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Response of two lateritic soils to cement kiln dust-periwinkle shell ash blends as road sub-base materials

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Abstract

The stabilization potential of cement kiln dust (CKD) and periwinkle shell ash (PSA) was investigated using laboratory analysis. This was aimed at evaluating the effect of CKD and PSA on the stabilization of two lateritic soils for use as pavement layer materials. Two soils (Soil A and B) were treated with various percentages (by weight of dry soil) of CKD at 0, 5, 10, 15 and 20% and PSA at 0, 2, 4, 6, 8 and 10% and compacted using British Standard light (BSL) energy. Their effects were evaluated on the compaction characteristics: maximum dry density (MDD), optimum moisture content (MDD), unconfined compressive strength (UCS) and California bearing ratio (CBR) tests based on American Standard Testing Materials (ASTM) codes. Microstructural analysis using the Scanning Electron Microscope (SEM) was used to identify the morphological changes in the properties of the stabilized soils. Significant improvement with the addition of CKD and PSA was observed with increased MDD, UCS, and CBR for both soils. Peak MDD of 1.745 mg/m^3 and 1.810 mg/m^3 was recorded for both soil samples considered. The results of the peak unconfined compressive strength (UCS) for all the curing ages considered and California bearing ratio (CBR) were obtained at 10% CKD/8% PSA. Peak UCS of 994.17 and 1019.46 kN/m^2 was obtained for soil A and B respectively. Microstructural analysis of the stabilized soils resulted in strength improvement through the formation of new compounds. Based on this study, PSA and CKD can be used to improve deficient lateritic soils for road construction.

Keywords: Lateritic soil; Soil stabilisation; Periwinkle shell ash; Cement kiln dust; Strength characteristics; Scanning electron microscopy

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1. Introduction

The need for a good road network cannot be overemphasized. Increasing urbanization has also increased continual demand road construction materials. Locally available material (soil) is usually used for the sub-base layer of the road. In the tropics where there is elevated temperature and intense rainfall, laterite and lateritic soil are the most available soil and are thus frequently used [1]. Laterites and lateritic soil can be granular in structures and possess low plasticity and excellent drain ability. There are sometimes, however, that the laterite available on or close to a construction site possess poor engineering properties such as high swell potential, high moisture susceptibility, low bearing capacity and high shrinkage. It becomes uneconomical to disregard such soil. An alternative common practice is to utilize chemical additives to improve the engineering properties of those deficient soils before structures are built on them. This is so especially when it is uneconomical to import suitable material.

Several additives that have been successfully utilized are cement, lime, bitumen, fly ash, etc. However, cement and lime are the two widely and most commonly used either individually or as a mixture with other stabilizers [2–4].

However, the use of Portland cement (PC) has led to an increase in greenhouse gas emission being that PC on its own is a high-carbon-footprint commodity [5]. It becomes necessary to seek an alternative utilization of sustainable environmentally friendly cementitious materials such as fly ash [6]; bagasse ash [7]; cement kiln dust [8,9]; oyster shell ash [10]; periwinkle shell ash [11]; sludge ash [12]; ground granulated blast furnace slag [13] as stabilizers. Some of these agricultural wastes when calcinated at the right temperature, possess silica, with which calcium from cement or lime can react and form cementitious compounds (Calcium Silicate Hydrate, CSH) within the soil thereby improving the engineering properties of the soil.

Cement kiln dust (CKD) is an industrial waste material from the manufacture of PC, having a similar appearance to that of PC. It has been reported that huge quantities of CKD accumulate over the world with an estimate of about 30 million tons per year being generated [14]. It has therefore become more economical to use

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them for soil stabilization where they are accessible. Several reports from the literature have proven that CKD is a viable soil stabilizing agent in the improvement of strength properties, reduction of permeability and improved durability of weak fine-grained soils, especially when admixed with pozzolanic materials [8,15,16]. Furthermore, there is an enhancement of long-term strength when pozzolanic materials are being introduced [17–19]. Periwinkle shell is one of these wastes whose edible portion (flesh) has been removed. The management of these wastes is becoming a challenge and the wastes pose an environmental risk. In recent times, researchers in Nigeria have used the periwinkle shell for construction and non-construction purposes [20]. Some of these researches have focused on replacing coarse aggregates with periwinkle shells for lightweight concrete [21,22]. Periwinkle Shell Ash (PSA) obtained by calcining periwinkle shells has been shown to significantly improve the properties of the soil. Chemical analysis of PSA and CKD conducted by [9,23,24] shows that it is mainly composed of CaO which is similar to that of lime and cement [3,25–28]. Few studies on PSA reveals it contains a substantial amount of calcium oxide with a remarkable improvement in the properties of the soil. The authors concluded that PSA cannot be used as a standalone additive although being a potential soil stabilizing agent. They, therefore recommended it for use as an admixture in either cement or lime [11,29].

For fine-grained soils which in its natural form has a poor engineering property, a single additive might not be sufficient in stabilizing such soil [17,30,31]. As a result, the introduction of PSA recently known to be a pozzolanic material enhances strength, improves compaction properties with a resultant decrease in the plasticity and swelling characteristics of the soil [11,29]. The combination of these two additives has the potential of improving the stability of the soil thereby resulting in a sustainable and cost-effective alternative to the traditional stabilizers of cement, lime and bitumen so that the combined purpose of soil improvement and safe disposal can be safely achieved. The primary objective of this study is to examine the combined effect of these cementitious materials (CKD and PSA) on the compaction and strength characteristics of the stabilized soils. The scanning electron microscope was used to observe the changes in the morphological properties of the stabilized soils. It is expected that the excess calcium supplied by CKD will beneficially react with the silica supplied by PSA to form cementitious compounds within the soil and in turn, serve as an alternative to the traditional expensive additives (cement and lime) so that the combined purpose of soil improvement and disposal of waste in a safe manner can be greatly achieved.

2. Materials and test methods

The two soils (termed soil A and B) were collected from two different locations used as borrow pits for road construction in South West, Nigeria. Soil A was collected from Latitude 7° 37' 1652.25"N and Longitude 4° 44' 1782.08"N, while soil B was collected from Latitude 7°30' 1813.27" and Longitude 4° 27' 1667.09"N. The geotechnical characterization of the two soils is provided in Table 1. The periwinkle shell (PS) was collected from a dumpsite in Nwaniba road, Uyo, Akwa Ibom State, Nigeria, calcined at a temperature of 800°C (so it can retain its pozzolanic properties) and allowed to cool inside the kiln. The calcined PS was pulverized to powdered form (periwinkle shell ash, PSA) and sieved through BS sieve No. 200 (with 0.075 mm aperture) and stored in a sealed polythene bag. The cement kiln dust (CKD) was sourced from a local cement industry in Nigeria after which it was sealed in sacks to avoid moisture loss which can result in hardening and loss of properties. The oxide composition of the soils (in their natural states), CKD and PSA both having properties of Calcium carbonate ($CaCO_3$) and $Ca(OH)_2$ was determined with X-ray Fluorescence (XRF) technique using the Thermo Fisher Model ARL 9990 are presented in Table 2. ASTM C 618-91 [32] classify the PSA as class C pozzolan because the sum of silica, alumina and iron oxide in the PSA is 50.29>50%.

Collected soil samples were airdried, pulverized and sieved through sieve No. 4 (with 4.75 mm opening). Dosages of CKD were selected at 0, 5, 10, 15 and 20% of dry weight of soil, and dosages of PSA were selected at 0, 2, 4, 6, 8 and 10% of the dry weight of soil. The stabilizers were mixed with the soil separately and then together. The specimen for tests was prepared by mixing weighted dry soil with various dosages of stabilizers thoroughly until uniformity was observed. Various tests such as compaction (ASTM D 698), unconfined compressive strength, UCS (ASTM D 2166) and California Bearing Ratio, CBR (BSI 1377 and 1924 (1990) were performed in the laboratory.

The maximum dry density (MDD) and optimum moisture content (OMC) for each soil specimen were obtained from the compaction test. Soil specimens for UCS tests were compacted at their respective OMCs after which cylindrical samples of 38 mm (diameter) x 76 mm (height) were carefully extruded using a manual extruder. The extruded specimens were completely sealed

Table 1
Geotechnical properties of soils.

Property	Soil A	Soil B
Liquid Limit LL (%)	45.0	43.5
Plastic Limit PL (%)	28.5	22.5
Plasticity Index PI (%)	16.5	21.0
Percentage passing sieve No. 200 (P_{200})	45.46	40.94
Percentage passing sieve No. 40 (P_{40})	81.34	57.36
AASHTO classification	A-7-6	A-7-6
Group Index	3	7
Maximum Dry Density, MDD (mg/m^3)	1.600	1.770
Optimum Moisture Content, OMC (%)	20.50	17.00
pH	6.2	6.5
Specific Gravity (Gs)	2.55	2.51

Table 2
Oxide compositions of soils, CKD and PSA.

Chemical (% Oxide Concentration)	Chemical compositions by weight (%)			
	Soil A	Soil B	CKD	PSA
Silica (SiO_2)	57.02	56.42	9.87	33.85
Alumina (Al_2O_3)	22.70	19.17	3.80	9.24
Iron oxide (Fe_2O_3)	6.01	10.49	2.41	7.20
Calcium oxide (CaO)	0.46	0.13	45.08	33.87
Magnesium oxide (MgO)	0.21	0.15	1.08	0.06
Sulphur oxide (SO_3)	0.00	0.00	0.22	0.16
Potassium oxide (K_2O)	2.29	1.46	0.17	0.06
Sodium oxide (Na_2O)	0.00	0.00	0.00	0.00
Dinitrogen pentoxide (N_2O_5)	0.11	0.13	0.07	1.40
Phosphorous pentoxide (P_2O_5)	0.09	0.12	0.60	0.37
Tin oxide (TiO_2)	0.76	1.53	0.24	0.09
Loss on Ignition	9.73	8.45	35.66	8.68

and stored in a humidity-controlled chamber for 7, 14 and 28 days. A Minimum of two representative samples was tested after the expiration of the curing age using the triaxial machine and the average value of UCS obtained. A 6-day curing period was employed in curing specimens used for the CBR test. At the expiration of the sixth day, the specimen was immersed in water for 48 hours before testing as stipulated by [33].

The durability of the stabilized soils was assessed using a variant of loss of strength upon immersion test outlined in BS 1924 [34] and used by Oluwatuyi et al. [35]. The relative volumetric stability was obtained by dividing the soaked CBR by the unsoaked CBR.

3. Results and discussion

The preliminary geotechnical investigation results presented in Table 1 show that both lateritic soils are silt clay material according to the AASHTO classification system (because they both have fines content greater than 35%) and are unsuitable as sub-base materials. The values of the ratio of silica-sesquioxides [$SiO_2/(Al_2O_3 + Fe_2O_3$] are 1.99 and 1.90 for soil A and B, respectively, which implies that both soils are lateritic soils according to [36].

3.1. Compaction characteristics

Figs. 1 and 2 show the compaction characteristics (MDD and OMC) of soil A and B, respectively. The addition of the stabilizers to the soil increased the MDD of both soils A and B. CKD led to a higher increase in MDD of the soils than PSA. The combination of CKD and PSA caused the highest increment in the MDD of both soils. The values of the MDD for soil A ranged from 1.60 to 1.745 mg/m^3 and while that of soil B ranged from 1.770 to 1.810 mg/m^3. A similar trend of increasing MDD was reported by various researchers who used varying stabilizers such as Non-traditional additives [37], cement kiln dust [9], periwinkle shell ash [11] and oyster shell ash [10]. The increase in MDD might be attributable to the admixtures acting as a filler within the soil voids which causes an increase in weight of the soil and stabilizer matrix. The increase might also be due to the densification of the soil mass due to increased workability caused by the stabilizers. The higher specific gravity of each of the stabilizers than the soils can also contribute to this. The specific gravity of PSA and CKD are 2.63 and 2.93, respectively. Furthermore, CKD releases more calcium oxide (CaO) while PSA releases more silica oxide (SiO_2); the combined effect of these admixtures causes an increase in MDD thereby leading to flocculation and agglomeration of clay particles. This increment was in consistency with recent findings of [38,39].

Two-way analysis of variance (ANOVA) on MDD results of soil A shows that the effects of CKD and PSA on lateritic soil were statistically significant for CKD ($F_{CAL} = 22.957 > F_{CRIT} = 2.866$; p = 3.08×10^{-7}) and PSA ($F_{CAL} = 12.629 > F_{CRIT} = 2.711$; p = 1.27×10^{-5}) at 5% significance level. Also, the results of the two-way ANOVA on MDD results of soil B were also statistically significant for CKD ($F_{CAL} = 25.410 > F_{CRIT} = 2.866$; p = 1.35×10^{-7}) and PSA ($F_{CAL} = 5.364 > F_{CRIT} = 2.711$; p = 0.0027) at 5% level of significance.

The effect of CKD and PSA on the OMC of soil A and B is presented in Figs. 1 and 2 for soils A and B, respectively. The results show a general increasing trend in OMC as the amount of CKD increased and a decreasing trend with increasing PSA contents for both soil samples. The reason for the general increase in optimum moisture content with increased CKD concentrations for both soil samples may be attributed to the CKD which has more tendency to absorb water due to its similar properties as that of cement because more water was needed by various cations and the clay minerals for the complete hydration of CKD [40]. Furthermore, an increase in the effective size of the soil grains leading to the formation of soil lumps as the additives increased, caused an increase in surface area, such that more water is needed for the lubrication of the entire soil-CKD-PSA mixtures.

On the other hand, the decrease in optimum moisture content values as the PSA treatment increases could be due to the decrease in the amount of free silt and clay fraction, as well as increased coarser materials with smaller surface areas. The decrease in the OMC with increased proportions of PSA content might also be attributed to cation exchange that resulted in the clay particles changing from face-face orientation to a more compact edge-face orientation. Furthermore, it could probably be due to self-desiccation in which all the water is used up, resulting in low hydration. When no transfer of water was permitted to and from the CKD-PSA paste, the available water was used during the hydration reaction until only a small amount of water was left to lubricate the stabilized soil eventually leading to a reduction in the relative humidity of the soil matrix [40].

Statistical analysis of the results using two-way ANOVA on the OMC results of soil A had CKD and PSA statistically significant with CKD ($F_{CAL} = 83.722 > F_{CRIT} = 2.866$; p = 3.37×10^{-12}) and PSA ($F_{CAL} = 8.546 > F_{CRIT} = 2.711$; p = 0.00018) at 5% level of significance. Similarly, two-way ANOVA on OMC results of soil B shows that both additives had significant effects on the stabilized soil with CKD ($F_{CAL} = 16.899 > F_{CRIT} = 2.866$; p = 9.47×10^{-9}) and PSA ($F_{CAL} = 17.853 > F_{CRIT} = 2.711$; 4.07×10^{-8}) at 5% level of significance. The data in Fig. 1 was subjected to descriptive statistics and the results show that the data is normally distributed. A descriptive statistic is considered to be consistent with a normal distribution if the mean is nearly equal to the median and both the skewness and kurtosis are between -3 and +3. These conditions are largely satisfied. The mean for each set of data ranged between 1.614 and 1.69 while the median ranged between 1.615 and 1.71. This show that the mean is nearly equal to the median. The skewness ranged between -1.05 and +0.57 while the kurtosis ranged between -2.68 and 0.18. These values show a normal, close to mesokurtic type distribution according to Velasco and Verma [41]. A typical descriptive statistic result for soil A is presented in Table 3.

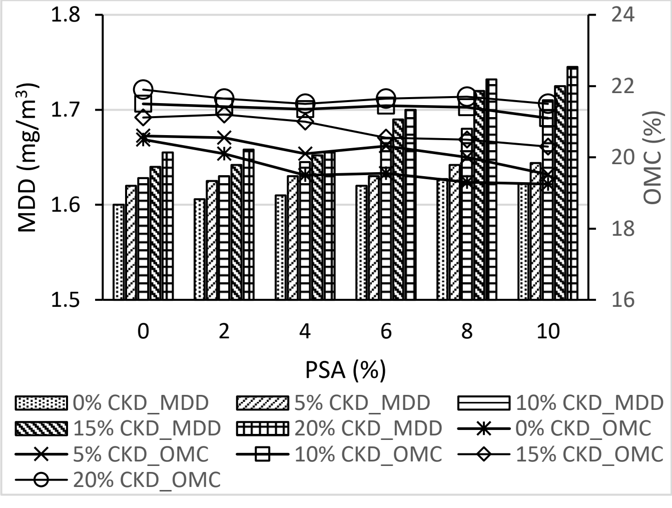

Fig. 1. Compaction properties of treated soil A.

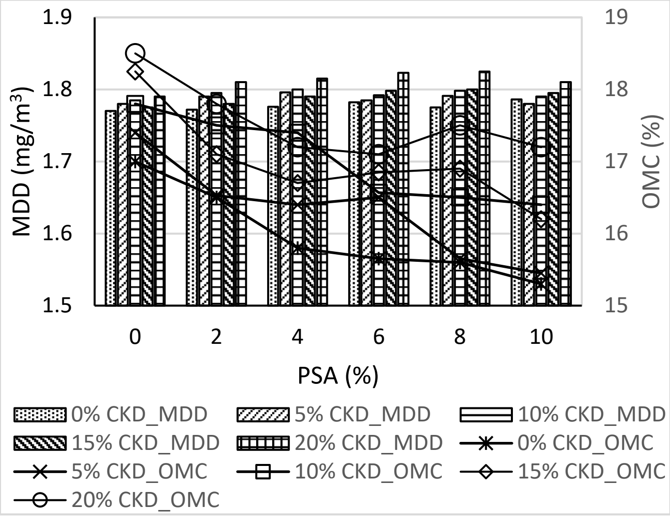

Fig. 2. Compaction properties of treated soil B.

Table 3
Descriptive Statistic Result for Soil A.

	0	5	10	15	20
Mean	1.614	1.63	1.66	1.678	1.69
Median	1.615	1.63	1.66	1.671	1.679
Kurtosis	-1.7	-1.4	-0.837	-2.49	-2.26
Skewness	-0.17	0.3	0.57	0.29	0.45

3.2. Unconfined compressive strength

The pretreatment unconfined compressive strength (UCS) of the soils A and B (presented in Figs. 3 to 5) suggests that the samples are of stiff consistency according to the findings of [42] which state that UCS of 0 - 25 kN/m^2 indicates very soft, 25 - 50 kN/m^2 is soft, 50 - 100 kN/m^2 is medium soft, 100 - 200 kN/m^2 is stiff, 200 - 400 kN/m^2 very stiff and greater than 400 kN/m^2 indicates hard clay. The variation of UCS of treated soils A and B with CKD-PSA blends and cured for 7, 14, and 28 days are presented in Figs. 3, 4 and 5, respectively. The A and B at the end of the legends in Figs. 3 to 5 imply soil A and soil B, respectively. For example, 5% CKD_A means soil A treated with 5% CKD.

The results show a general increasing trend for the various percentages of admixtures considered for all the curing periods. The UCS of PSA (only) treated soil A after 7 days curing had a maximum 144% increase at 8% PSA, while there was about (a maximum of) 124% increase in UCS of soil B at the same 8% PSA. The UCS (after 7 days of curing) of CKD (only) treated soils A and B increased as CKD content increased as presented in Fig. 3. PSA and CKD blend caused a consistent increase in the UCS of both soils A and B with the maximum UCS obtained with 8% PSA and 10% CKD blend with about 743 and 646% increase for soil A and B, respectively. The reason for the observed increase in UCS at 7 days of curing of the two samples might be because of flocculation and agglomeration of the clay particles resulting in more compact particles, accompanied by cation exchange within their surface. The higher amount of Ca^{2+} in the additives also as shown in Table 1, effectively combines with the lower valence metallic ions in the clay structure of the soil leading to flocculation and agglomeration of the particles [9,40].

At 14 days curing period, similar trends of increased UCS were observed for both soil samples with peak strength obtained at

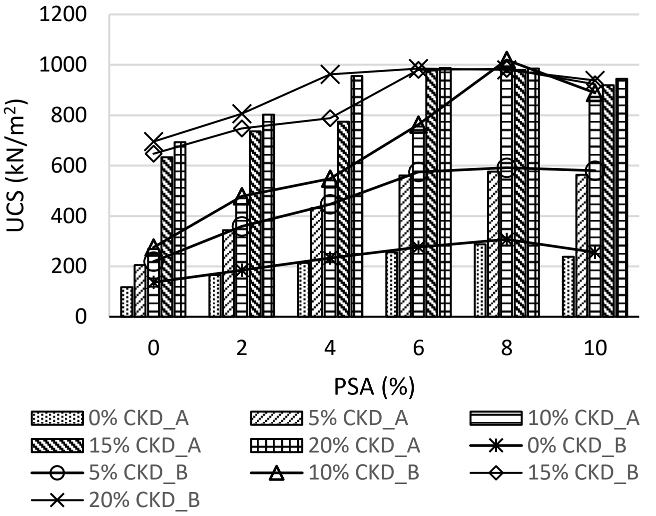

Fig. 3. Variation of unconfined compressive strength of soils A and B after 7 days of curing period.

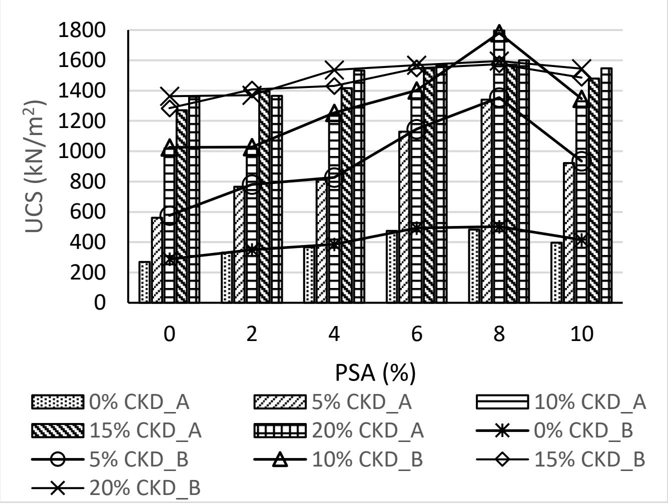

Fig. 4. Variation of unconfined compressive strength (14 days curing period) of lateritic soil–CKD mixtures with PSA content.

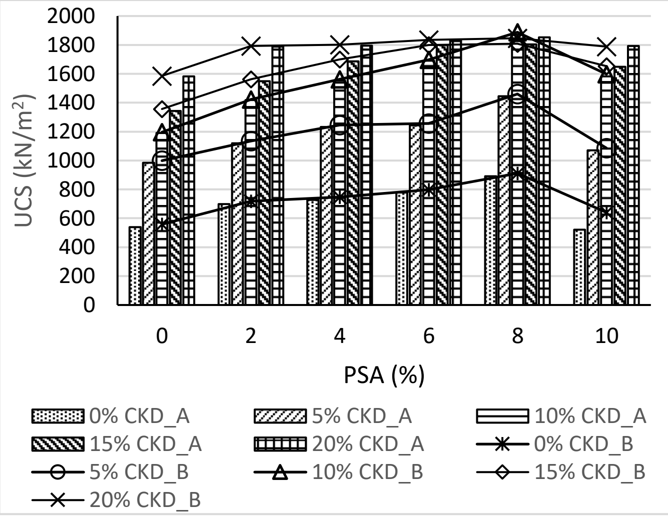

Fig. 5. Variation of unconfined compressive strength (28 days curing period) of lateritic soil– CKD mixtures with PSA content.

1797.18 kN/m^2 and 1780.08 kN/m^2 for soil A and B, respectively, both at 10% CKD/8% PSA. In the case of 28 days curing period, peak strength was obtained at 1871.16 kN/m^2 and 1887.86 kN/m^2 for soil A and B, respectively at 10% CKD/8% PSA. The significant increase in shear strength of the soil at 28 days curing period may be attributed to the flocculation and agglomeration of the clay particles caused by cation exchange reaction within their surface. Furthermore, the presence of the admixtures (PSA and CKD) in the soil which possesses highly pozzolanic properties coupled with its ability for reducing adsorbed water which in turn causes soils with higher clay content to behave as though it is a granular soil. This behavior contributed to an increase in shear strength of the stabilized soil and agrees with the findings of [42]. The subsequent decrease in UCS after 8% PSA might be attributed to the insufficient amount of water required to complete the hydration process and a large amount of PSA occupying the soil matrix [7,43]. Furthermore, it could be attributed to insufficient water necessary for the pozzolanic reaction to take place coupled with a larger quantity of PSA present in the soil-CKD-PSA matrix. Statistical analysis of data on UCS for all the curing periods considered using the two-way ANOVA shows that the effects of both additives were statistically significant on the soil-CKD-PSA admixtures. The 7 days peak strength of 994.17 kN/m^2 and 1019.46 kN/m^2 for soil A and B, respectively, fell short of 7 days strength requirements of 1720 kN/m^2 for adequate cement stabilization of base courses specified by [24].

3.3. *California bearing ratio*

The California bearing ratio (CBR) is a penetration test for the evaluation of mechanical strength of road sub-grades and base courses. The results obtained from these tests are used with the empirical curves to determine the thickness of pavement and its component layers. It is an important parameter used to indicate the strength and bearing capacity for base and sub-base in a pavement structure. [33] recommends a soaked CBR of ≥ 30% and ≥ 80% for sub-base and base course materials, respectively. The pretreated soaked and unsoaked CBR (CBR_s and CBR_u) of both soils presented in Figs. 6 and 7 do not satisfy the minimum requirements, thus the soils need to be stabilized. The effects of CKD and PSA on CBR of the treated soils considering both unsoaked and soaked conditions are presented in Figs. 6 and 7 for soil A and B, respectively. The results show that the CBR_u of both soils tend to increase as PSA contents increased. The optimum percentage of PSA for both (PSA only treated) soils is 8% when there was about 115 and 83% increase in the CBR_u of soils A and B, respectively. The CBR_u of CKD only treated soils also increased with increasing CKD content. The highest CBR_u value was obtained at 20% CKD content with 452 and 324% increase for soils A and B, respectively. These results show that CKD caused a higher increase in the CBR_u of both soils than PSA.

The stabilization of the soils with blends of PSA and CKD caused more increase/improvement in the CBR_u of both soils. The optimal blend for soil A is 8% PSA and 10% CKD at which the CBR_u increased to about 554 and 420 folds for soil A and B, respectively. The increase in CBR_u of both soils may be attributed to the formation of calcium-aluminate-hydrates (C-A-H) and calcium-silicate-hydrates (C-S-H) cementitious compounds [2,29], which are the major compounds that have contributed to strength gain. In the same vein, the reduction in CBR values beyond 10% CKD/8% PSA additions may be because additional PSA increased the fines content of the soil by changing the gradation of the soil structure which in turn lead to a reduction in the cohesive bond existing between the clay particles and shear strength cum CBR of the soil.

Statistical analysis using Two-way ANOVA on the results show that that PSA ($F_{CAL} = 14.214 > F_{CRIT} = 2.711$; $p = 5.3 \times 10^{-6}$) and CKD (($F_{CAL} = 217.233 > F_{CRIT} = 2.866$; $p = 3.58 \times 10^{-16}$) at 5% significance level have significant effect on the CBR_u of soil A. PSA ($F_{CAL} = 15.577 > F_{CRIT} = 2.711$; $p = 2.64 \times 10^{-6}$) and CKD ($F_{CAL} = 192.047 > F_{CRIT} = 2.866$; $p = 1.19 \times 10^{-15}$) at 5% significance level have significant effects on the CBR_u of soil B.

There was a general increment in the soaked CBR (CBR_s), following the same trend as that of CBR_u. The CBR_s, however, was lower than the CBR_u of all the treated soils. It was reported that the reduction might be due to the movement of water into the specimen during the process of curing and soaking after 48 hrs which further resulted into weakening and reduction in strength [7]. This can result to changes in the cohesion of the soil structure with a resultant change in grain size arrangement so that the specimen possesses more affinity for moisture. The percentage increases in the CBR_s of the different blends of PSA and CKD are more than that obtained for CBR_u. There were about 168 and 115% increases

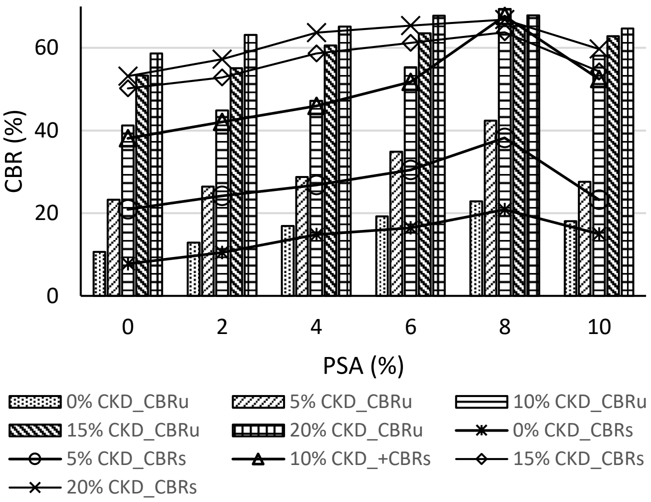

Fig. 6. Soaked and unsoaked CBR of treated soil A.

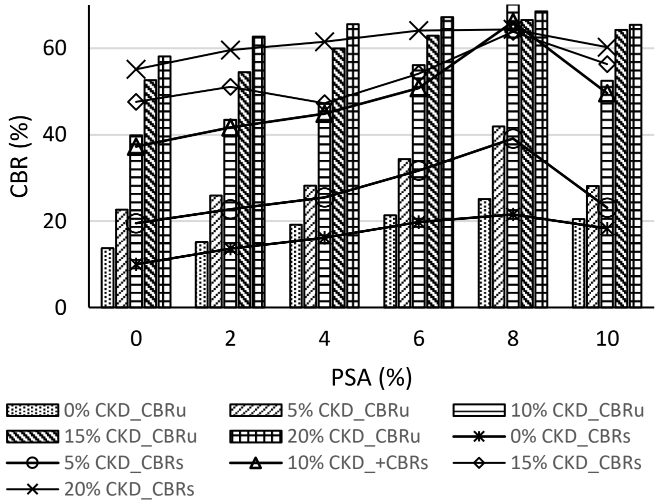

Fig. 7. Soaked and unsoaked CBR of treated soil B.

in the CBR_s of 8% PSA treated soils A and B, respectively. The increase in 20% CKD stabilized soil A and B are 584 and 451%, respectively. The optimum CBR_s was obtained at 8% PSA and 10% CKD for both soils A and B (as observed for CBR_u) with 772 and 561% increase. Statistical analysis using Two-way ANOVA on the results show that that PSA ($F_{CAL} = 19.075 > F_{CRIT} = 2.711$; $p = 5.37 \times 10^{-7}$) and CKD (($F_{CAL} = 251.804 > F_{CRIT} = 2.866$; $p = 8.46 \times 10^{-17}$) at 5% significance level have significant effect on the CBR_u of soil A. PSA ($F_{CAL} = 20.898 > F_{CRIT} = 2.711$; $p = 2.57 \times 10^{-7}$) and CKD ($F_{CAL} = 198.555 > F_{CRIT} = 2.866$; $p = 8.60 \times 10^{-16}$) at 5% significance level have significant effects on the CBR_u of soil B.

The CBR value of 180% should be attained in the laboratory for adequate cement stabilization as recommended by [33]. Nevertheless, for the unsoaked CBR, 80% is required for bases while a soaked CBR value of 20-30% is recommended for sub-bases when compaction is done at optimum moisture and 100 % relative compaction [44]. Based on the above criterion, the 69.41% and 71.20% maximum CBR_u of soils A and B, respectively, compacted using British Standard Light (BSL) compaction effort failed to meet the requirement for highway base materials. Suffice to say that at higher compactive effort, there may be an increase in these values. However, the 67.68% and 66.10% maximum CBR_s value recorded for soils A and B, respectively, met the 20-30% requirement for sub base materials by [33].

3.4. Durability

The plots of relative volumetric stability against percentages of PSA at different percentages of CKD are presented in Figs. 8 and 9 for Soil A and B, respectively. The results show that the durability of all the stabilized soils (with the exception of 15% CKD/4% PSA stabilized soil B) are satisfactory because the obtained relative volumetric stability were higher than 80% recommended by BS 1924 as stated in [35]. The relative volumetric stability for both unstabilised soil sample is below 80%, this further shows the need for stabilizing the two soils.

3.5. Microanalysis

3.5.1. Scanning Electron Microscope

The physical properties and macroscopic behavior of compacted and untreated soils are progressively being enhanced with the utilization of Microstructural studies. The scanning electron microscope (SEM) works by scanning a firmly focused electron beam over a sample. Electrons in the beam dissipate off of the sample and onto a cathode ray tube, or screen. Each point on the sample matches with a pixel or picture component on the screen. The more electrons that hit a specific component of the screen, the more splendid the pixel that shows up. Presented in Figs. 10 and 11 is the morphology of the natural and treated soil at 10% CKD/ 8% PSA. The untreated soil A (Fig. 10(a)) is made up of well packed dense particles with a closed void as in form of blocks while soil B (Fig. 10(b)) shows a well pronounced shrinkage cracks with a fewer visible presence of inter-grain pores linking the sand grains within the clay matrix. The shrinkage cracks at the background might be the presence of clay content known to possess some polar properties which make their affinity for water more pronounced. Furthermore, the whitish particles at the background may be due to the presence of SiO_2 peradventure due to its size when compared to the background. The morphology of both treated soils shows a smooth and scaly surface, respectively. The smooth surface might probably be due to the clay particles

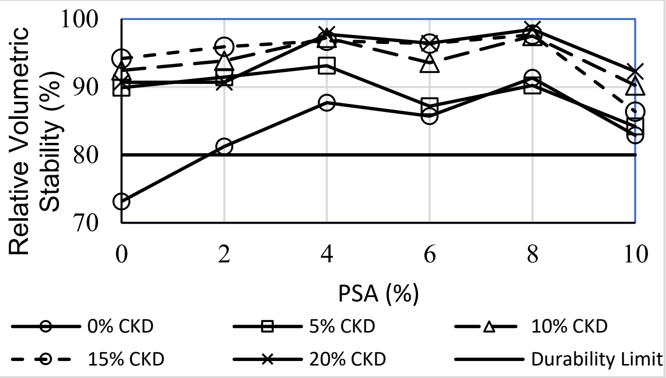

Fig. 8. Variation of relative volumetric stability with percent stabilizers for soil A.

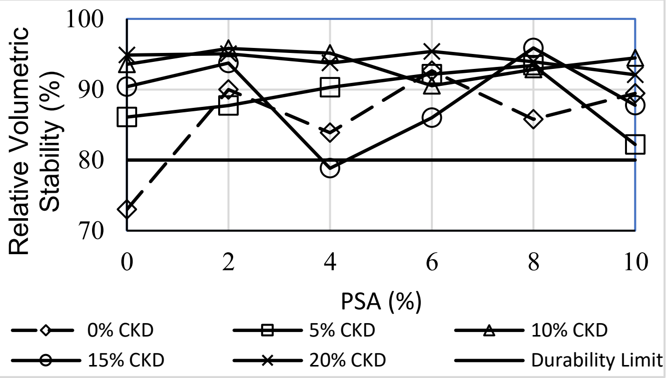

Fig. 9. Variation of relative volumetric stability with percent stabilizers for soil B.

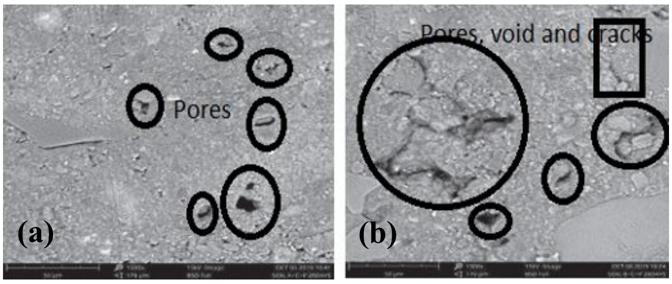

Fig. 10. SEM micrographs at 50µm Magnification after 28 days of curing of unstabilized soil (a) A and (b) B.

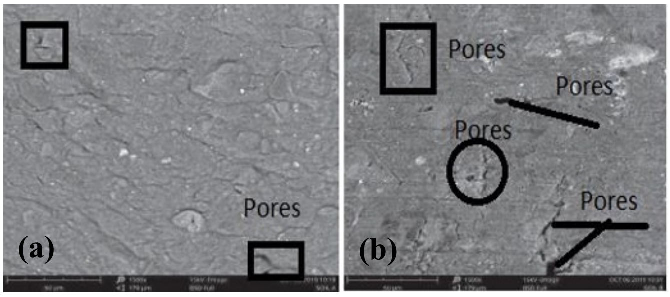

Fig. 11. SEM micrographs at 50µm Magnification after 28 days of curing of stabilized soil (a) A and (b) B.

surrounding the surface during the process of compaction while the scaly surface on the other hand might be a combined reaction of dissolution and precipitation, respectively [45,46]. The SEM of 10% CKD/ 8% PSA of both soils shows a clustering clay system dominating the entire soil matrix leading to the formation of whitish particles of calcium ions and cementitious compounds of CSH and CAH within the pores as a result of pozzolanic reactions between the soil particles and the additives which in turn contributed to strength development [11,45,47].

3.5.2. Energy-Dispersive X-Ray Spectroscopy

The Energy-dispersive x-ray spectroscopy (EDS) gives a description of elemental compositions of scanned imaged materials in an SEM for all elements whose atomic number is greater than boron. The presented figures as shown in Figs. 12 and 13 is the EDS for the untreated and treated soil A optimally stabilized with 10% CKD/8% PSA based on the outcome of the CBR after curing for 28 days. Similarly, as presented in Figs. 14 and 15 is the EDS of the natural and stabilized soil B. The predominant elemental composition of Si, Al and Fe [48] with fewer traces of Mg, Ti, Ca can be observed in the natural soil which shows that the natural soil contains some significant amount of kaolinite and quartz which is a non-clay mineral. Generally, for both untreated soils (soils A and B), the silicon and aluminium contents were higher than the optimally treated soils. Also, the higher content of Ca for both soils might be a result of the excessive availability of PSA that did not contribute to the chemical reaction thereby combining with Si to form CSH which might have resulted in strength gain.

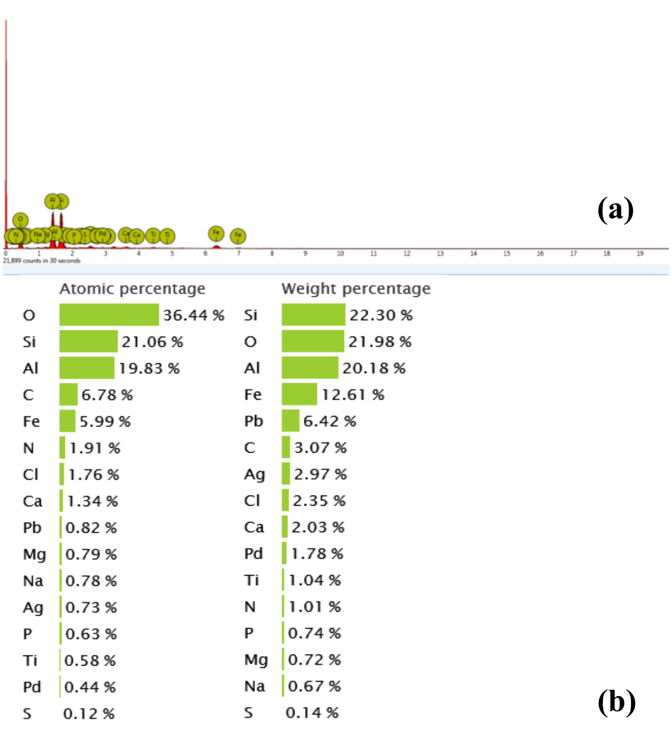

Fig. 12. (a) EDS of the natural soil A after 28 days curing and (b) Atomic and Weight representation (%) of elements for the natural soil A from the EDS spectrum.

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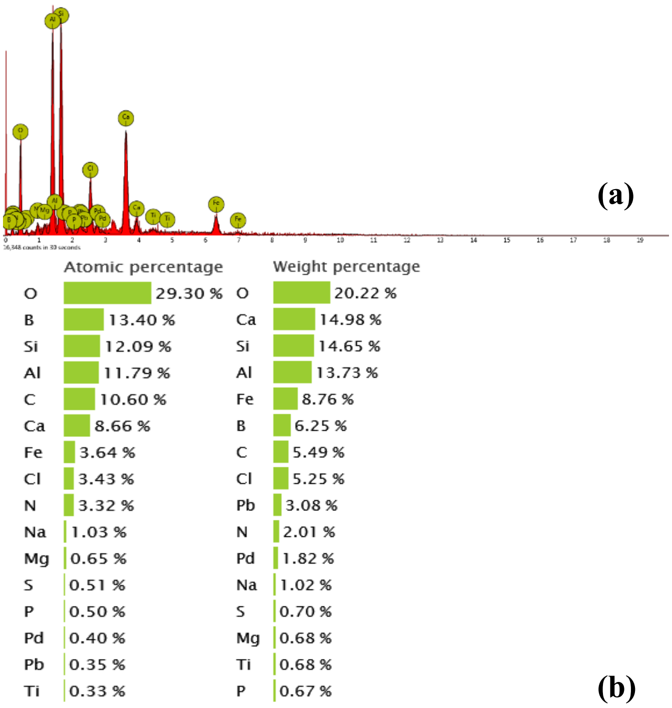

Fig. 13. (a) Elemental composition of optimally stabilized soil A after 28 days curing from the EDS spectrum and (b) Atomic and Weight representation (%) of elements of the optimally stabilized soil A from the EDS spectrum.

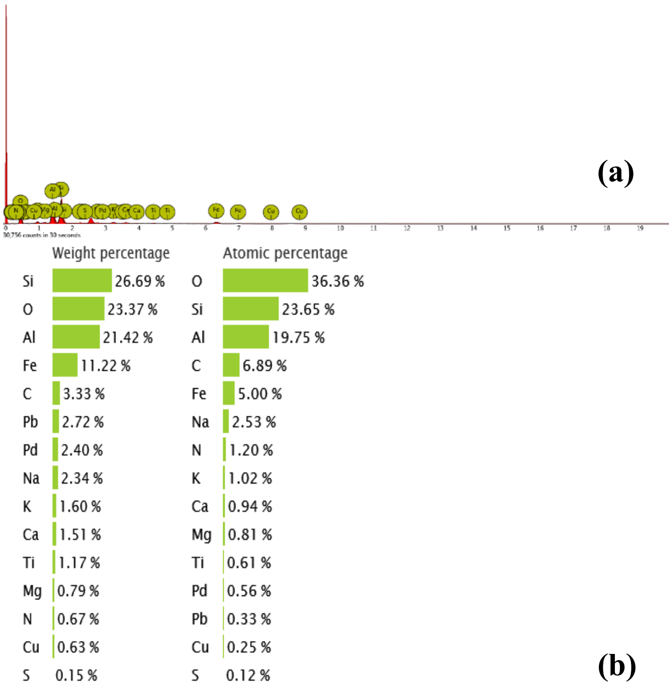

Fig. 14. (a) EDS of the natural soil B after 28 days curing and (b) Atomic and Weight representation (%) of elements of the natural soil B from the EDS spectrum.

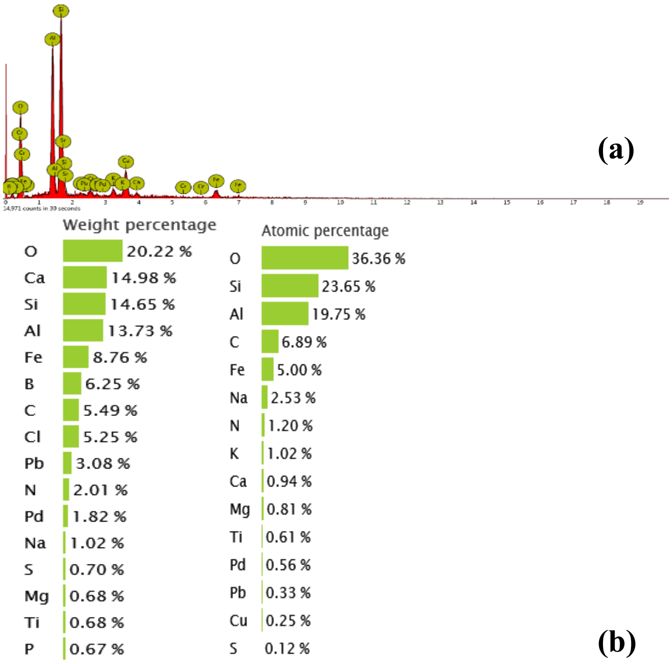

Fig. 15. (a) Elemental composition of the optimally stabilized soil B after 28 days curing from the EDS Spectrum and (b) Atomic and Weight representation (%) of elements of the optimally stabilized soil B from the EDS spectrum.

4. Conclusion

The possibility of using cement kiln dust (CKD) and periwinkle shell ash (PSA) as stabilizers for two lateritic soils (soil A and B) is investigated. The results from the investigation show that both soils were classified according to AASHTO and USCS systems as A-7-6(3) and A-7-6(7) or CL (i.e. low plasticity clay) for soil A and B, respectively. These classifications show that both soils are not suitable as road construction materials and most geotechnical work. The two soils were thus treated with 0, 5, 10, 15, 20% CKD and 0, 2, 4, 6, 8, 10% PSA by dry weight of the soil. The maximum dry density increased with a corresponding decrease in optimum moisture contents for both soil samples. The strength characteristics (i.e. UCS and CBR) increased with higher percentages of CKD and PSA. The 7-day peak UCS values of 117.93 kN/m^2 and 136.55 kN/m^2 obtained at 10% CKD/8% PSA treatment fell below the 1720 kN/m^2 minimum specification of the Federal Ministry of Works and Housing for adequate cement stabilization. On the other hand, the CBR (unsoaked and soaked) increased with increasing PSA content. The 24-hour soaked CBR of 67.68 and 66.10% at 10%CKD/8%PSA for soil A and B respectively, satisfied the 20-30% requirement recommended for subbase material by the Federal Ministry of Works and Housing. Statistical analysis using the two-way analysis of variance (ANOVA) showed an improvement in the geotechnical properties of both soils with CKD having a more pronounced effect. Micro-characterization techniques conducted using a scanning electron microscope (SEM) showed that the treated soils were aggregated and a change in the fabric orientation of the soil particle occurred. The SEM micrographs also revealed the presence of crystalline hydration products of CSH AND CAH which were presumed to be the major factors that contributed to strength improvement. Based on the above results presented concerning strength characteristics, it can be inferred that an optimal blend of 10% CKD/8% PSA is recommended for the stabilization of lateritic soils for pavement construction. The advantage of the application includes but is not limited to reducing the environmental effects of CKD and PSA disposal.

Declaration of Interest Statement

The authors wish to declare that there is no conflict of interest known to them.

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