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Portland limestone cement stabilization of laterite modified with calcium carbide waste slurry

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ABSTRACT : *This research examines the stabilization potential of Portland limestone cement (PLC) on laterite modified with calcium carbide waste slurry (CCWS). Laterite obtained from Apir region, in Makurdi Local Government Area of Benue State, Nigeria was mixed with 2-10% PLC at 2% increments and 4-12% CCWS at 4% increments by dry weight of soil, respectively. Atterberg limits, compaction, California bearing ratio (CBR), and unconfined compressive strength (UCS) tests were performed on untreated and PLC plus CCWS-treated laterite. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) were performed on untreated and PLC plus CCWS-treated laterite. The liquid limit of untreated laterite decreased from 40 % to 32 % when treated with 10% PLC plus 12% CCWS, while the plastic limit of untreated laterite increased from 20% to 28% when treated with 10% PLC plus 12% CCWS. Similarly, the plasticity index of the untreated laterite was reduced from 20% to a minimum value of 4% when treated with 10% PLC plus 12% CCWS. The optimum moisture content and maximum dry density increased from 12.5% to 15.5% and 1.84 Mg/m³ to 1.98 Mg/m³, respectively, when treated with 10% PLC plus 12% CCWS. The 7-day UCS and soaked CBR of Apir laterite increased from 500 kPa and 12.68% to 1460 kPa and 156%, respectively, when treated with 10% PLC plus 12% CCWS. SEM/EDX analysis shows that Apir laterite treated with PLC plus CCWS has a more integrated composition, smaller voids, and a significant presence of Ca, suggesting cementitious reactions, compared to natural Apir laterite. The significant content of Ca, Si, and Al in PLC plus CCWS-treated Apir laterite suggests the availability of cementitious compounds (CSH and CAH). A combination of 6% PLC plus 8% CCWS, having UCS, CBR, and resistance to loss in strength values of 957 kPa, 102%, and 80%, respectively, is recommended for treating Apir laterite for use as a sub-base material in road pavement.*

KEYWORDS: *Portland limestone cement, Calcium carbide waste slurry, Stabilization, Laterite, Road pavement.*

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I. INTRODUCTION

The construction of engineering infrastructure such as roads in developing countries by Government and Engineering specialist is confronted with limited resources and high cost of building roads due to increasing cost of construction materials. Additionally, at the construction sites, contractors are challenged with limited suitable construction materials close to the site. This avails them with the choice of either importing suitable materials from other locations or improving the unsuitable locally materials within the site. Consideration is made on the cost of removing and disposing in-situ soil plus that of importing suitable materials on one hand and the cost of in-situ stabilization of the available material. When the cost of stabilizing in-situ soil is cheaper than that of importing plus removing unsuitable soil, the stabilization of locally available soil is used.

In Nigeria, one of the readily available common materials is laterite (Joel and Edeh, 2014).

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However, laterite may contain clay content, making it an unsuitable material for constructing road pavements, such as sub-base or base, and thus requiring treatment (Otieno *et al*., 2023). One way to stabilize laterite soils for suitability in road pavement is by utilizing cementitious binders like cement and lime. For economic purposes, combinations of cement and waste materials have been used for soil stabilization. Laterite has been successfully stabilized with combinations of ordinary Portland cement (OPC) and other wastes, such as wood ash, calcium carbide waste (CCW), and bamboo leaf ash (BLA) (Joel and Edeh, 2014; Otieno *et al*., 2023; Nnochiri *et al*., 2021).

Research by Joel and Edeh (2014) on Ikpayongo laterite, reported that the geotechnical properties of the natural laterite is only suitable for subgrade and fill material, but unsuitable for sub-base and base course materials. The authors combined CCW and OPC for treatment of Ikpayongo laterite and reported that, the laterite treated with 8 % OPC plus 10 % CCW can be used as base course material in road pavement.

Another research on treatment of laterite with OPC plus BLA, and OPC plus rice husk ash (RHA) (Nnochiri *et al*., 2021) established that the treatment of laterite with 6 % OPC plus 8 % BLA, and 8 % OPC plus 8 % RHA could be used as sub-base material. Additionally, Wahab *et al.* (2021) used OPC to treat laterite obtained at Johor campus, Universiti Teknologi Malaysia, Malaysia. Based on Malaysia Public Works Department standard, treatment of the laterite with 6 % OPC content produced adequate strength (7 day UCS) and durability that was sufficient for use in low-volume road work.

Researchers (Iyaruk *et al*., 2022) used hydraulic cement (HC) for the treatment of laterite blended with biomass ash (BA). The laterite was obtained at HatYai Sub-district, Songkhla, Province, Thailand. The authors found that the addition of 5 % HC to laterite blended with 80 % BA content, resulted in remarkable strength (CBR and UCS) which is suitable for sub-base material in road work according to the Department of Highway in Thailand (DOHT). Also, the treatment had no environmental impact and met the environmental requirement. Thus, the use of 5 % HC was recommended for the stabilization of laterite blended with 80 % BA, for use as a sub-base material in road work.

Also, Joel and Edeh (2015) conducted a comparative assessment between the modification of cement treated Ikpayongo laterite and that of lime Ikpayongo treated laterite. From their study, it was found that, the use of 6 % cement or 4 % lime additions could achieve modification of the laterite. The use of 4 % lime was recommended for better modification, followed by cement stabilization. This shows that, for effective stabilization, lime or lime-based material should be used for soil modification, followed by cement treatment.

Recently, OPC has been scarce in Nigeria's open market. This is because the cement industry in the country has shifted to producing Portland limestone cement (PLC), which is classified as CEM II (NIS 444-1, 2003) instead of OPC production, which is classified as CEM I (NIS 444-1, 2003). In Nigeria, OPC can only be obtained through a bulk special order from cement factories (Mode *et al.*, 2021). Currently, PLC is the widely available cement in Nigeria, likely due to its cheaper production costs compared to OPC. PLC can contain a maximum of 35 % limestone and a minimum of 65 % clinker, whereas OPC can contain a maximum of 5% limestone and a minimum of 95% clinker (Mode *et al*., 2021; Tosun *et al*., 2009). The cost of raw limestone is \$4/ton, while that of raw clinker is \$25/ton (Zanoli *et al*., 2022). This notable difference in raw materials makes the use of higher limestone content in cement (as in PLC) cheaper than the use of lower limestone content, as in OPC. Additionally, processing limestone releases significantly less carbon dioxide than processing clinker. Therefore, Nigeria's cement industry has preferred the production of PLC over OPC due to better cost-effectiveness and environmental friendliness of PLC (Mode *et al*., 2021; Chopperla *et al*., 2022). However, research on treatment of laterite with PLC is lacking. This, prompted the need to assess the use of PLC on stabilization of laterite.

Due to the increasing cost of traditional stabilizers such as lime and cement, acquiring construction materials for providing economic, safe, and durable fundamental infrastructures for the growing population, especially in developing nations like Nigeria, has become a challenge. To address this challenge, researchers have been using lime-based waste alone or in combination with traditional stabilizers in the construction of affordable, durable, safe, and sustainable infrastructures (Zadawa and Omran, (2019).

A study by Ishola (2025 used cashew leaf ash (CLA) to treat laterite and found that the use of 6 % CLA in treatment of laterite could achieve its modification.

The mixture of cow bone powder (CBP) and lime was used by Akinwunmi and Agbude (2023) for the treatment of laterite along Ado-Ikere road, Ekiti State, Nigeria. The result showed that treatment of the laterite with 8% Stabilizer (50% CBP + 50% lime) content could result in modification of the laterite.

Researchers Saldanha *et al.*, (2018) conducted physical, chemical and mineralogical characterization of CCW (referred to as carbide lime), obtained as residue from acetylene gas production plant at Grande do Sul, in southern Brazil. It was found that the main mineralogical contents were 81 % of Portlandite $[Ca(OH)_2]$ and 9.4 % of calcite ($CaCO_3$). Using X-Ray Fluorescence (XRF) Spectrometry results, the carbide lime contained dominantly 74 % CaO and 3.1 % SiO_2. Based on properties and composition of the CCW, it was recommended for suitability in soil stabilization. Studies by Ihejirika (2018) on chemical characteristics of calcium carbide waste reported that the major chemical composition of the waste is calcium hydroxide $[Ca(OH)_2]$, which can readily react in the presence of carbon dioxide to form calcium carbonate ($CaCO_3$). This shows that CCW when dried to the air would react through carbonation and reduce its chemical reactivity.

Studies by Ogunro *et al.* (2025) showed that weak mortar can be produced with combination of CCW with some calcined clay (CC). A combination of CCW to CC obtained at Ifonyintedoin in Ogun State, Nigeria at a ratio (40:60) produced peak 28-day compressive strength of 10 MPa. This is 42 % compared to the standard mortar compressive strength of 24.1 MPa. This shows the stabilizing potential of CCW. Furthermore, Quadri *et al*. (2020) performed studies on a mixture of CCW and calcined clay (CC) for the treatment of subgrade material obtained along Ota-Idiroko road, Ogun State. It was found that the treatment of the subgrade soil with 8%CCW plus 6%CC content could be used as a base course material in road pavement.

From previous studies, it is deduced that

1. The geotechnical properties of natural laterite such as Ikpayongo laterite are only suitable for subgrade and fill material, but unsuitable for sub-base and base course materials (Joel and Edeh, 2014). To make the material suitable for sub-base and base course materials, stabilization of the laterite would be required.
2. The improvement of laterite with traditional stabilizers (cement and lime) for road pavement has been successful. However, due to the increasing cost of traditional stabilizers, the use of waste materials alone or in partial substitution for traditional stabilizers to achieve cheaper, durable, and sustainable engineering infrastructure is being explored
3. CCW has properties and composition that are suitable for soil stabilization. CCW alone has been used to treat weak soils leading to improvement of plasticity properties, hence soil modification. This shows that CCW has the potentials for use as soil modifier in soil improvement. Also, the major composition of CCW is calcium hydroxide which reacts with carbon dioxide to form calcium carbonate. This shows that using CCW slurry with minimal exposure to air, would maintain its chemical reactivity than when exposed to air during drying.
4. Recently OPC has been scarce in Nigeria's open market, instead PLC is the new and available cement in the country. There are previous researches on stabilization of soils using mixture of OPC and CCW. However, research on the use of combined PLC and CCWS in stabilization of laterite is scarce. Thus prompted the need for the current study on assessing the stabilization potential of PLC and CCW slurry mixture in treatment of Apir laterite. In this study, CCW slurry (CCWS) was used instead of CCW, to maintain high chemical reactivity of CCW, which when exposed to air reduces due to carbonation.
5. Considering the soil improvement potentials in either in CCW and PLC, the combination of PLC and CCW offers a potential opportunity to enhance the stabilization of laterite soils, by improving their strength and durability properties.

The aim of this study is to determine whether the mixture of PLC and CCWS could be used to stabilize laterite for use in road pavement. This was achieved through determination of the strength (UCS, CBR) and durability of PLC plus CCWS treated Apir laterite. Examination of the microstructure of PLC plus CCWS treated Apir laterite. Also, assessment of the combined strength and durability properties of PLC plus CCWS treated Apir laterite. Then, determine the suitability of the treated laterite in road pavement work.

The findings from this study will provide the baseline information about stabilization of Apir laterite using PLC and CCWS mixture. This will be utilized by Civil Engineers for the design of flexible pavement involving combined PLC and CCWS stabilization of Apir and similar laterite. Also, this will promote the use of industrial waste materials like CCWS as sustainable substitute to traditional binders.

II. MATERIALS AND METHODS

2.1 Materials

Laterite Soil: The laterite used in the current study was collected from Apir region, Makurdi Local Government Area of Benue State in Nigeria. Apir is situated along Makurdi – Aliade road at 14 km from Makurdi town, the headquarter of Benue state, Nigeria. The sample was collected at a borrow pit located on latitude $7^0 3$ 7’60’’ and longitude $8^0 33$’0’’. The pit is situated at 90° East and 4 km from the centre line of Makurdi – Aliade road. The disturbed sample was collected at a depth of 1.0 m after removing top soil. The sample was collected in an airtight polyethylene bag and taken to the Civil Engineering laboratory, Joseph Sarwuan Tarka University Makurdi (JOSTUM) for laboratory tests.

CCWS was obtained from a welding shop at the Wadata mechanic village in Makurdi, and was used as slurry for the soil improvement. The choice of CCWS was to maintain high chemical reactivity, which when exposed to air reduces due to carbonation of CCWS. PLC cement branded as Dangote 3X was used in this study. It was purchased from a supplier in Makurdi, Benue State.

2.2 Methods

For laboratory tests, Apir laterite was mixed with different proportions of PLC and CCWS, ranging from proportions 2 % to 10 % for PLC, and proportions of 4 % to 12 % for CCWS by dry weight of soil respectively. Laboratory tests were performed on untreated and PLC plus CCWS treated laterite in accordance with BS 1924 (2018), BS 1377 (BSI, 2016) and Nigerian General Specification for Road and Bridges (1997). Such tests include particle size distribution (PSD) analysis, liquid limit (LL), plastic limit (PL), shrinkage limit (SL), and compaction tests. Other tests include unconfined compressive strength (UCS), durability, and California Bearing Ratio (CBR) tests. The PSD of the laterite was ascertained using wet sieving method. Compaction was performed using the West African standard compactive effort in accordance with the Nigerian General Specification for Road and Bridges (1997). Similarly, CBR test was performed using the Nigerian General Specification for Road and Bridges (1997) whereby the specimen in CBR mould is cured for six days under dry laboratory condition, after which it is immersed in water for 24 hours before testing with the CBR machine.

The resistance to loss in strength (RLS) was conducted in accordance with BS 1924 (2018) which specify that the UCS of specimen which is firstly cured for 7 days in dry condition, then immersed in water for 7 days be compared with the UCS of corresponding specimen cured for 14 days.

Chemical composition was performed on CCWS, PLC and laterite using the compact energy dispersive X-ray spectrometer method (mini Pal) at the Centre for Energy Research and Training, ABU Zaria, Nigeria. Mineralogical test such as X-ray diffraction (XRD) was performed on untreated and PLC plus CCWS treated laterite samples to determine the minerals’ content.

To analyze the microstructural arrangement and assess the presence of bonding structure between the soil particles, scanning electron microscopy (SEM) test was carried out on the PLC plus CCWS treated Apir laterite and untreated Apir laterite (control). The SEM was performed using JOEL-JSM 7600F model. Energy dispersion X-ray spectrometer (EDX) was conducted on the untreated and PLC plus CCWS treated laterite to ascertain the changes in chemical composition resulting from the treatment.

III. RESULTS AND DISCUSSION

3.1 Index Properties

The PSD results of Apir laterite are presented in Fig. 1, while the summary of index properties is shown in Table 1. According to the AASHTO and USCS classifications, Apir laterite is classified as A-2-6 and GC, respectively. Based on the AASHTO classification, A-2-6 soil has a good subgrade rating, indicating that Apir laterite is suitable for use as subgrade material in road pavement.

The geotechnical properties of natural Apir laterite show a plasticity index (PI) of 20 % and an unconfined compressive strength (UCS) value of 500 kPa. The National House Building Council (2024) recommends that natural soils for engineered fill materials should have a PI value lower than 40 % and a minimum UCS value of 40 kPa. Based on these requirements, natural Apir laterite can be used as a fill material. The findings that Apir laterite has properties suitable for use as subgrade and fill material are consistent with other studies on laterite obtained from Ikpayongo, Nigeria (Joel and Edeh, 2014), and Kiambu County, Kenya (Otieno *et al.*, 2023).

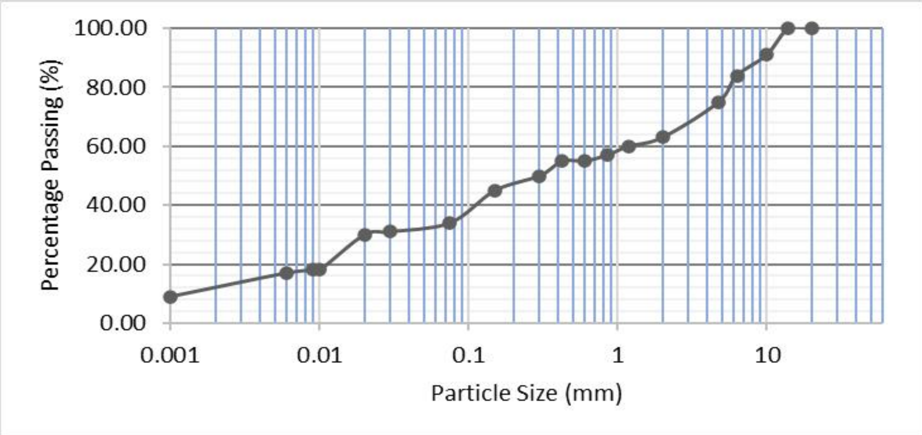


Fig. 1: Particle size distribution of Apir laterite

Table 1: Index properties of Apir laterite

Property	Quantity
Percentage Passing BS Sieve No 200 (%)	34
Liquid Limit, (%)	40
Plastic Limit (%)	20
Plasticity Index (%)	20
AASHTO Classification	A-2-6
USCS Classification	GC
Maximum Dry Density Mg/m^3	1.84
Optimum Moisture Content (%)	12.5
Unconfined Compressive Strength kPa	500.57
California Bearing Ratio, % (unsoaked)	15.47
California Bearing Ratio, % (after 24hrs soaking)	12.68
Specific Gravity (Gs)	2.67
Colour	Reddish brown
Natural Moisture Content (%)	11.2

However, the Nigerian General Specification for Road and Bridges (1997), specifies that material should have at least a CBR value of 30 % and 160 % for use as sub-base natural and cement treated base material respectively. Also, sub-base and base material should have a minimum (RLS) value of 80 %. Based on the combined criteria of strength and durability, natural Apir latrite is inappropriate for application as a sub-base and base material. In order to make the material satisfy strength and durability criteria for use in at least sub-base material, stabilization will be an option.

3.2 Chemical Composition

The chemical compositions of Apir laterite, CCWS slurry and PLC grade 42.5 R are presented in Table 2. The results show that some cementitious oxides are found in CCWS similar to that in PLC stabilizer. The major content is CaO with 60.7 % in CCWS and 62.6 % in PLC. Also, SiO_2 which contributes to cementation is 3.84 % in CCWS and 19.7 % in PLC. Additionally, Al_2O_3 in CCWS is 1.66 % while that in PLC is 3.81 %.

The oxide composition of CCWS in the current study is similar to that in the studies by other researchers (Joel and Edeh, 2014; Fulignati, 2020). Their studies show oxide composition of CaO from 61.41-65.85 %, SiO_2 from 2.69-5.20 % and Al_2O_3 from 1.60-2.13 %. This show that, CCWS used in this study composed of some cementation oxide as also contained in PLC. Therefore, it could be added to other stabilizers for the improvement of low strength soil.

From the oxide composition of Apir laterite (Table 2), the silica-sesquioxide ratio (SSR) of the soil is determined to be 0.76. This ratio is less than 1.33 which is the maximum SSR for classification as laterite soil. This shows that the Apir soil in the current study is classified as laterite soil (Chandrasasi *et al*., 2021).

3.3 Mineralogical Composition

The results showing the mineralogical composition of Apir laterite is presented in Fig. 2. The major composition of Apir laterite is quartz, albite, muscovite and orthoclase. The presence of albite is an indication of swelling and shrinking behaviour of the soil. Albite is known to be a precursor to montmorillonite. Previous studies show that, the hydrolysis of albite produces Na-Montmorillonite (Fulignati, 2020). Hence, albite has expandable tendency with seasonal changes as in the case of montmorillonite. Additionally, muscovite has similar properties with illite clay (Fulignati, 2020), hence muscovite has expandable tendency similar to illite.

The presence of albite and muscovite in the laterite could be responsible for the weak strength due to its expandible and shrinkage tendency.

Table 2: Chemical composition of Apir laterite, Portland limestone cement and calcium carbide waste

Element Oxide	Apir Laterite	CCWS	PLC
CaO	0. 0.27	60.7	62.6
MgO	0.381	4.08	1.72
SiO_2	35.21	3.839	19.7
Al_2O_3	23.10	1.66	3.81
V_2O_5	0.097	-	-
Cr_2O_3	0.024	-	-
MnO	1.78	0.07	-
Fe_2O_3	23.25	0.06	1.57
CO_3O_4	0.009	-	-
CuO	0.37	-	-
Nb_2O_3	0.037	-	-
K_2O	6.079	1.01	0.1
BaO	0.133	-	-
Ta_2O_5	0.023	-	-
TiO_2	0.401	1.23	0.329
ZnO	0.505	-	-
ZrO_2	0.025	-	-
SrO	0.031	-	-
SO_3	-	-	2.32
P_2O_5	-	0.05	-
Na_2O	-	0.87	-
LOI	-	26.38	1.30
$SiO_2/(Al_2O_3 + Fe_2O_3)$	0.760		

Note: PLC= Portland limestone cement, CCWS=Calcium carbide waste slurry

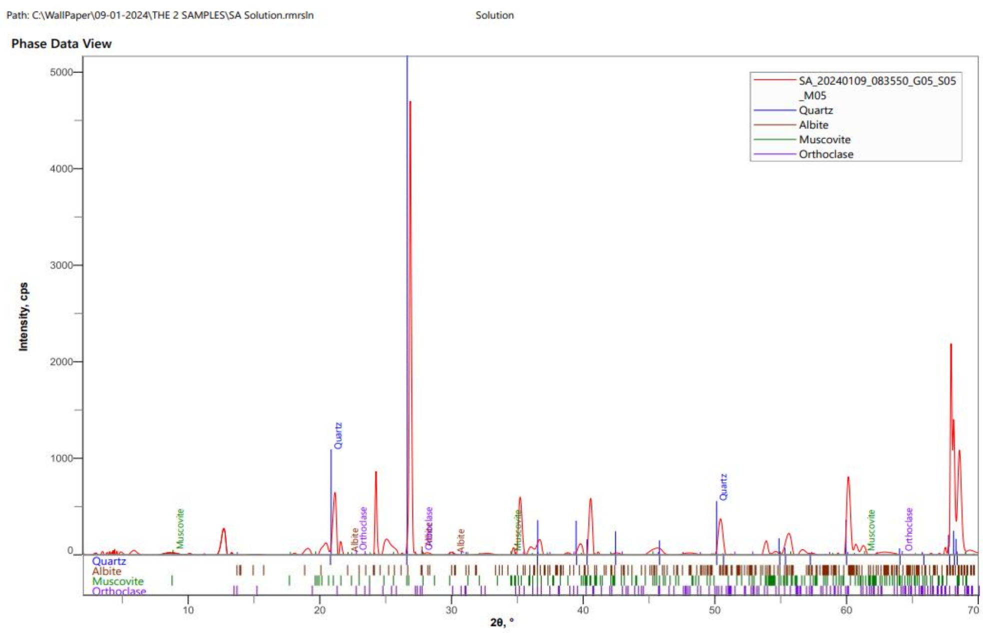
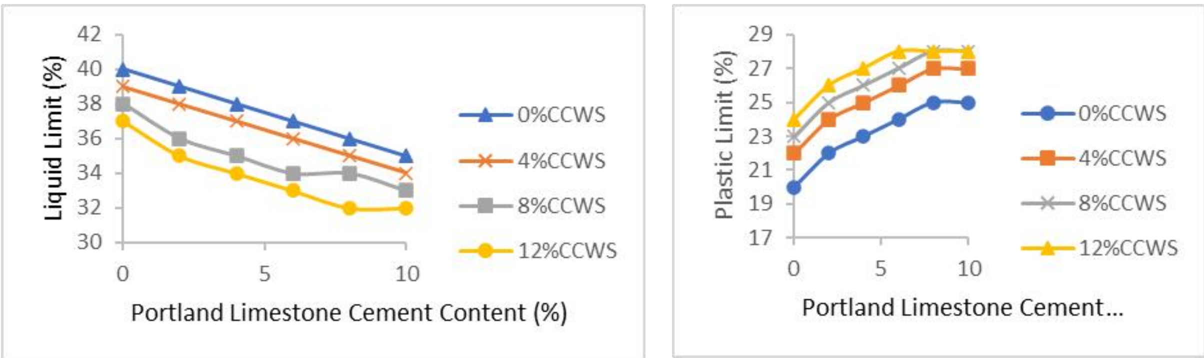


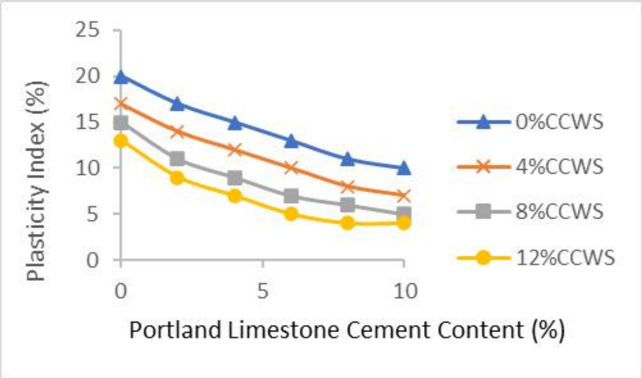
Fig. 2: Mineralogical composition of Apir laterite

3.4 Plasticity Properties of Apir Laterite Treated with PLC and CCWS

The variation of plasticity properties of Apir laterite treated with PLC and CCWS is presented in Fig. 3. For all additions of PLC and CCWS, the LL decreased, while the plastic limit PL increased, resulting in a decreased PI. For example, the untreated laterite had LL, PL, and PI values of 40 %, 20 %, and 20 %, respectively, which changed to 32 %, 28 %, and 4 % when treated with 10% PLC plus 12% CCWS.



(a) (b)



(c)

Fig. 3: Variation of Atterberg's limit with PLC plus CCWS content: (a) Liquid limit versus PLC plus CCWS content (b) Plastic limit versus PLC plus CCWS content (c) Plasticity index versus PLC plus CCWS content. Note: PLC= Portland limestone cement, CCWS= Calcium carbide waste slurry

The variations in Atterberg's limits with PLC additions could be caused by hydration reactions, while those with CCWS additions could be due to flocculation and agglomeration of clay particles. Additionally, it could be due to cation exchange reactions between calcium released by lime and the cations provided by the clay, resulting in reduced attraction of clay to water (Rogers and Glendinning, 1996); Vitale *et al*., 2020). Furthermore, Figure 3 shows that the PI values of Apir laterite treated with PLC plus CCWS decreased with all treatments, whether using PLC or CCWS alone or in combination. Specifically, the PI value of untreated laterite reduced from 20 % to 10 % when treated with 10 % PLC, and from 20 % to 13 % when treated with 12 % CCWS. For the combined treatment, the PI value reduced from 20 % to 4 % when treated with 10 % PLC plus 12 % CCWS.

The reduction in PI with PLC and CCWS additions could be due to the hydration process of cement. Additionally, the lime-based waste additions of CCWS would cause aggregation of clay particles, leading to the formation of friable particles and a subsequent PI reduction (Rogers and Glendinning, 1996). Furthermore, the addition of lime-based waste CCWS could release calcium cations, which would displace sodium or hydrogen ions from the clay through cation exchange reactions, leading to PI reduction (Rogers and Glendinning, 1996). Generally, PI is a measure of the range of water content over which a soil exhibits plastic behavior.

The reduction in PI in this study indicates that the laterite will be less sensitive to changes in water content, thereby improving workability and increasing shearing strength (Amadi *et al*., 2020). This suggests that the addition of PLC plus CCWS to Apir laterite would contribute to increased workability and shearing strength. The decrease in PI of laterite with the addition of stabilizers is consistent with studies by others (Joel and Edeh, 2014; Otieno *et al*., 2023; Nnochiri *et al*., 2021; Amadi *et al*., 2020).

3.5 Compaction Characteristics

The variation of the optimum moisture content (OMC) of Apir laterite with PLC and CCWS additions is illustrated in Fig. 4. The OMC of the laterite increased with PLC additions. Specifically, the OMC value increased from 12.5 % for natural laterite to 17 % when treated with 10 % PLC. Similarly, treating the natural laterite with 12 % CCWS increased the OMC value from 12.5 % to 15.5 %. Notably, the combined treatment of the laterite with 10 % PLC and 12 % CCWS resulted in an overall increase in OMC from 12.5 % to 20 %.

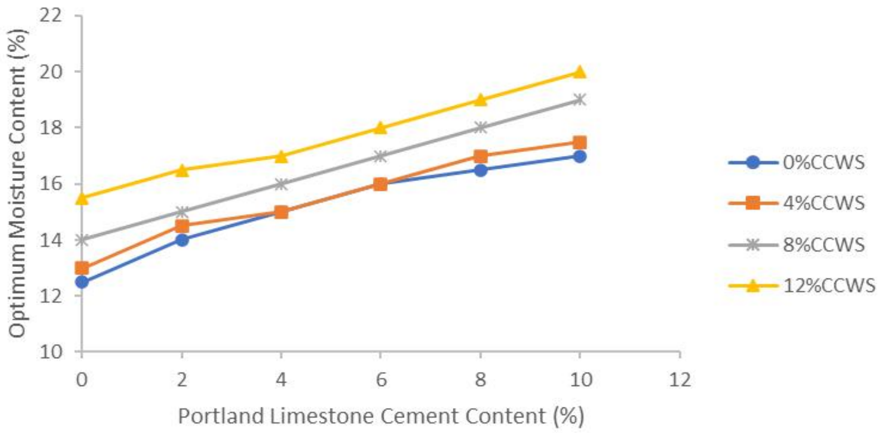


Fig. 4: Variation of OMC with PLC plus CCWS addition to Apir laterite
Note: PLC= Portland limestone cement, CCWS= Calcium carbide waste slurry
OMC= Optimum moisture content.

The effect of adding PLC and CCWS on the maximum dry density (MDD) of Apir laterite is presented in Fig. 5. The results show that MDD increased with the additions of PLC and CCWS. Specifically, the MDD increased from 1.84 Mg/m^3 for untreated laterite to 1.98 Mg/m^3 when treated with 10% PLC plus 12% CCWS content.

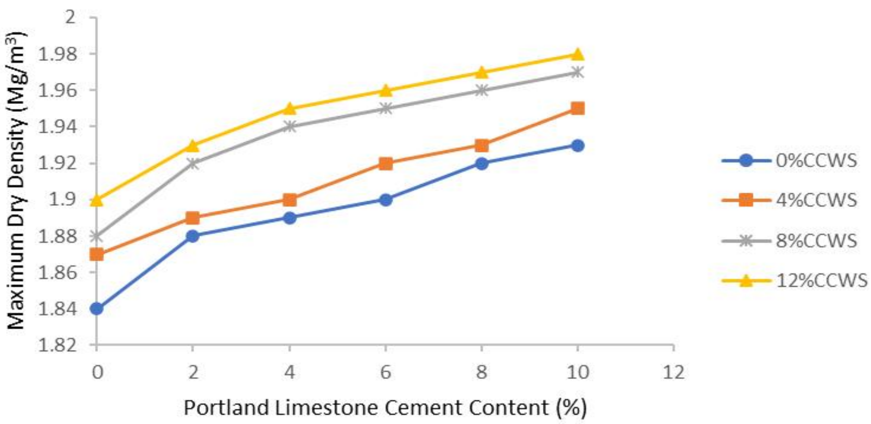


Fig. 5: Variation of MDD with PLC plus CCWS addition to Apir laterite
Note: CCWS= Calcium carbide waste slurry

The increase in OMC with increasing PLC plus CCWS additions could result from additional water demand for full hydration of cement and the need by pozzolanic processes from the mixture of CCW and laterite (Akinwunmi and Agbude, 2023). Similarly, the increase in MDD with additions of PLC plus CCWS could result from a reduction in the surface area of the clay content in the laterite. The replacement of clay with PLC and CCWS, which have a relatively smaller surface area, would lead to an overall decrease in surface area and volume. A fixed volume would accommodate more mass of PLC plus CCWS-treated laterite compared to untreated laterite, leading to increased dry density. Additionally, the wet fine particles of PLC have the tendency to fill the voids within the compacted soil, making the PLC-treated laterite denser than untreated laterite.

Generally, compaction conducted at the OMC enables the right amount of water to be added. When compaction is performed at OMC with predetermined energy, the soil particles move closer to each other, achieving the densest compaction. This leads to increased shear strength and stability, and reduced risk of structural damage or failure (Vijayakumar and Govidhasamy, 2024). The current study achieved OMCs and corresponding MDDs (Figures 4 and 5) that could serve as benchmark when compacting PLC plus CCWS-treated Apir or similar laterite.

The trend of increased MDD and OMC in laterite with additions of cement plus CCWS is similar to those observed in (Joel and Edeh 2014;

Wahab *et al.*, 2021; Vijayakumar and Govidhasamy, 2024). Although their cement was OPC, while the cement in the current study is PLC, both exhibited a similar trend of increased MDD and OMC with cement plus CCWS additions

3.6 Compressive Strength of Apir Laterite

The variation of 7, 14, and 28-day UCS with PLC plus CCWS-treated laterite is presented in Table 3. The results show that there is an increase in UCS of Apir laterite due to the addition of PLC, CCWS, or their mixtures. The 7-day UCS value of untreated laterite, which is 500 kPa, increased to 1459.8 kPa when treated with a mixture of 10 % PLC and 12 % CCWS. Similarly, the 14 and 28-day UCS values of untreated laterite increased from 500 kPa to maximum values of 1685 kPa and 1871.86 kPa, respectively. The strength increases at 7, 14, and 28 days of curing indicate that longer curing would lead to corresponding strength development (Horpibulsuk, 2012).

The maximum 7-day UCS value of 1460 kPa in this study is lower than the 1720 kPa specified for cement-stabilized base material (Millard, 1993). However, Millard (1993) specifies a minimum UCS value of 750 kPa for sub-base materials. Based on the 7-day UCS and economic mix (at most 8% cement content), all treatments resulting in 7-day UCS values greater than 750 kPa are suitable for use as sub-base material. Mixes with cement content above 8 % PLC are considered uneconomical (Millard, 1993).

The maximum 7-day UCS value of 1460 kPa for 10 % PLC plus 12 % CCWS-treated Apir laterite in this research is less than the 7-day UCS value of 3157 kPa obtained in Ikpayongo laterite when treated with 10% OPC plus 10% CCWS (Joel and Edeh, 2014). This difference could be due to variations in the type of cement and laterite used. While PLC and Apir laterite were used in this study, OPC and Ikpayongo laterite were used in the other study (Joel and Edeh, 2014). OPC contains at least 95% clinker and at most 5% limestone, classified as CEM I, whereas PLC contains at least 65 % clinker and at most 35 % limestone, classified as CEM II (NIS 444-1, 2003; Mode *et al*., 2021). The higher 7-day UCS produced in laterite treated with OPC may be attributed to the higher early strength of CEM I compared to CEM II (Rumman *et al*., 2016).

3.7 Resistance to Loss in Strength

The results of RLS of untreated and PLC plus CCWS-treated Apir laterite are also presented in Table 3. The results show that there is an increase in the RLS value of Apir laterite with the addition of PLC, CCWS, or their mixture. The RLS value of untreated laterite, which is 0 %, increased to 90.28 % when treated with 10 % PLC plus 12 % CCWS. Within the economic cement content limit of at most 8 % cement, the treatment of Apir laterite with 6 % PLC plus 8 % CCWS produced the minimum required RLS value of 80 % (Nigerian General Specification for Roads and Bridges, 1997; TRL, 2023).

This trend of cement plus CCWS-treated laterite meeting the requirements for loss in strength and economic cement limit is similar to another study (Joel and Edeh, 2014). Their study established that treating Ikpayongo laterite with 6 % OPC plus 8 % CCWS yielded the minimum requirements for loss in strength and economic cement content. This indicates that Apir laterite treated with a minimum mixture of 6 % PLC plus 8 % CCWS satisfies the requirements for economic cement content and RLS durability, thus can resist adverse weather conditions

Table 3: Variation of 7, 14 and 28 days unconfined compressive strength with PLC plus CCWS treated laterite

PLC Content (%)		0	2	4	6	8	10
0% CCWS	7dUCS	501	568	675	796	865	1006
	14dUCS	501	677	723	845	984	1177
	28dUCS	501	780	827	965	1074	1246
	R (%)	0	36	46	60	68	75
	CBR (%)	13	53	60	81	99	122
4%CCWS	7dUCS	559	634	718	836	904	1112
	14dUCS	639	785	866	922	1182	1330
	28dUCS	749	857	927	1123	1293	1432

	R (%)	34	45	51	67	76	80
	CBR (%)	27	57	66	87	105	138
8%CCWS	7dUCS	673	720	815	957	1186	1332
	14dUCS	722	841	922	1106	1259	1587
	28dUCS	825	1037	1167	1346	1515	1775
	R (%)	56	63	70	80	85	89
	CBR (%)	37	59	84	102	116	151
12%CCWS	7dUCS	732	846	929	1065	1201	1460
	14dUCS	753	905	1071	1216	1399	1685
	28dUCS	903	1130	1295	1434	1629	1872
	R (%)	65	69	75	82	88	90
	CBR (%)	45	71	92	106	149	156

Note:7d UCS= 7 day unconfined compressive strength (kpa), 14 dUCS= 14 day unconfined compressive strength (kpa), 28 dUCS = 28 day unconfined compressive strength (kpa). R = Resistance to loss in strength, CBR = California bearing ratio. CCWS = calcium carbide waste slurry

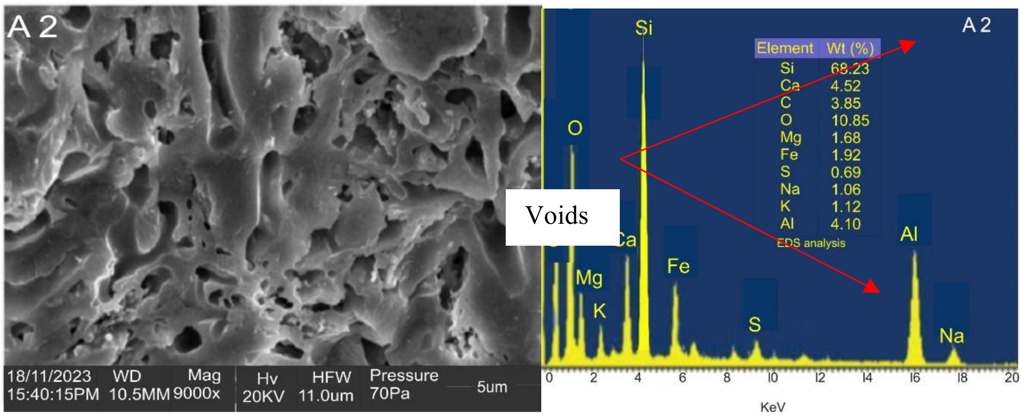
3.8 Californian Bearing Ratio

The results of CBR values for untreated and PLC plus CCWS-treated Apir laterite are contained in Table 3. The results show that there is an increase in the CBR value of Apir laterite with the addition of PLC, CCWS, or their mixture. The CBR value of Apir laterite increased from 12.68 % to 156 % when treated with 10 % PLC plus 12 % CCWS.

The maximum CBR value of 156 % in this study is less than the minimum required value of 160 % for base course materials (Nigerian General Specification for Roads and Bridges, 1997). It is found that Apir laterite treated with 6 % PLC and 8 % CCWS yielded a CBR value of 102 %. This combination corresponds to the one that produced a minimum RLS value of 80 %. Since the CBR value of 102 % exceeds the minimum required value of 30 % for sub-base materials (Nigerian General Specification for Roads and Bridges, 1997), Apir laterite treated with 6 % PLC plus 8% CCWS is recommended for use as a sub-base material

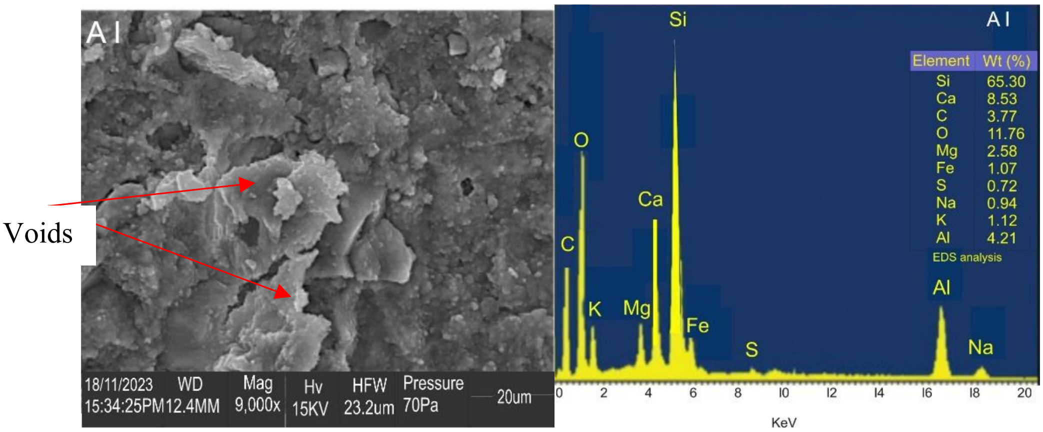
3.9 Scanning Electron Microscopy Results

The SEM micrograph and EDX of untreated and treated Apir laterite with 6 % PLC plus 8 % CCWS is shown in Figs. 4 and 5 respectively. The SEM micrograph of untreated laterite (Fig. 4a) shows larger voids spaces and discontinuous structure compared with the PLC plus CCWS treated laterite (Fig. 5a). The more visible voids in untreated laterite suggests the lack of hydration reaction. The SEM image of treated laterite (Fig. 5a) shows a more clustered matrix, suggesting cementation process.



(a) (b)

Fig. 4: Untreated Apir Laterite: (a) Scanning Electron Microscopy Micrograph (b) Energy Dispersive X-ray Spectroscopy (EDX)



(a) (b)

Fig. 5: 6 % PLC + 8 % CCWS treated Apir Laterite (a) Scanning Electron Microscopy Micrograph (b) Energy Dispersive x-ray spectroscopy (EDX). Note: CCWS= Calcium carbide waste slurry, PLC = Portland limestone cement.

The EDX analysis performed on the untreated laterite (Figure 4b) presents the content of silicon (68.23 %), oxygen (10.85 %), calcium (4.52 %), aluminium (4.10 %), carbon (3.85 %), iron (1.92 %), magnesium (1.68 %) etc. The composition of oxygen, aluminium and iron suggest the characteristics of laterite. For the EDX analysis results of 6 % PLC plus 8 % CCWS treated laterite (Figure 5b), there is also composition of silicon (65.30 %), oxygen (11.76 %), calcium (8.53 %), aluminium (4.21 %), carbon (3.77 %), magnesium (2.58 %), potassium (1.12 %), iron (1.07%) etc. Again, the composition of oxygen, aluminium and iron suggest the characteristics of laterite. Calcium content was observed to have increased significantly from 4.52 % (for untreated laterite) to 8.53 % (for 6% PLC plus 8% CCWS-treated laterite).

The significant content of Ca, Si and Al in the treated laterite indicates the availability of cementitious compound such as CSH and CAH (Bye, 2011). The CSH and CAH contents is responsible for binding of soil and subsequently increase in strength (Horpibulsuk, 2012). This could be the reason for the increase in strength of UCS and CBR in Apir laterite when treated with PLC plus CCWS as typified in 6 % PLC and 8 % CCWS treated laterite.

3.10 Cost Analysis for the Use Portland Limestone Cement and Calcium Carbide Waste in Treatment of Apir Laterite

The cost analysis of using PLC and CCWS for stabilizing Apir laterite is presented in Table 4. The cost of purchasing and transporting 50 kg of PLC is N11,500, which translates to N230 per kilogram. The cost of acquiring 50 kg of CCWS is N2,000, covering transportation from the welder's shop to the laboratory, resulting in a cost of N40 per kilogram. Table 4 presents the costs of stabilizing 1,000 kg of Apir laterite with varying percentages of PLC and CCWS.

Table 4: Cost Analysis of using different contents of Portland limestone cement and calcium carbide waste required for treatment of 1 Metric Ton (1000 Kg) of Apir laterite.

Additive Content (%)	0	2	4	6	8	10	12
Cost of PLC (₦)	0	4,600	9,200	13,800	18,400	23,000	27,600
Cost of CCW (₦)	0	800	1,600	2,400	3,200	4,000	4,800

The cost analysis shows that using CCWS for treatment is approximately six times more cost-effective than using PLC. However, the cost increases with PLC and CCWS content, as evident from the treatment costs with 10 % PLC (N23,000) and 12 % CCWS (N4,000). For the optimal combination of 6 % PLC and 8 % CCWS, the cost of acquiring 8 % CCWS for treating 1,000 kg of laterite is N3,200 (Table 4). Notably, the recommended economic cement content is 8%, which is the maximum required for soil treatment. In this study, the cost of stabilizing Apir laterite with 6% PLC plus 8% CCWS is N17,000 (N13,800 + N3,200), which is cheaper than using 8% PLC (N18,400) for laterite treatment (Table 4). Moreover, treatment with 6% PLC plus 8% CCWS makes the laterite suitable for sub-base material, whereas treatment with 8% PLC does not (Table 4). This implies that using 6% PLC plus 8% CCWS for stabilizing laterite for sub-base material is both economical and suitable.

IV CONCLUSION AND RECOMMENDATIONS

This research addressed the potential of using PLC for stabilization of laterite modify with CCWS. The conclusions drawn are:

a) Apir laterite is an A – 2 – 6 and GC soil, based on AASHTO and USCS soil classification systems respectively.
b) The plasticity index of Apir laterite decreased from 20 % to 7 %, when mixed with 10 % PLC plus 12 % CCWS.
c) The maximum 7-day UCS of 1460 kPa was achieved in Apir laterite when treated with a combination of 10 % PLC and 12 % CCWS. This value is less than 1720 kPa which is the least value specified for base course material (Millard,1993).
d) Apir laterite treated with the combination of 6 % PLC and 8 % CCWS yielded the least resistance to loss in strength value of 80 %.
e) The treatment of Apir laterite with 6 PLC and 8 CCWS mixture resulted in UCS and CBR values of 957 kPa and 102 % respectively. These are greater than 750 kPa and 30 % respectively, thus could be used in construction of sub-base.
f) Using SEM/EDX analyses, Apir latrite treated with 6% PLC and 8% CCWS has more integrated composition and smaller voids than untreated Apir laterite. The EDX results showed higher calcium content (8.53%) in Apir laterite treated with 6% PLC plus 8% CCWS than the content (4.52 %) in untreated laterite. There is significant presence of Ca, Si and Al in Apir laterite treated with PLC plus CCWS. These suggests the presence of cementitious compound, CSH and CAH (Bye, 2011).
g) Considering strength and durability criteria (Nigerian General Specification for Roads and Bridges, 1997; BS 1924, 2018), the treatment of Apir latrite with 6% PLC plus 8% CCWS mixture is recommended for use as a sub-base material in road pavement work.

Civil Engineers would use the findings from this study, as baseline information for the design of flexible pavement involving combined PLC and CCWS stabilization of Apir and similar laterite. Also, these findings will promote the use of industrial waste materials like CCWS as sustainable substitute to traditional binders.

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