimens.

Table 1 Properties of the natural lateritic Soil

Property	Quantity
Natural moisture content (%)	18.50
Percentage passing BS No 200 sieve (%)	52.40
Liquid limit (%)	40.70
Plastic limit (%)	28.10
Plasticity index (%)	12.60
Specific gravity	2.60
Linear shrinkage (%)	9.70
AASHTO classification	A-7-5(4)
USCS	CL
Maximum dry density (Mg/m^3)	
British standard light	1.81
West African standard	1.87
British standard heavy	1.93
Optimum moisture content (%)	
British standard light	15.60
West African standard	14.90
British standard heavy	13.00
Unconfined compression strength (kN/m^2)	
British standard light	278.5
West African standard	401
British standard heavy	493
California bearing ratio (48-h soaking) (%)	
British standard light	4.80
West African standard	11.20
British standard heavy	13.50
Cation exchange capacity (Cmol/kg)	19.30
Colour	Reddish-brown
Dominant clay mineral	Kaolinite

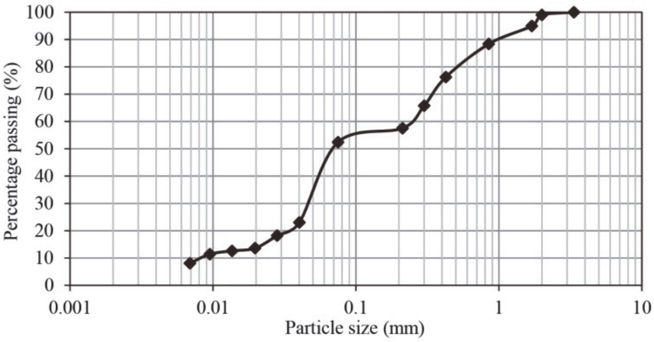


Fig. 1 Particle size distribution curve of the natural soil

Table 2 Oxides composition of natural lateritic soil and periwinkle shell ash used

Oxide	Laterite Soil Concentration (%)	Periwinkle Shell Ash Concentration (%)
Fe_2O_3	17.52	9.84
Al_2O_3	25.12	7.52
SiO_2	41.82	32.83
CaO	0.061	41.36
K_2O	0.05	0.10
Na_2O	0.08	0.31
MnO	0.015	0.221
SO_3	0.31	0.08
ZnO	0.001	0.03
MgO	0.83	0.63
Cr_2O_3	0.011	–
V_2O_5	0.013	–
TiO_2	0.578	0.041
LOI	12.6	6.3

3.2 Compaction Characteristics

The effect of periwinkle shell ash (PSA) on the maximum dry density (MDD) is presented in Fig. 2. The MDD ranged from 1.81 to 1.968 Mg/m^3 for BSL, 1.866 to 1.975 Mg/m^3 for WAS and from 1.932 to 2.02 Mg/m^3 for BSH compaction effort. There is an increase in MDD with increase in both PSA content and compaction effort. It is important to note that results in this study are consistent with the report of other researchers who used varying additives ranging from conventional stabilizers (cement, lime and bitumen) to industrial and agricultural additives such as iron ore tailing, fly ash, polypropylene, cement kiln dust, groundnut shell ash, and concrete wastes (Osinubi *et al.* 2015; Phanikumar and Sharma 2004; Jadha and Nagarnaik 2008; Kumar and Puri 2014; Ijimdiya *et al.* 2014; Moses *et al.* 2018). The increase in MDD with compaction efforts could be as a result of densification of the soil mass with increase in compaction energy. Also, MDD increased with PSA content due to the fact that PSA particles having higher specific gravity (2.65) replaces the soil having lower specific gravity (2.60). The effect is filling of voids spaces with resultant dense matrix of higher specific gravity. The findings of the current study are consistent with those of Osinubi *et al.* (2015) and Etim *et al.* (2017b) who used iron ore tailings as admixture in cement and lime stabilization of black cotton soil, respectively.

The variation in optimum moisture content (OMC) of the soil mixed with various proportions of PSA is shown in Fig 3. The OMC ranged from 11.4% to 15.6% for BSL, 10.4% to 14.9% for WAS and from 9.6% to 13% for BSH compaction

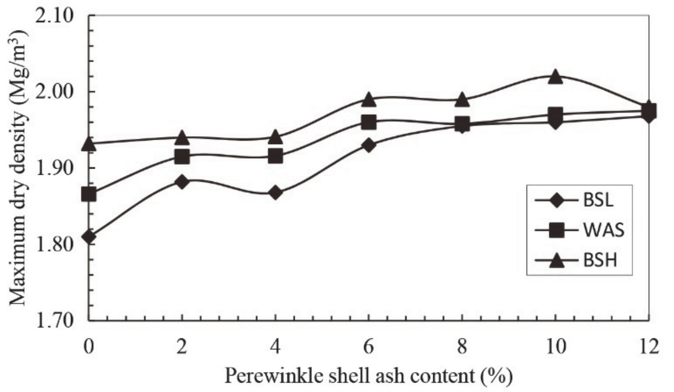


Fig. 2 Variation of maximum dry density of lateritic soil with periwinkle shell ash

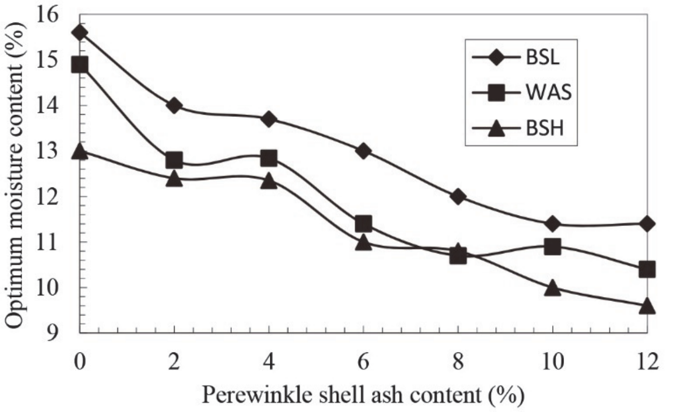


Fig. 3 Variation of optimum moisture content of lateritic soil with periwinkle shell ash

effort. The OMC generally decreased with increase in PSA content and compaction energy. The decrease in OMC was due to self-desiccation in which the available moulding water was immediately used up, giving rise to low hydration. When no water transfer to or from PSA paste was allowed, the available mould water was used up in the hydration reaction until limited water was set aside to wet through the laterite-PSA compacted surfaces and then the relative humidity within the matrix reduced (Moses *et al.* 2012). Another reason for the decrease in the OMCs was that PSA required small amount of water for pozzolanic reaction with the silt and clay fractions of the soil (Umar 2015). This form of reaction is accountable for the strength development of the stabilized soil as the calcium ions in PSA react with the silica or alumina in soil that leads to the development of bonds of calcium silicate hydrate (CSH) or calcium aluminate hydrate (CAH) or both (Amadi and Okeiyi 2017; Umar *et al.* 2015; Grau *et al.* 2015; Al-Swaidani *et al.* 2016). The decrease in OMC as compaction effort increased could also be due to decreased voids present in the soil owing to more densification of the soil particles (Ijimdiya *et al.* 2014).

3.3 Strength Characteristics

3.3.1 California Bearing Ratio

The soaked and unsoaked California bearing ratio (CBR) value of a soil/stabilized soil is an important parameter in evaluating the suitability of such material for use in road construction. Although CBR rating is in percentage, its provide clues for gauging the bearing ability and mechanical potency of the soil in highway design and construction stages. This gauging is one of the preconditions in material selection for subgrades and or sub-bases of embankment, roadway and shoulder, pavement and related uses. The CBR (unsoaked and soaked) values for the soil treated with up to 12% PSA content are shown in Fig. 4 and 5. The unsoaked CBR increased with increase in PSA content from 0% PSA up to 6% PSA as shown in Fig. 4. As the compaction efforts increased, unsoaked CBR increased; this shows that the matrix becomes impenetrable and denser owing to higher compaction effort with corresponding higher strength. The CBR value for BSL, WAS and BSH increased to peak values of 43.2, 48.2 and 55.5% respectively at optimal 6% PSA treatment and decreased steadily with further PSA addition. The increment in unsoaked CBR could also be credited to the presence of cementitious compounds (CSH and CAH), which are major compounds responsible for strength gain (Amadi and Okeiyi 2017; Khemissa and Mahamedi 2014; Nnochiri and Aderinlewo 2016). Also, further treatment with PSA beyond 6% translates to a continuous reduction in the CBR values. The reason could be that additional PSA increased the fine content by changing the grading of the soil structure which may have thus lead to reduction in (1) the cohesive bond between clay particles, (2) the interlocking friction between soil structure, and (3) the shear strength and CBR since CBR is also a gauge of shear strength at realized dry density of compaction as well as moisture content.

In the case of soaked CBR values, an increment was recorded with higher proportion of PSA content from 0% PSA up to 6% PSA content. As the compaction efforts increased, soaked CBR values progressively increased as shown in Fig. 5. Highest soaked CBR values of 14.8, 25.7, and 31% was obtained for BSL, WAS and BSH compaction efforts respectively, at optimal 6% PSA dosage. It is observed that CBR values reduced drastically with further treatment of soil past 6% of PSA. The reduction in the CBR value of soaked samples when compared with the unsoaked CBR value was basically caused by ingress of water into the specimen which weakened it and reduced its strength. This could be linked to changes in moisture content and inherent cohesion of the material brought by variations in grain distribution and plasticity of the material induced by additional dosage of PSA further than the optimum. These factors explain the relatively good connection between CBR and grain size, plasticity and cohesion of fine grain soil.

The 55.5% peak unsoaked CBR value at optimal 6% PSA dosage and compacted using BSH compaction effort did not meet the requirement of 80% value for highway base materials (Nigerian General Specification 1997). However, 31% peak soaked CBR recorded crossed the 20% ~ 30% requirement for sub base materials (Nigerian General Specification 1997). The upper limit 30% is the minimum CBR to be attained for sub base of heavy traffic road (sub base course Type 1) while the lower limit 20% is the minimum CBR to be attained for sub base of light traffic road (sub base course Type 2), Also, the condition according to the Nigerian General Specification (1997) is that specimen for CBR be soaked for 24 hours, but specimens were rather soaked for 48-hours to simulate cases of extremely worst condition in the field.

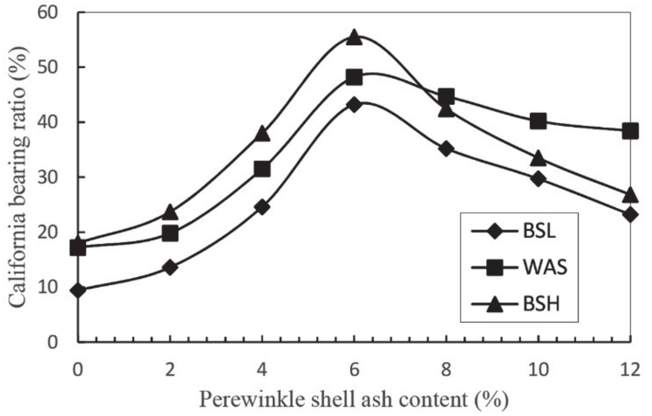


Fig. 4 Variation of California bearing ratio (unsoaked) of lateritic soil with periwinkle shell ash content

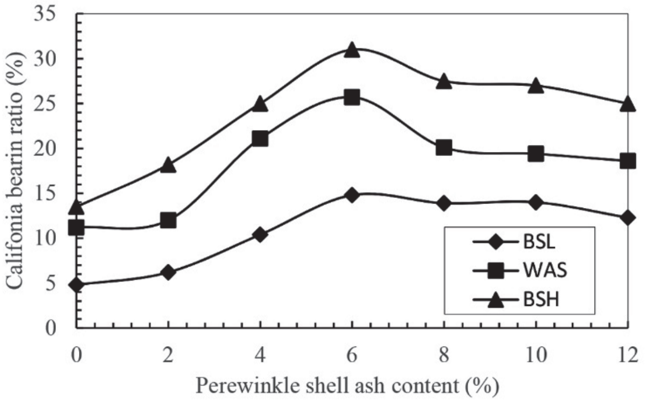


Fig. 5 Variation of California bearing ratio (soaked) of lateritic soil with periwinkle shell ash content

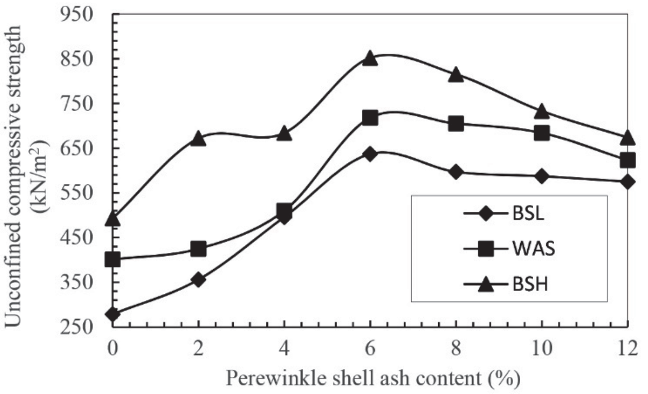


Fig. 6 Variation of unconfined compression strength (7 days) of lateritic soil with periwinkle shell ash content

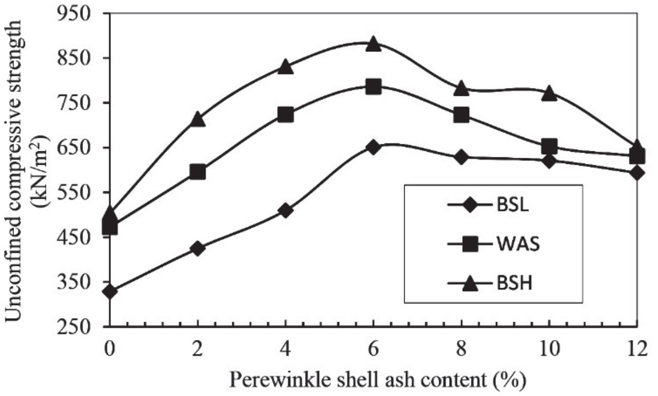


Fig. 7 Variation of unconfined compression strength (14 days) of lateritic soil with periwinkle shell ash content

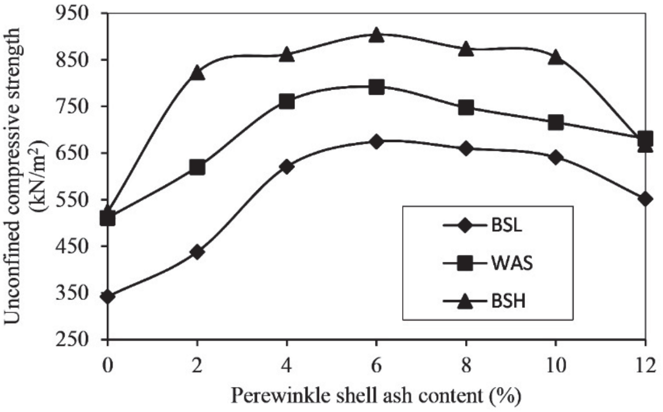
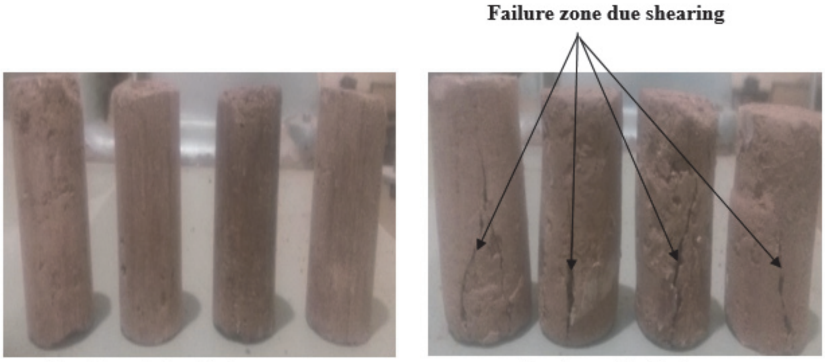


Fig. 8 Variation of unconfined compression strength (28 days) of lateritic soil with periwinkle shell ash content

3.3.2 Unconfined Compression Strength

The measure of unconfined compression strength (UCS) of lateritic soil treated with PSA content cured for 7, 14, 28 days curing period are shown in Fig. 6 to 8 respectively. The UCS specimens before and after testing is shown in Fig. 9. Results show that an optimal 6% PSA content produced a peak UCS values for all curing periods and compaction efforts considered. The UCS at 7 days curing increased from its natural values of 279, 401 and 493 kN/m^2 to highest values of 637, 718 and 852 kN/m^2 at 6% PSA content for BSL, WAS and BSH compaction energies, respectively. For 14 days curing, UCS increased from its natural values of 329, 473 and 504 kN/m^2 to peak values of 651, 786 and 882 kN/m^2 at 6% PSA content for BSL, WAS and BSH compaction efforts, respectively and for 28 days curing, UCS increased from its natural values of 342, 511 and 524 kN/m^2 to peak values of 674.6, 792 and 904 kN/m^2 at 6% PSA content for BSL, WAS and BSH compaction efforts, respectively. The reason for the significant rise in UCS can be attributed to flocculation and agglomeration of the clay structure triggered by cation exchange within their surface. The Ca^{2+} in the PSA reacted with the lower valence metallic ions in the clay structure of the soil giving rise to packaging of the clay particles of the soil to form larger clogs (Salahudeen *et al.* 2014; Moses *et al.* 2012; Puppala *et al.* 2006). Moreover, the increase could be due to the couple effect of structural micro fabric changes imparted by compaction and the formation of cementitious compounds of CSH and CAH. These compounds were induced by hydration reaction made effective by the oxides of Ca, Si and Al in the PSA-soil mixtures. The present findings seem to be consistent with other research which found the crystalline products (CSH and CAH) of hydration reaction acting as a binding agent inside the soil structure and being responsible for strength development with curing age (Onyelowe and Duc 2018 a, b; Amadi and Okeiyi 2017; Grau *et al.* 2015; Al-Swaidani *et al.* 2016; Etim *et al.* 2017; Harichane *et al.* 2012; Negi *et al.* 2013). Results of 7, 14 and 28 days UCS for the various compaction efforts used fell below the 7 days'

Waxed specimens wrapped with cellophane



Specimen before testing Specimen after testing

Fig. 9 UCS specimens before and after failure

strength requirement of 1,034 kN/m^2 for lime specified by (TRB 1987). These findings have important implications in developing sustainable material that will meet standard requirement needed for soil stabilization, but not provided by Nigerian General specification (1997).

3.3.3 Effect of Curing Period on Unconfined Compression Strength

The influence of curing time examined over 28 days on the trend of strength mobilization for soil treated with up to 12% PSA is shown in Figs. 10, 11 and 12 for BSL, WAS and BSH respectively. In general, the UCS increased with curing age. The trends show a marginal strength development after the first 7 days for the three compaction efforts. Thus, 14 and 28 days curing age did not significantly influence the unconfined compression strength. This could probably be an upshot of inadequate moisture required to take the pozzolanic influence of PSA on the soil to completion (Joel and Agbede 2010).

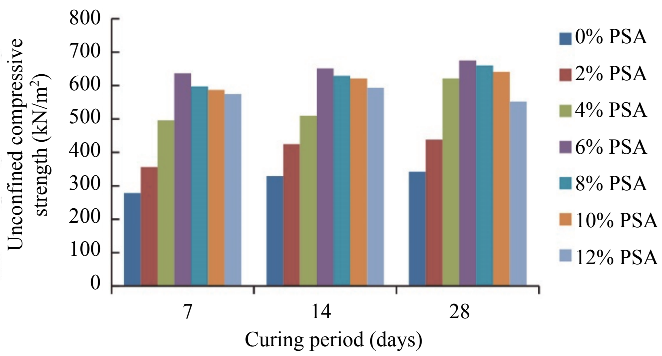


Fig. 10 Variation of unconfined compression strength of soil-PSA mixtures with curing period for BSL compaction effort

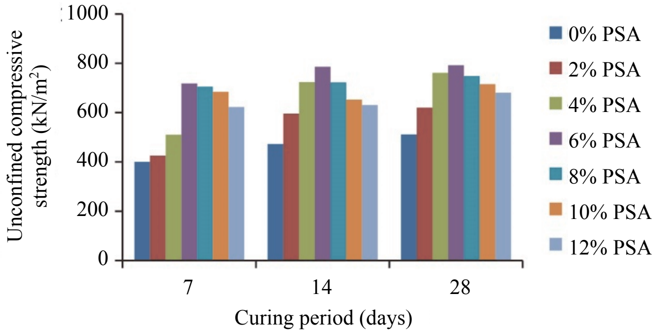


Fig. 11 Variation of unconfined compression strength of soil-PSA mixtures with curing period for WAS compaction effort

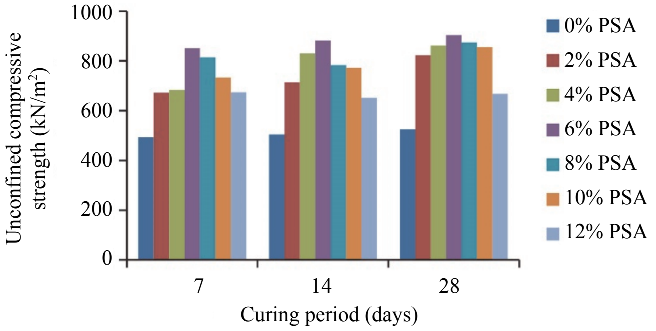


Fig. 12 Variation of unconfined compression strength of soil-PSA mixtures with curing period for BSH compaction effort

3.4 Durability Assessment

Durability of a stabilized soil is equally or even more relevant than the strength gained by the stabilized soil. The variation of resistance to loss in strength with PSA content for BSL, WAS and BSH compaction energy levels is shown in Fig. 13. Generally, the resistance to loss in strength increased with PSA content up to 6% PSA for BSL and 8% PSA for both WAS and BSH compaction efforts. According to Ola (1983), resistance to loss in strength should be a minimum of 80% for 7 days curing and 4 days soaking periods. The peak resistance to loss in strength value of 22.3% at 6% PSA content for BSL, 23.7% at 10% PSA content for WAS and 24.3% at 8% PSA content for BSH compaction efforts, fell short of the acceptable 80% requirement (Ola 1974). However, specimens for this study were exposed to a harsher condition of 7 days soaking periods and not 4 days (Ola 1983). An implication of this is the possibility that PSA had found use in soil improvement but may not provide a sustainable strength under adverse condition if considered a standalone stabilizer.

3.5 Analysis of Variance

The two-way analysis of variance (ANOVA) without replication was considered based on the relative effects of PSA content and compaction efforts on strength and compaction properties. The effect of PSA content and compaction effort on compaction and strength properties was statistically significant (see Table 3). This trend suggests a possible influence of PSA content and compaction effort on compaction and strength properties. Statistical significance was established when a calculated value of F-statistic (Fcal) was greater than the corresponding critical F-statistic Fcrit) (tail probability, $p < 0.05$). The p-values for the variations in PSA content and compaction effort were all less than 0.05 (see Table 3).

3.6 Microanalysis

Microanalysis is used in the study of the morphological structure at both natural and stabilized state. It involves the study of microstructural behaviour, distribution and connectivity of pores (Collins and McGown 1974; Mitchell and Soga 2005; Romero and Simms 2008). The type of soil and quantity of clay minerals in the soil, and the mutual interactions with the pore water in a soil have robust influence on the strength, fluid seepage and compressibility of the soil (Marshall 1958). To provide an in-depth examination on the fabric changes induced by treatment with PSA, microstructural morphologies of the natural soil and PSA treated soil cured for 7 days were studied using scanning electron microscopy (SEM) with an inbuilt fibermetric application. The most important limitation lies in the fact that the pore sizes are not modal pore size, but the modal artefact size (*i.e.* the “pores” in all image are not factual pores, but are just the minutest object that can be viewed within the greyscale range).

3.6.1 Morphologies of Natural Specimens Cured for 7 days

The SEM image of natural soil after cured for 7 days (see Fig. 14) shows a blotchy like surface morphology with a well-built linkage of cracks. This could be an indication that the soil particles might still be cohesive as no meaningful reaction between clay minerals of specimens had taken place except for the changes in micro fabric orientation which ultimately translates to a discontinuous phase structure. This is consistent with the reports of Osinubi *et al.* (2014) and Etim *et al.* (2017b). Spread of inter-grain pores stimulated by drying the soil specimen was also observed. These pores became more visible due to lack of hydration products. This is expected as gradual loss of moisture was possibly eminent due to the wax curing effect. This report is similar to the findings of Osinubi *et al.* (2014), Grau *et al.* (2015), and Al-Swaidani *et al.* (2016).

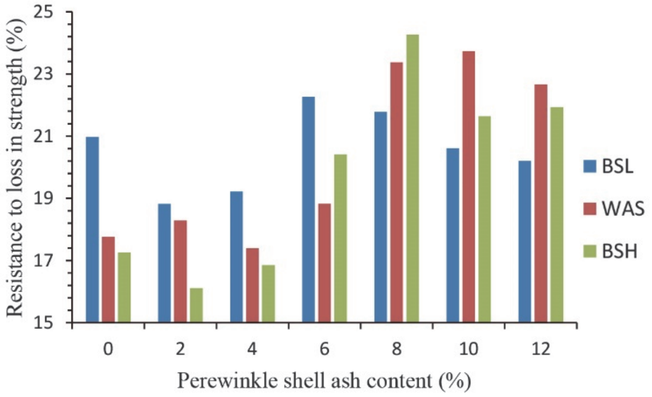


Fig. 13 **Variation of resistance to loss in strength of lateritic soil with periwinkle shell ash content**

Table 3 **Two-way analysis of variance for compaction characteristics and strength properties**

Property	Source of variation	DOF	Fcal	p-value	Fcrit	Remark
MDD	PSA content	6	18.94	1.79E−05	2.996	Fcal >Fcrit SS
	Compaction effort	2	19.46	0.000171	3.885	Fcal > Fcrit SS
OMC	PSA content	6	50.48	8.02E−08	2.996	Fcal >Fcrit SS
	Compaction effort	2	40.61	4.55E−06	3.885	Fcal > Fcrit SS
CBR (us)	PSA	6	33.103	8.67E−07	2.996	Fcal >Fcrit SS
	Compaction effort	2	13.617	0.000819	3.885	Fcal > Fcrit SS
CBR (s)	PSA	6	29.882	1.53E−03	2.996	Fcal > Fcrit SS
	Compaction effort	2	120.967	1.11E−08	3.885	Fcal > Fcrit SS
UCS (7 days)	PSA	6	25.512	3.63E−06	2.996	Fcal >Fcrit SS
	Compaction effort	2	38.798	5.77E−06	3.885	Fcal > Fcrit SS
UCS (14 days)	PSA	6	15.145	5.72E−05	2.996	Fcal > Fcrit SS
	Compaction effort	2	28.636	2.70E−05	3.885	Fcal > Fcrit SS
UCS (28 days)	PSA	6	17.562	2.66E−05	2.996	Fcal > Fcrit SS
	Compaction effort	2	39.318	5.39E−06	3.885	Fcal > Fcrit SS

DOF = Degree of freedom, SS = statistically significant, Fcal = F calculate, p-value = Probability of failure, Fcrit = F critical

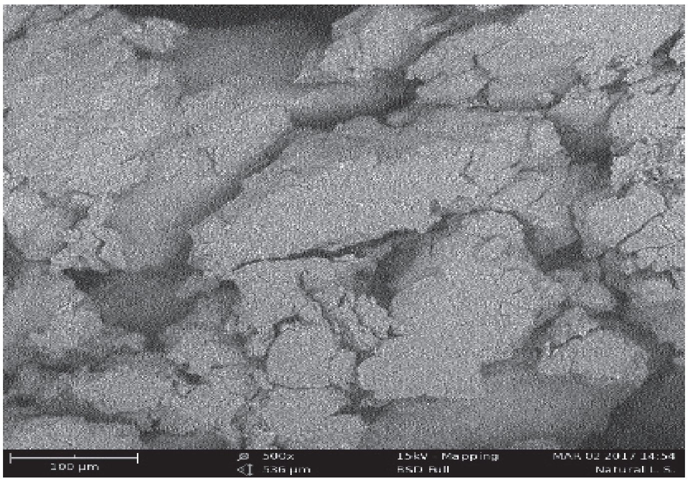


Fig. 14 SEM image of natural lateritic soil after 7 days curing period

3.6.2 Morphologies of Treated Specimens Cured for 7 days

The SEM morphology of lateritic soil treated with optimal 6% PSA after 7 days curing period (see Fig. 15) show significant changes in microstructure and grain size distribution which transposed into a denser structure than that of the untreated soil. Changes in the mineralogical composition and plasticity properties of the soil could be expected (Osinubi et al 2015; Grau *et al.* 2015; Jaritngam *et al.* 2014). This is caused by cation exchange, flocculation and agglomeration of the clay particle. Thus the soil particles became denser resulting in a closed void. It could also be that changes in chemical compounds such as carbonate, aluminium oxides, iron oxides and silicon oxides had taken place. These compounds are suspected to have possibly form precipitate of cementitious products of CSH and CAH at inter particle contact of soil grains, and thus act as cementing agent. These results agree with the findings of other studies, in which the microstructural changes eventually contribute to strength development with time (Sani et al, 2018; Etim *et al.* 2017b; Osinubi *et al.* 2015; Romero and Simms 2008; Jaritngam *et al.* 2014; Lav and Lav 2001; Mallela *et al.* 2004; Chaunasli and Peethamparan 2010; Deneele 2010; Wang *et al.* 2017). It could also be said that the cementitious products were fully formed as this was reflected in the UCS results which did not show any significant increase after 7 days of curing. Generally, the spatial distribution of openings on the surfaces of both natural and treated specimen could be a fall out of the modifications in the material structure that occurred during preparation of compacted specimen (see Fig. 15 and 16). Beckett et al (2013) who studied the morphological variations of compressed soil subjected to loading observed similar behaviour. One limitation to this study is the lack of EDS and XRD reports which could have possibly evaluate the qualitative formation of crystalline products.

3.7 Fibermetric Analysis

The disparities in soil fabrics and pore surface area of the natural and optimally treated specimen cured for 7 and 28 days was explored from SEM micrograph of samples with the aid of a fibermetric interactive software program integrated in SEM. The results are revealed like a collaborative fiber and pore size collection (see Figs. 16(a)-16(b) and Figs. 17(a)-17(b)).

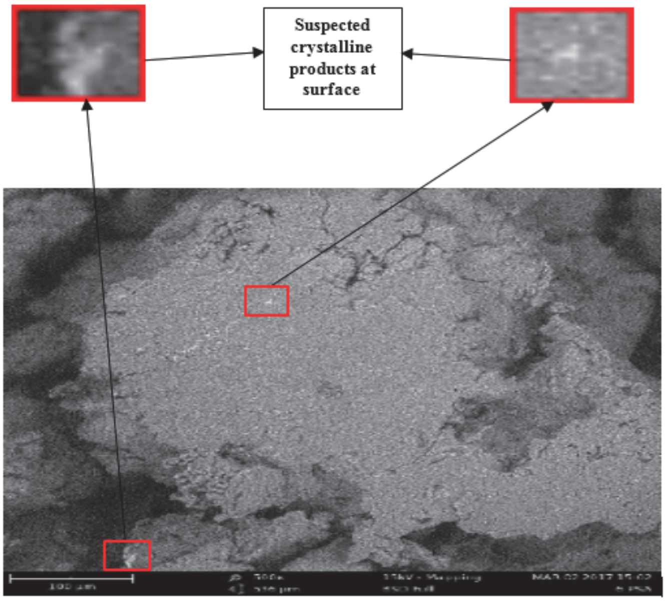
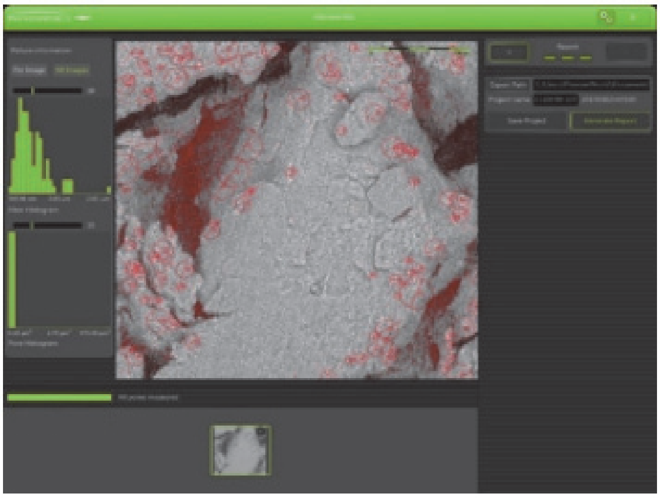
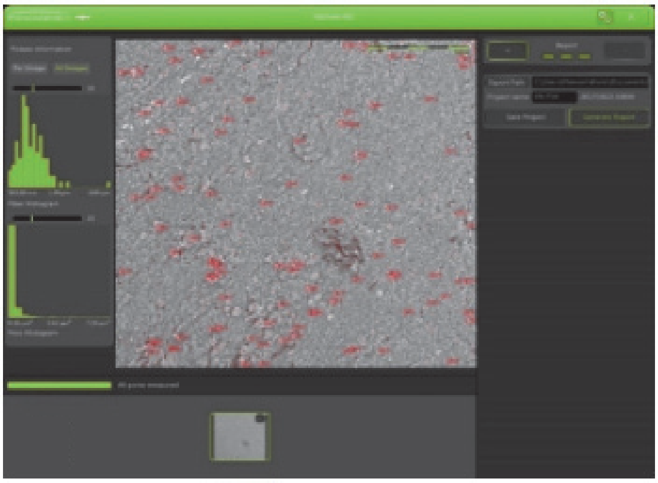


Fig. 15 SEM morphology of lateritic soil optimally treated with 6% PSA after 7 days curing period

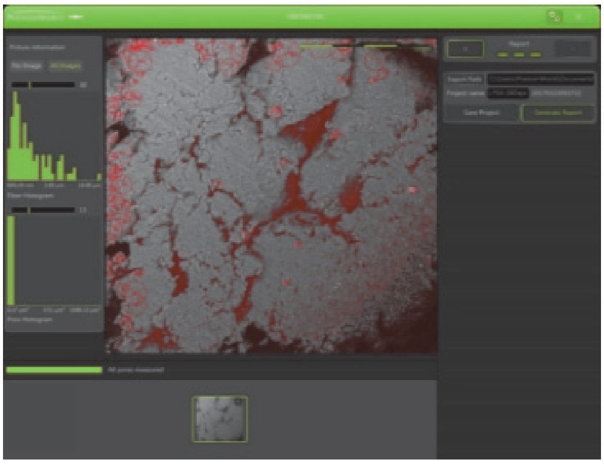


(a) Natural lateritic

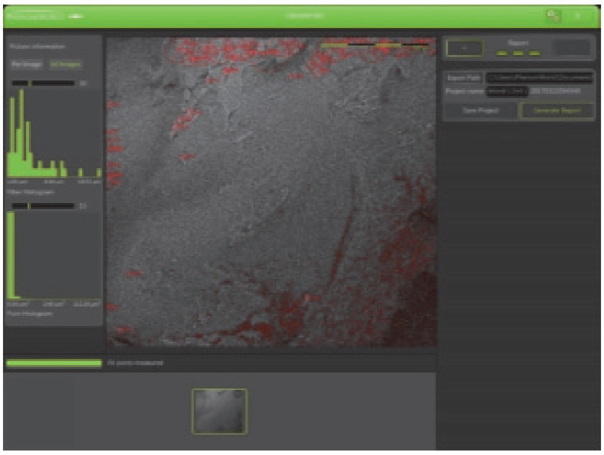


(b) 6% PSA optimally treated lateritic soil after 7 days curing period showing fiber histogram and pore histogram

Fig. 16 Screen shot image of fibermetric analysis



(a) Natural lateritic



(b) 6% PSA optimally treated lateritic soil after 28 days curing period showing fiber histogram and pore histogram

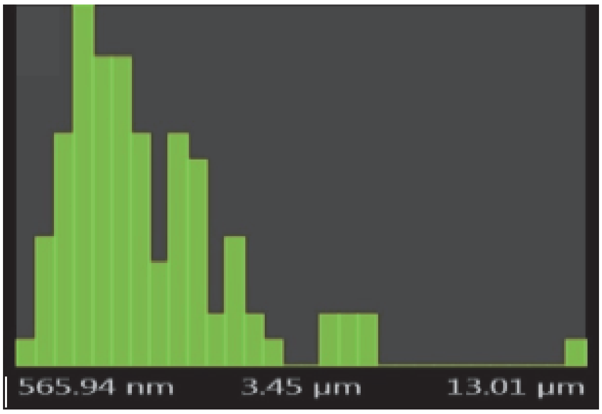
Fig. 17 Screen shot image of fibermetric analysis

3.7.1 Fiber Histogram

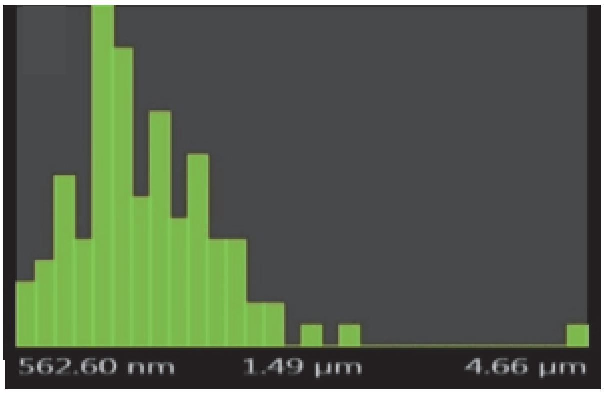
The investigation into the soil fabric arrangement/and or distribution before and after treatment were achieved. The variation of soil fabrics of natural and 6% PSA optimally treated lateritic soil after 7 days curing period is shown in Fig. 18(a) to 18(b). The fiber histogram recorded results of soil fabrics ranging from 565.94 nm to 13.01 μm for the natural soil and from 562.60 nm to 4.66 μm for the treated soil. There is a reduction in micro fabric orientation for the treated sample which signifies improvement in the geotechnical properties of the soil. In the same vein, results of 28 days curing as shown in Fig. 19(a) to 19(b) followed similar trend with that of 7 days and ranged from 1.06 μm to 18.53um for the natural soil and from 669.28 nm to 14.14 μm for the stabilized/treated soil. These results are in agreement with those by Osinubi *et al.* (2015).

3.7.2 Pore Histogram

The pore histograms present the analysis results into the surface area of pores detected by the fibermetric interactive software program integrated in SEM. The results of the natural and 6% optimally treated soil on 7 and 28 days period are revealed in Figs. 20(a) to 20(b) and 21(a) to 21(b). For the 7 days curing period, the pore surface area for the natural soil ranged from 0.18 μm^2 to 973.39 μm^2 while the treated soil ranged from 0.18 μm^2

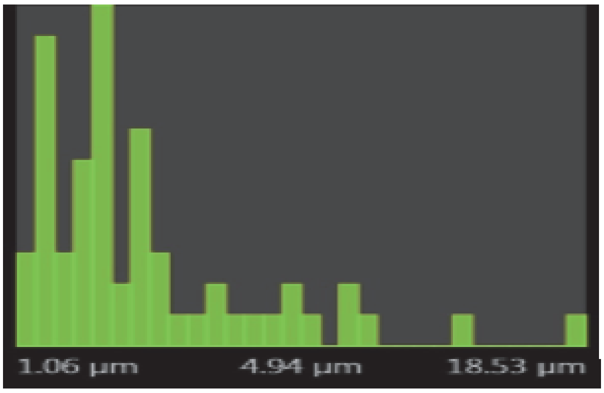


(a) Natural latertic soil

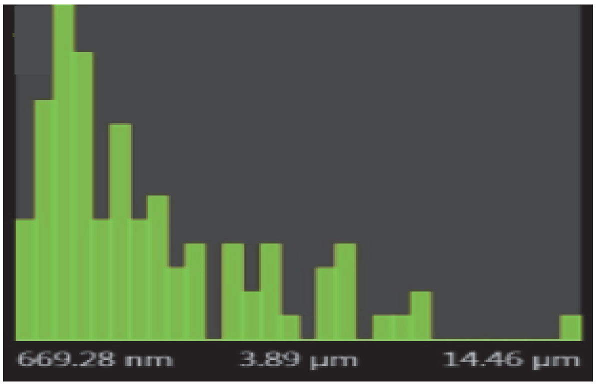


(b) 6% PSA treated lateritic soil after 7 days curing

Fig. 18 Fiber histogram distribution

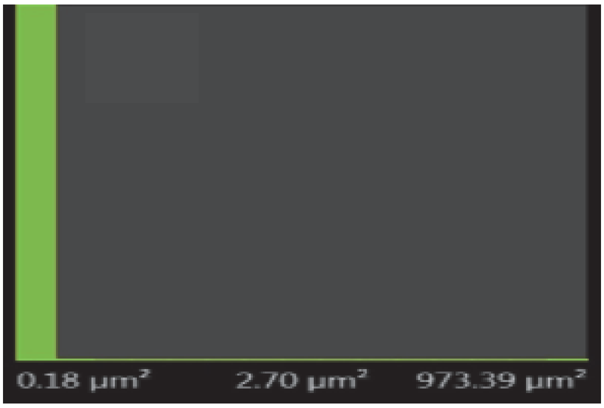


(a) Natural latertic soil

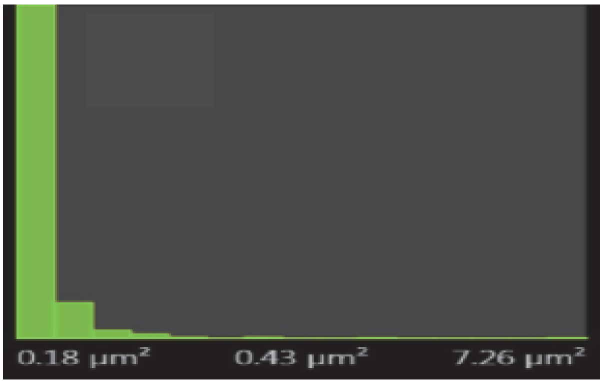


(b) 6% PSA treated lateritic soil afer 28 days curing

Fig. 19 Fiber histogram distribution

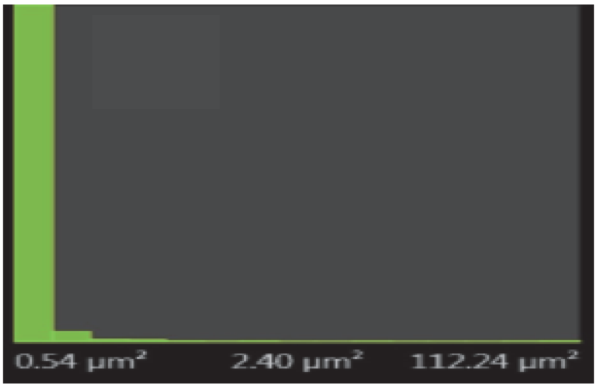


(a) Natural latertic soil

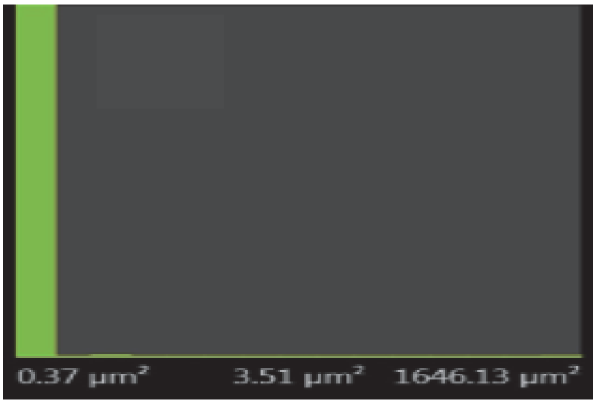


(b) 6% PSA treated lateritic soil afer 7 days curing

Fig. 20 Pore histogram distribution



(a) Natural latertic soil



(b) 6% PSA treated lateritic soil afer 28 days curing

Fig. 21 Pore histogram distribution

to 7.36 μm^2 (see Fig. 20(a) to 20(b)). In this range, the surface area of pore space is reduced. This result could be attributed to PSA filling the voids of the soil fabrics, and thus result to a closed packed structure and less surface area (Morales *et al.* 2015; Osinubi *et al.* 2015).

4. CONCLUSIONS

A lateritic soil classified as A-7-5 (4) in AASHTO or CL in Unified Soil Classification Systems was treated with up to 12% periwinkle shell ash. The MDD increased with increase in PSA content compaction energy. The OMC decreased with an increase in PSA content and compaction efforts. The CBR (unsoaked and soaked) increased with increase in PSA content up to 6% optimal content. Generally, CBR (unsoaked and soaked) increased as compaction energy increased. The UCS at 7 days curing increased to peak values of 637, 718, and 852 kN/m^2 for BSL, WAS, and BSH compaction efforts, respectively. The 14 days UCS increased to peak values of 651, 786, and 882 kN/m^2 for BSL, WAS, and BSH compaction efforts, respectively and the 28 days UCS increased to peak values of 674.6, 792, and 904 kN/m^2 for BSL, WAS, and BSH compaction efforts, respectively. An optimal 6% PSA content produced a peak UCS and CBR (unsoaked and soaked) value for all curing periods and compaction efforts. Maximum values of the resistance to loss in strength of 22.3%, 23.7%, and 24.3% was attained at 6%, 10%, and 8% PSA content using BSL, WAS, and BSH compaction energy, respectively. These values fell short the requirement (80%) for effective stabilization. Microanalysis of natural and optimally treated lateritic soil showed that the strength improvement was evident of the crystalline effect of calcium silicate and calcium aluminate hydrate formed inside and within the inter-aggregate pores. Based on this, it can be inferred that lateritic soil treated with optimal 6% PSA show great improvement, but did not meet the UCS and CBR strength criterions specified by Transportation Research Board and Nigeria General Specification requirement for base course, but it is still recommended as road pavement material for lightly trafficked road. An implication of this is the prospect of PSA being a potential soil stabilizer but may not provide a sustainable strength under adverse weather condition if it is used as a standalone stabilizer. Therefore, in future investigations, it might be possible to use PSA as admixture in either cement or lime stabilization of lateritic soil.

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