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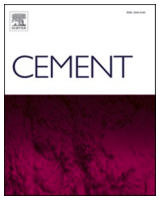



Stabilization characteristics of cemented lateritic soil produced with selected cement types

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ABSTRACT

It is recognized that different cements have different properties and stabilization effectiveness for different applications. The challenge of using the right type of cement should be a concern for practitioners in civil engineering construction. In this study, an experimental testing programme was conducted to evaluate and compare the stabilizing effects of CEM I 42.5 N, CEM II/B-L 42.5 N and CEM III/A 42.5 N types of cement on some physical and mechanical properties of lateritic soil. Laboratory tests performed on soil mixtures containing the selected cements added to constitute 0, 3, 6, 9 and 12 % of the dry weight of the composite materials include the consistency and compaction tests determined on the basis of fresh mixtures. In addition, unconfined compressive strength (UCS) test on specimens compacted at optimum moisture conditions with the British Standard Light (BSL) compaction effort and cured for 7, 28 and 90 days was performed. In equal proportions, soil mixtures prepared with the different types of cements yielded comparable results in terms of reducing the plasticity index (PI) from values as high as 60 % in untreated state to 5.05 %, 7.05 % and 8.2 % respectively for CEM I, CEM II and CEM III at 12 % cement content. Addition of cement also increased both the maximum dry unit weight (γ_{dmax}) and optimum moisture content (OMC) of the soil with CEM I cement having the greatest effect while CEM III cement affected the γ_{dmax} of the soil the least. For example, when compacted with BSH effort, CEM I achieved $\gamma_{dmax} = 1.95$ kN/m^3 and OMC = 25 %, while for CEM III, $\gamma_{dmax} = 1.63$ kN/m^3 and OMC = 22.6 % compared to γ_{dmax} of 1.53 kN/m^3 and OMC of 21.1 % for the untreated soil. Regardless of the cement type, there was an overall improvement in the strength properties of the lateritic soil represented by a range of 11 – 14 times for UCS and 31 - 62 folds for E_{50} at 12 % cement after 90 days curing duration in comparison with the untreated soil. While strength gain was higher in CEM I based mixtures at early (7 day) age (1635.44, 1622.85 and 1599.55 kN/m2 for CEM I, CEM II and CEM III respectively at 12 % cement content), CEM III provided superior strength improvement at the long term (90 day) curing period (2566.25 compared to 2444.58 and 2465.77 kN/m^2 respectively for CEM I and CEM II at 12 % cement content). Using the variance analysis (ANOVA) at a significance level (α) of 0.05, the influence of cement type was statistically confirmed for the liquid limit, optimum moisture content and UCS at 28 and 90 days curing ages.

1. Introduction

Lateritic soils are products of rock weathering over time in the tropical and sub-tropical regions where warm, humid and high amount of annual rainfall are the prevalent weather conditions. The soil is typically dominated by weathered ferro-alumino silicate materials while sesquioxides ($Al_2O_3 + Fe_2O_3$) are deposited within the profile [1–3]. In tropical and sub-tropical regions, this soil is a valuable construction material in roads, foundation fill, embankment etc., however, due to variations in geological conditions, some grades of the soil become problematic particularly when wet [4–7].

Foundation design on problematic laterite/lateritic soil deposits and use of such materials for construction purposes have constantly been a source of concern in civil engineering practice [2,3,8,9]. The major problems posed by building on/with these types of the soil comprises of excessive plasticity, marginal shear strength, excessive swelling and shrinkage capacity, which results in bearing capacity and settlement challenges in foundations, highways and airfield pavement.

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Conventional methods of improving the strength and stability of such soils include treatment with cementing materials including fly ash, lime and cement [10–13].

For many years, stabilization with cement has been the dominant effective technique for a wide range of materials including the laterite soil [13,14]. The stabilized material develops high stiffness and strength and becomes more water resistant than the unstabilized material and generally exhibit good performance in terms of durability and serviceability.

Cement stabilized soil has applicability in numerous infrastructure developments which includes slope protection of dams and embankments, pavement of roadways, building pads, rail and truck terminals, parking lots, channels and reservoir linings, mass soil–cement placement for dikes and foundation treatment.

Theoretically, the main mechanisms of cement stabilization which control the performance of soil–cement mixtures are the cementitious hydration reaction and the pozzolanic reactions which are direct reactions between calcium hydroxide (Ca(OH)2) and adjacent clay surfaces [7,15]. The reactions result in the formation of pozzolanic materials (e.g., calcium silicate hydrates, CSH), adding further strength to the soil–cement mixture. Nonetheless, the pozzolanic reaction involving the silica and alumina from the soil and the calcium ions provided by cement occurs when sufficient concentration of hydroxide ions (OH-) is achieved in the pore water ([9,16]. Hydrated gels, including calcium silicate hydrates (CSH), calcium aluminate hydrates (CAH) and calcium aluminum silicate hydrates (CASH) are generated as a result [9,17]. These cementitious materials and the calcium hydroxide are the main factors responsible for strength gain when cement is mixed with soil. These reactions and the resultant cementitious products also assist in enhancing the gradation of the stabilized soil by creating larger aggregate particles from fined-grained particles which together produce the stabilizing effect on soils.

It is recognized that different cements have different properties and performance. The challenge of using the right type of cement should be a concern for practitioners in civil engineering construction.

EN 197-5 [18] differentiates five main types of cement depending on the composition and chemistry. They include:

CEM I cement that requires 95 % Portland cement clinker and up to 5 % of other main constituents for production. CEM II cement is available as CEM II/A for clinker percentage between 80 – 94 % with supplementary constituents varying between 6 - 20 % while the class designated as CEM II/B is a blend of 65 – 79 clinker with 21 - 35 % mineral additives.

CEM III cement, another type of blended cement contains up to 35–64 % clinker and greater amounts of blast furnace slag than in a CEM II cement. Slag content from 36 - 65 % is designated as CEM III/A, 66 - 80 % as CEM III/B while 81 - 95 % is CEM III/C. CEM IV comprises of Portland cement clinker (65 - 89 % for CEM IVA and 45 – 64 % for CEM IV B) and greater quantities of pozzolana than in CEM II cement. Similarly, CEM V cement type is a compound cement that consist of Portland cement clinker (40 – 64 % for CEM V/A, 20 – 38 % for CEM V/B) and mixtures of blast furnace slag and pozzolana or fly ash.

The behavior of cemented soils has been extensively investigated [10,14,16,19,20,21], and it has been shown that all cemented soils show similar patterns of behaviour, nevertheless, there are significant differences in the effectiveness of different cements [22].

Although the use of some cement types in the stabilization of lateritic soil has been investigated in previous studies, none of these studies in the open technical literature provide a solution to the challenge of discerning the effectiveness of these cement types and the use of the right type in the stabilization of lateritic soil, a major concern confronting civil engineering practitioners in regions where this soil type occur in abundance. This research provides a novel contribution by evaluating and comparing the stabilizing effects of selected cement types on some physical and mechanical properties of lateritic soil. Additionally, the potential of simplified yet reliable approach to predict the compressive strength development of soil stabilized with the selected cement types which is relevant in practical applications was investigated.

2. Materials and methods

The lateritic soil sample used in the present study was excavated from a borrow pit in Minna situated at 9.536063°N, 6.469160°E, Nigeria at a depth of approximately 2.0 m after removing the top organic matter. It is a clayey soil locally abundant in most parts of Nigeria, in some cases containing relics of somewhat hard weathered materials.

The three cement types selected for this research were CEM I 42.5 N, CEM II/B-L 42.5 N and CEM III/A 42 .5N. Although CEM II is widely used for stabilization of soils in Nigeria, it is paramount to explore the suitability and advantages of other cement types produced in the country such as CEM I and CEM III particularly for the treatment of this grade of lateritic soil which is prevalent in different parts of the country.

Materials used in the production of the selected cements include: Portland cement clinker (obtained from a cement plant in Lokoja, Nigeria) and granulated blastfurnace slag, gypsum as well as limestone collected from a gypsum plant in Ajaokuta, Nigeria.

While CEM I 42.5 N blend was made by inter-grinding 95 % of Portland cement clinker together with 5 % of gypsum in a laboratory ball mill, CEM II/B-L 42.5 N cement produced in the factory indicate 65 % clinker, 25 % ground blastfurnace slag (GBFS), 5 % ground limestone and 5 % gypsum (as indicated on the cement label). Similar to CEM I, CEM III/A 42.5 N cement is a composite of 46 % Portland clinker, 50 % granulated blast-furnace slag, 2 % gypsum and 2 % powdered limestone blended in a ball mill. The percentages of the components of each of the cement types are based on the ranges specified by EN197–5 [18]

2.1. Specimen preparation and testing procedure

Specimens were prepared with cement contents of 0, 3, 6, 9 and 12 % for the different cement types, with the cement composition expressed as a percentage of soil-cement mixture. This range of cement content was adopted based on past studies on cement stabilization of lateritic soil [2,4,6,7,10] together with the authors' practical experience in the study area. The effects of the various proportions of these cements on the Atterberg limits (liquid limit LL, plastic limit PL and plasticity index PI), compaction parameters and compressive strength of the soil were thus investigated.

In the liquid limit test, the Casagrande equipment was used where sufficient portion of the soil mixture that passed the 425 μm sieve was mixed with water to form a homogeneous paste. The paste was spread in a brass cup, divided into two by a grooving tool, and then allowed to flow together from the shocks, caused by repeatedly dropping the cup in a standard mechanical device. The test was carried out five times over a range of moisture contents. The plastic limit was determined by rolling into a 3 mm diameter thread of the specimen until its water content was reduced to a point at which the thread crumbled and could no longer be pressed together and re-rolled. The water content of the soil at this point was recorded as the plastic limit. The Plasticity index is the numerical difference between the liquid limit and the plastic limit (PI= LL-PL).

Compaction test was carried out using the British Standard Light (BSL) compaction effort according to the British standard. The soil mixture was compacted in a mould of 1000cm3 vol by a 2.5 kg hammer falling through 300 mm onto three layers, each receiving 27 blows [23]. From the data, a smooth curve was plotted for the dry unit weight as a function of the water content to deduce the optimum water content (OMC) and corresponding maximum dry unit weight.

For the strength tests, soil mixtures were prepared at optimum moisture condition and cured for 7, 28 and 90 days under 100 % relative

humidity and temperatures of 25± 2 °C. On completion of the specified curing periods, the specimens were pruned to the stipulated dimensions of 76 mm height and 38 mm diameter. A loading machine with a capacity of 50 kN and proving rings with a resolution of 0.005 kN was used for the tests. The loading rate of uniaxial compression test was maintained at 1 mm/min until the failure of samples. The average values with a coefficient of variation (COV) values of <5 % indicative of the repeatability of the results were recorded. After each experiment, stress and strain values were calculated for analysis. The strain at failure and secant modulus E_{50} evaluated at the stress level equal to 50 % of q_u (max) from the stress – strain curve were recorded. A flow chart of the methodology used in the study is shown in Fig. 1.

3. Results and discussion

3.1. Base soil characterization

The particle distribution of the soil (Fig. 2) indicates that the sample consists of 36.9 % of sand and 63.10 % fines (silt + clay fractions). The basic properties of the soil including the particle size distribution, plastic limit *PL*, liquid limit *LL* and specific gravity are listed in Table 1. Earlier geotechnical studies on specimens from this borrow pit showed that the soil is ferruginous in nature from igneous and metamorphic rocks [5]. Under the degree of laterization classification system, the soil sample is identified as lateritic soil (silica-sesquioxide ratio = 1.38). Similarly, it is categorized as a fine-grained soil (A-7–6) in the American Association of State Highway and Transportation Officials (AASHTO) soil classification system as well as inorganic silt of high plasticity (MH) under the Unified Soil Classification System (USCS).

The oxide analysis of the soil by X-ray fluorescence analyzer is reported in Table 2 and the main clay mineral of the soil determined by X-ray analysis is kaolinite ($Al_2Si_2O_2(OH)_4$) while quartz (SiO_2) is the major non-clay mineral detected in the soil sample (Fig. 3). Similarly, the chemical attributes of the cements are also reported in Table 2 while the physical and particle size distribution characteristics are presented in Table 3 and Fig. 2 respectively.

3.2. Consistency limits of soil mixtures

Fig. 4 summarizes the instant result of including different proportions of cement on the Atterberg limits of the soil. The liquid limit LL, plastic limit PL and plasticity index PI of the natural soil sample were estimated to be 60.0 %, 39.44 % and 20.56 % respectively resulting from the consistency limit test results. The addition of any of the cement types had an immediate effects of decreasing the LL while the PL was slightly increased which led to a reduction in the PI. For instance, at 12 % cement content, the LL decreased to 49.05 % for CEM I, 51 % and 53.2 % for CEM II and CEM III respectively. Similarly, PL of soil mixtures containing 12 % cement were determined as 44 %, 43.95 % and 45 % for CEM I, CEM II and CEM III mixtures respectively. The resulting PI reached 5.05 % for CEM I based mixtures, 7.05 % and 8.2 % respectively for CEM II and CEM III based mixtures. These outcomes show that the effectiveness of CEM II and CEM III cements is close to that of CEM I cement and therefore no significant difference can be found between these cements in terms reducing the plasticity index. Notwithstanding this inference, specimens formed with CEM I provides marginally lower PI than the other two due to greater fineness and higher specific surface of this cement type [22,24,25].

These findings agree and corroborate the observations in previous studies for a variety of soils stabilized with various cement types [17].

On the other hand, the outcome deviates from the results reported by Sariosseiri and Muhunthan [26] as well as Al-Zoubi [27]. Sariosseiri and Muhunthan [26] reported an initial increase in liquid limit followed by a decrease with increasing cement content causing an initial increase in PI

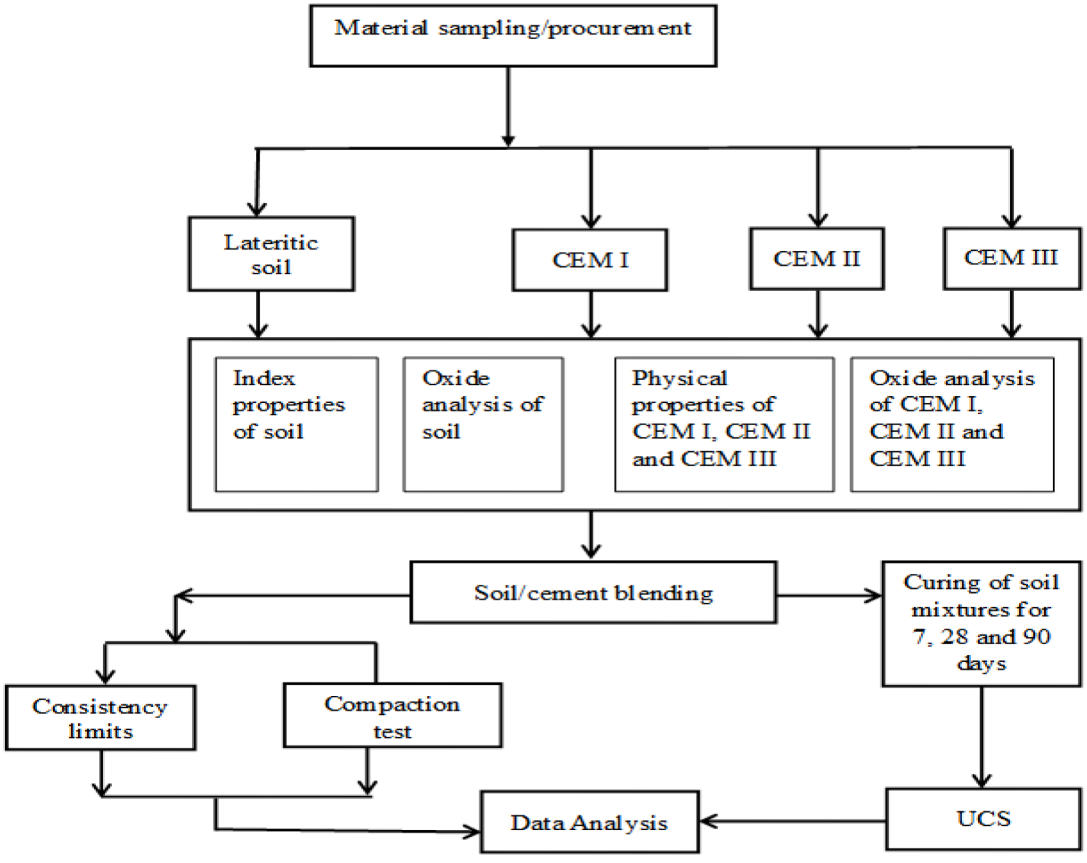


Fig. 1. Flow chart of methodology used in the study.

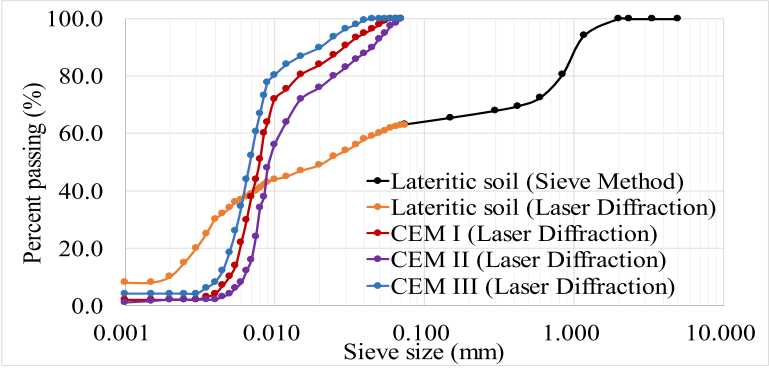


Fig. 2. Particle size distribution curve of lateritic soil used in the study.

Table 1
Some Basic and Geotechnical Properties of the Lateritic Soil.

Property	Value
% passing BS sieve No 200	63.10
Liquid limit (%)	60.00
Plastic limit (%)	39.44
Plasticity Index (%)	20.56
Specific gravity	2.76
Soil class (USCS)	MH
Soil class (AASHTO)	A – 7 - 6
Colour	Dark brown

Table 2
Oxide analysis of CEM I, CEM II and CEM III cements as well as the soil used.

Composition	CEM I 42.5N	CEM II/B-L 42.5N*	CEMIII/ A42.5N	Soil
Silicon dioxide SiO_2	20.43	25.82	29.72	36.20
Aluminum oxide Al_2O_3	5.16	5.79	6.31	23.40
Ferric oxide Fe_2O_3	3.41	2.85	2.23	2.80
Potassium oxide K2O	0.43	0.78	0.69	1.67
Calcium oxide CaO	62.13	59.78	54.07	0.28
Magnesium oxide MgO	1.75	2.22	3.60	0.22
Sulphur trioxide SO_3	2.31	3.52	2.74	0.85
Sodium oxide Na_2O	0.20	0.26	0.38	0.33
Cl	0.03	0.05	0.06	ND
Loss on ignition LOI	1.45	1.50	1.62	14.60

ND – not determined.
* Taken from the manufacturer manuscript.

that decreased at higher cement content. Similarly, Al-Zoubi [27] recorded a dramatic reduction in the liquid limit in the range of cement contents up to 6 %, but, in the range of 6 - 10 %, the liquid limit was raised. The resultant PI decreased until the cement contents reached 7 % beyond which the plasticity index increased with cement contents.

The changes in consistency limits of soil mixtures can be ascribed to the cation exchange reaction, soil particle restructuring (the flocculation and agglomeration of soil particles) caused by the hydration reaction of cement together with pozzolanic reaction associated with the existence of $Ca(OH)_2$.

Using PI to assess the improvement in workability of soil mixtures, the immediate reduction in PI changes the soil from a plastic (PI = 20.56 %) to a more granular material (PI = 5.05 - 8.2 %) which translates to better workability. Generally, the workability of clays is known to improve with reduction in the PI [14,16,28].

To statistically establish the impact of cement content and type on the consistency limits (LL, PL and PI) of mixtures, two-way variance analysis (ANOVA) at the level of significance (α) = 0.05 was carried out. Table 4 describes the F-values together with p-values from the ANOVA establishing both cement content and cement type as influential variables (Fcal > Fcrit with a p-value <0.05) for LL. For the PL and PI of soil mixtures, neither the cement content nor cement type significantly affects the variation in these parameters as Fcal is less than Fcrit and p-values greater than 0.05.

3.3. Water content – unit weight of soil mixtures

Assessment of the impact of cement content and type on dry unit weight as well as the optimum moisture content OMC of soil after treatment is shown in Figs. 5a and 5b. For the various cement types, the dry unit weight is seen to increase approximately linearly with cement content not withstanding the initial flocculation and the structural changes due to the initial chemical reactions. For instance, the maximum dry unit weight of specimens increased from 13.9kN/m^3 for natural soil to 15, 15.8 and 16.9 kN/m^3 respectively for CEM III, CEM II and CEM I at the 12 % cement content. Apparently, mixtures containing CEM I provides higher maximum dry unit weight values when compared to those treated with CEM II and CEM III and the difference seemingly increased with cement content.

This is linked to cement hydration and pozzolanic reaction that reduced the water content of mixtures and produced solid cementation products (CSH and CAH), which then filled the voids and eventually increased the unit weight of stabilized soil [2,14,29]. Another possible reason for higher maximum dry unit weight with the cement inclusion would be the fact that the cement in the presence of water have a tendency to result in denser packing arrangement during compaction process. Besides, the fine particles of cement tend to fill the voids within the soil, resulting in a denser soil matrix.

In general, the OMC value increased with increasing cement content irrespective of the cement type. Meanwhile, for CEM I treated soil, the OMC increased from 28 % (for untreated state) to 31.40 % at 12 % while the OMC containing CEM II and CEM III cements were 30.48 and 29.88 % respectively. The difference in OMC of specimens is believed to be mainly due to the difference in water absorption capacity of the cements. CEM I cement with greater fineness and more surface area resulted in the requirement of greater amount of water for good lubrication, hence higher OMC values. These results match the trend observed in previous studies [22,25,30].

Table 5 presents the F-values, together with p-values for the ANOVA of the compaction factors i.e., maximum dry unit weight and OMC. Since the Fcal is greater than Fcrit for cement content in the case of maximum dry unit weight, the null hypothesis was rejected. Thus, cement content significantly affect the maximum dry unit weight. On the other hand, the Fcal is less than Fcrit for cement type and therefore, the null hypothesis was not rejected, consequently cement type does not significantly affect the maximum dry unit weight of soil mixtures at a level of 0.05. Likewise, the results reported in Table 5 confirmed that statistically significant relationship exist between the cement content and the OMC as well

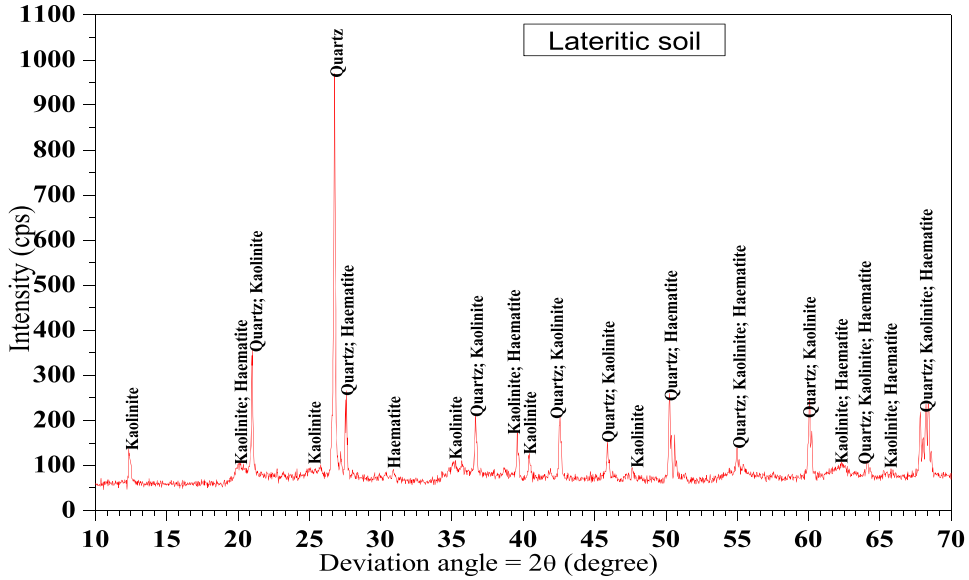


Fig. 3. X-ray diffractograph of the natural lateritic soil used in the study.

Table 3
Physical characteristics of CEM I, CEM II and CEM III cements utilized in the study.

Parameter	CEM I 42.5N	CEM II/B-L 42.5N*	CEM III/A 42.5N
Specific gravity	3.15	3.1	3.0
Surface area (Blaine method), m^2/kg	835	825	765
Density, g/cm^3	3.05	3.00	2.95
Consistency in vol. (mm)	0.8	0.8	0.8

* obtained from manufacturer's manuscript.

as cement type and OMC.

3.4. Impact of cement content and type on strength characteristics of soil mixtures

The stress-strain characteristics of soil mixtures at various cement contents and curing times for the selected cement types shown in Fig. 6a–d essentially followed similar pattern with an apparent peak point. Typical of stress-strain response for soil composites, the peak axial stress (defined as the unconfined compressive strength UCS) improved with increase in cement content and curing period while the strain corresponding to peak axial stress decreased.

Due to the somewhat plastic behavior of the natural soil, the strain at failure (ε_f) reached 4.96 %. This then decreased to 3.28 %, 3.64 % and 3.81 % respectively for mixtures containing 3 % of CEM I, CEM II and CEM III cements at the end of 7 days curing. When cement content was increased to 12 % cement, ε_f decreased to 2.17 % for CEM I based mixtures, 2.41 % for CEM II and 2.62 % for CEM III at 7 days curing duration. Greater reduction in ε_f were established when curing periods were extended to 28 and 90 days. For example, at 28 day curing and cement content of 12 %, failure occurred at axial strains in the range of 1.62 –1.82 % for all cement types. Further reductions in values such as 0.82 %, 1.13 % and 1.35 % were recorded for CEM I, CEM II and CEM III cements respectively following 90 days of curing. For equal cement contents, CEM I based mixtures seem to exhibited somewhat brittle characteristic in terms of lower values of ε_f and sudden drop in the post-peak stress as strain values increased while CEM II and CEM III mixtures were seen to exhibit a more gradual drop in the post-peak stress with strain, behaving more like a ductile material [11,22,24,28,31]. Comparable trends have been reported for calcareous soils as well as some lateritic soils stabilized with CEM I cement [10,24].

The development of UCS with varying cement content (3, 6, 9 and 12

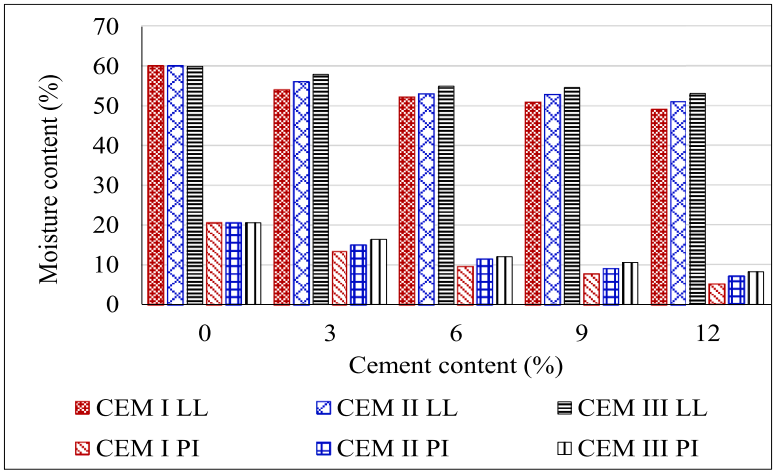


Fig. 4. Effect of cement content and type on liquid limit (LL), plastic limit (PL) and plasticity index (PI) of soil mixtures.

Table 4
Two way analysis of variance without replication for consistency limits of lateritic soil treated with selected cement types.

Property	Factors	df	F_{cal}	P-value	F_{crit}	Remark
Liquid limit	Cement content	4	47.84	1.25E-5	3.83	Significant effect
	Cement type	2	14.27	0.002	4.45	Significant effect
Plastic limit	Cement content	4	1.60	0.26	3.83	No significant effect
	Cement type	2	0.77	0.49	4.45	No Significant effect
Plastic Index	Cement content	4	1.37	0.32	3.83	No significant effect
	Cement type	2	0.34	0.71	4.45	No Significant effect

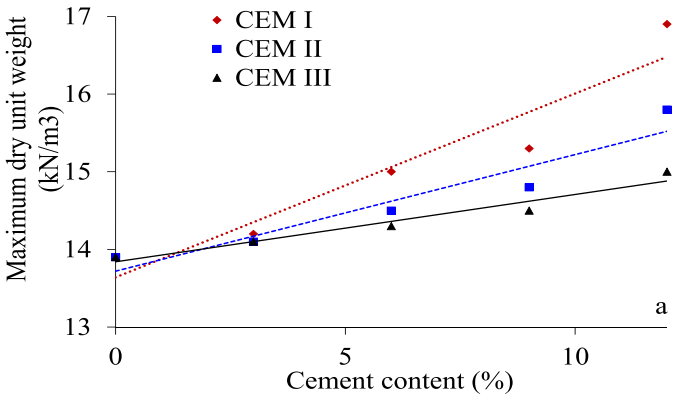


Fig. 5a. Variation of maximum dry unit weight of lateritic soil with cement content.

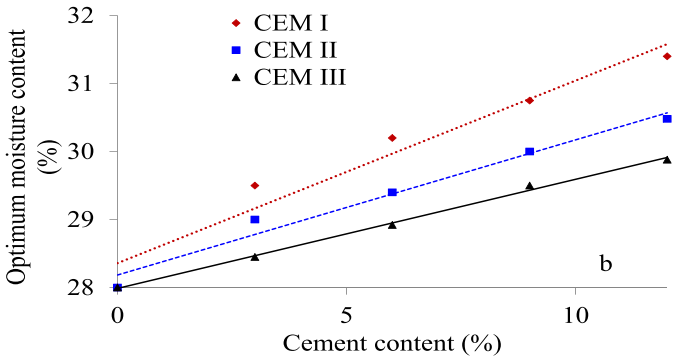


Fig. 5b. Variation of optimum moisture content of lateritic soil with cement content.

Table 5
Two way analysis of variance without replication for the compaction parameters of lateritic soil treated with selected cement types.

Property	Factors	df	F_{cal}	P-value	F_{crit}	Remark
Max. dry	Cement content	4	12.59	0.0015	3.83	Significant
	Cement type	2	4.31	0.053	4.45	effect No Significant effect
OMC	Cement content	4	33.12	5.02E-5	3.83	Significant effect
	Cement type	2	14.43	.002	4.45	Significant effect

%) for the various cement types (CEM I, CEM II and CEM III) is shown in Fig. 7. According to these results, cemented specimens generally exhibited increase in UCS with cement content for all cement types. As an overview, failure of the natural soil occurred at UCS of 187.52 kPa which is low and characteristic of clayey soils and does not qualify for use in most engineering construction. The UCS values for 3 % cement content at 90 days increased by 4.05, 4.37 and 4.63 times respectively for CEM I, CEM II and CEM III mixtures compared to that of untreated soil. When cement content was increased to 12 %, superior strength values and higher increases in strength that represent several magnitudes (13.03, 13.15 and 13.68 folds) were established for mixtures created with CEM I, CEM II and CEM III cements respectively. It is noteworthy that the greater increases in UCS ensued with greater percentages of cement (6 % and 12 %) which underscores the importance of providing appropriate amount of cement in order to achieve the requisite strength values. Generally, these results indicate that the UCS of the mixtures for the various cement types are comparable.

Matching the UCS values recorded in the current study with that of laterite/lateritic soil in the literature, it can be inferred that the values lie within the range of reported values [7,13,21,32]. The enhanced strength of a soil–cement mixture stems from the physicochemical reactions between soil and cement, such as the interaction involving the substances found in the soil and the products of the hydration of cement [15,21]. The manifestation of higher strength magnitudes and stiffness is accomplished as shown in Fig. 10c, e, and g by: (1) reduction of pore void space, (2) bonding of particles together and (3) maintaining flocculent structures [33]. Portland cement is made up of calcium aluminates and calcium silicates that hydrate after mixing with water, generating the cementitious materials namely calcium silicate hydrate and calcium aluminate hydrate [34].

Regression analysis indicate that exponential representations (Eqs. (1)–(3)) were used to correlate the UCS with the cement content for CEM I, CEM II and CEM III based mixtures respectively. This reflects the greater increases in UCS of mixtures at higher cement contents.

$$UCS = 257e^{0.17CC} \quad R^2 = 0.82 \tag{1}$$

$$UCS = 262.17e^{0.17CC} \quad R^2 = 0.81 \tag{2}$$

$$UCS = 266.18e^{0.17CC} \quad R^2 = 0.79 \tag{3}$$

Curing duration plays a critical role in the process of strength development as reported by many other researchers [21,25,34]. Fig. 8 presents the evolution of UCS with time for the various cement contents and types. The trend is distinguished by a high early increase in strength, followed by a stage of steady and much slower rate of increase at late curing times. After 7 days curing time, the UCS improved from 187.52 kPa to 1635.44 kPa, 1622.85 kPa, and 1599.55 kPa at 12 % for CEM I, CEM II and CEM III respectively. Thus, similar to concretes, CEM I-treated specimens provides slightly higher UCS values when compared with those treated with CEM II and CEM III cements at early ages (7 days) of curing. The greater effectiveness of the CEM I cement at this curing age is consistent with observations made by other studies in the literature [22,24,30].

However, extending the curing duration to 28 and 90 days witnessed significant increase in UCS values that represent 10 – 14 folds compared to the untreated specimen irrespective of the cement type. The UCS at 28 and 90 days for both mixtures containing slag (CEM II and CEM III) cements exceeded that of CEM I mixture. This happened because, cements containing mineral additions (slag and/or fly ash) tend to gain strength at a slower rate but exhibit long-term cementation properties which are usually higher. The delay in strength gain is attributed to the delayed hydration of mineral additions [15,16].

Thus, the maximum UCS values were achieved for mixtures created

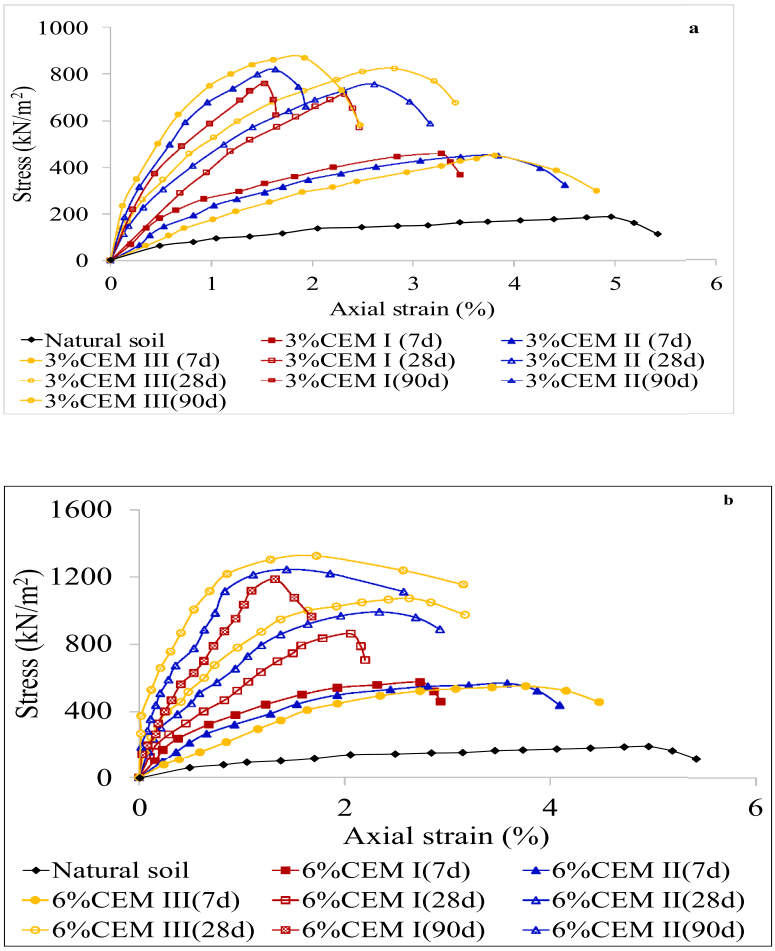


Fig. 6. Stress - strain relationship of lateritic soil specimen treated with different types of cements at (a) 3 % cement (b) 6 % cement (c) 9 % cement (d) 12 % cement contents.

from CEM III after 90 days of curing. Meanwhile, the ratio of the UCS at 90 days compared with that at 28 days was between 1.1 and 1.4 times indicating that the rate of increase in UCS for mixtures cured >28 days is less pronounced. The decrease in strength development over time is ascribed to the formation of thick calcium silicate hydrate crystals which prevents water molecules from reacting with un-hydrated tricalcium silicate. In addition, it can be linked to the paucity of water due to dry conditions or evaporation triggered by exothermic reactions [9,21]. The UCS results at different ages agreed with those of Mengue et al. [10], Vu et al. [17], Gu et al. [21] and Wahab et al. [32].

The observed increasing trend with curing duration is linked to the reaction products formed from cementitious hydration together with continuous pozzolanic reactions which are long term processes [25,35].

For UCS of soil mixtures tested at adopted curing regime, a two-way analysis of variance defined in terms of cement type and cement content was carried out. The significance of each factor on the UCS of the investigated soil mixtures was examined and validated as reported in Table 6. The results presented in Table 6 show that the Fcal is greater than the Fcrit and the p-value <0.05 only at 28 and 90 days of curing. Consequently, the null hypothesis is rejected and it can be stated with 95 % confidence that both cement type and cement content contributed significantly to the variations recorded in the UCS of soil mixtures at these curing ages. This is consistent with the results established previously. It also revealed that the UCS are more influenced by the cement content than the cement types.

Fig. 9 reports the variation in the measured strain at failure, εf with UCS of mixtures containing the three cement types CEM I, CEM II and CEM III prepared at 7, 28 and 90 days of curing. Generally, most values of ε_f distribute in the range of 0.6 to 4.95 % and presents a decreasing trend with increase in UCS.

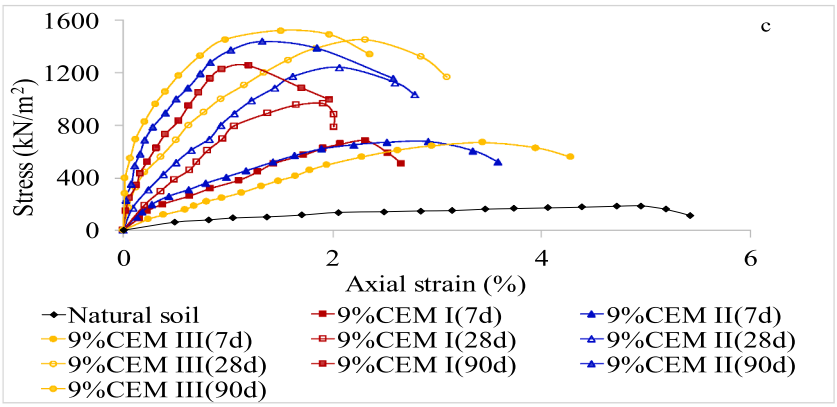
The decreasing tendency is particularly notable at UCS values <1000kPa. Thereafter the failure strain remained relatively constant. Thus, at higher UCS values, the rate of decrease was low.

From Fig. 9, it can be said that CEM I based mixtures presented lower ε_f values than mixtures containing CEM II and CEM III cements. It is further noted that the trend of failure strain for specimens containing CEM II and CEM III can hardly be distinguished.

To understand the microscopic changes of soil structure before and after stabilization with the selected cement types, the natural soil and samples stabilized with 12 % cement content and cured for 7 days prepared for UCS tests were selected for scanning electron microscopy. The resulting images in Fig. 10 represent SEM images of the natural lateritic soil and different soil mixtures produced with CEM I, CEM II and CEM III.

While the natural soil (Fig. 10a) exhibited a blocky arrangement of loosely packed particles, soil mixtures irrespective of the cement type used have compact and denser microstructure. The denser microstructure is caused by the filling of cementitious gels produced by the chemical and pozzolanic reactions between minerals of soil and cement ingredients such as calcium aluminate hydrate (CAH) and calcium silicate hydrate (CSH) in the pore space as illustrated in Fig. 10 (c, e and g).

The diffraction peaks observed in the X-ray diffractographs (Fig. 10b, d, f, h) indicate the presence of calcium which provides evidence of strength gain due to chemical reactions such as hydration and



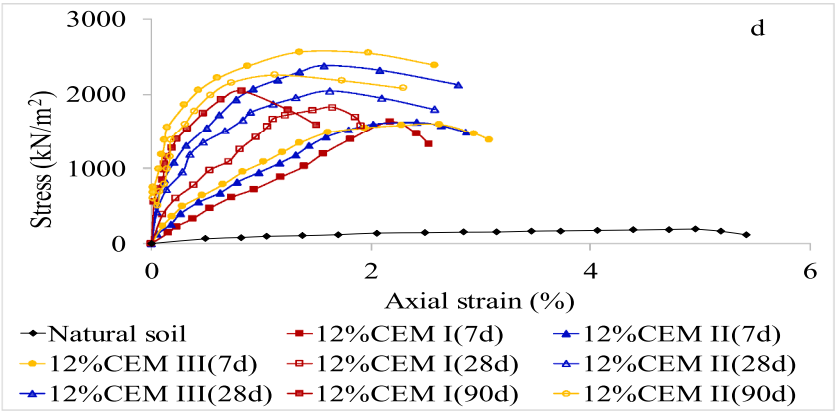


Fig. 6. (*continued*).

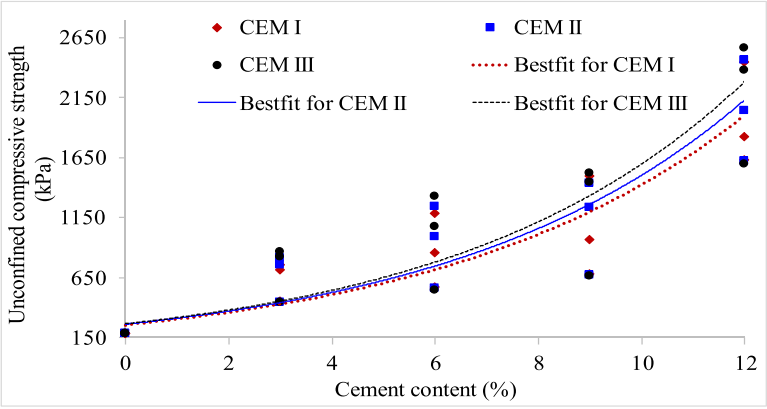


Fig. 7. Variation of compressive strength with cement content for the various cement types.

pozzolanic reactions. In addition, patterns different from that of untreated soil were observed for various cement types which may explain the differences in their strength properties.

Besides, the EDX results presented in Table 7 highlights the major elements in the soil mixtures with their atomic and weight percentage concentrations. The concentration of elements such as oxygen, silicon and calcium which are higher than other elements namely Aluminum, Iron, Titanium indicate CSH hydrates and portlandite formation in the mixtures. When compared to the unstabilized soil, the higher calcium concentration in the mixtures confirms the formation of portlandite.

3.5. *Stiffness of soil mixtures*

Secant modulus E_{50} of geomaterials reflects their stiffness at failure state. It is an important consideration required in elastic analysis for determination of stresses and strains at critical locations in ground improvement and foundation design. Secant modulus E_{50} in the present study was evaluated at the stress level equal to 50 % of the maximum UCS from the stress-strain curve. The effectiveness of the three cements in improving the soil stiffness after treatment is expressed by the normalized secant modulus, where the computed E_{50} values were normalized by the E_{50} value of soil specimen without treatment. Fig. 11 reports the normalized E_{50} of soil mixtures. As shown in Fig. 11, E_{50} of treated specimens increased with cement content similar to trends in the development of UCS as presented in Fig. 7. The normalized secant modulus of stabilized specimens distribute between 1 and 63, subject to the cement content and curing time. This result is classical for cement-stabilized soils and is also in accordance with measurements regarding

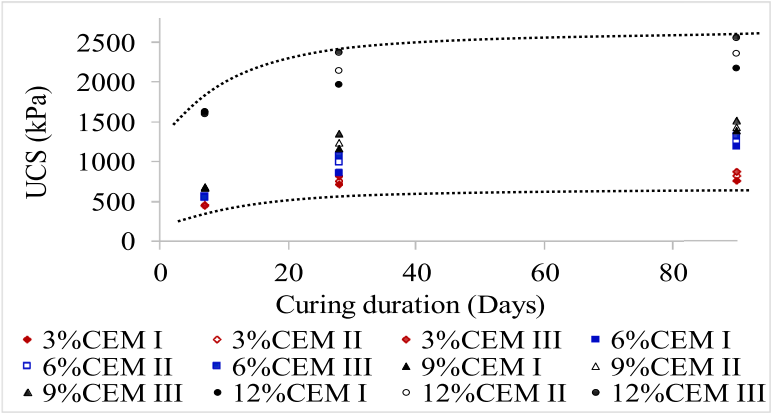


Fig. 8. Variation of unconfined compressive strength of specimens with curing duration.

Table 6
Two way analysis of variance without replication for UCS of lateritic soil treated with selected cement types.

Property	Factors	df	F_{cal}	P-value	F_{crit}	Remark
7-day UCS	Cement content	3	1.23	0.378	4.75	No Significant effect
	Cement type	2	1.01	0.420	5.14	No Significant effect
28-day UCS	Cement content	3	83.97	2.73E-5	4.75	Significant effect
	Cement type	2	9.68	0.013	5.14	Significant Effect
90-day UCS	Cement content	3	83.97	2.73E-5	4.75	Significant effect
	Cement type	2	9.68	0.013	5.14	Significant effect

the elastic modulus of soil-cement blends in the past [7,25,26]. For example, Balmer [36] established that the elastic modulus of soil-cement mixture improved with cement content and varies from 689 MPa to 13.79 GPa for granular soil-cement mixture and from 1.79 GPa to 5.24 GPa for fine-grained soil-cement mixture. Such increase in stiffness can be linked to generation of new cementitious compounds of CSH and CAH as a consequence of hydration and pozzolanic reactions. Greater cement amount will generate more cementing components of CSH and CAH and vice versa.

As previously stated, the generation and accumulation of these cementing materials is enhanced with extended curing duration resulting in the filling of the pores between voids, thus creating a dense structure with a consequent rise in the stiffness of the mixture.

The data in Fig. 12 shows that E_{50} of the soil-cement mixtures has a linear correlation with the UCS which lies between 132.16 and 223.53UCS for the various cement types. It can therefore be stated that an improvement in soil stiffness is complemented by an increase in strength of specimens. Good correlations (R^2 = 0.96 – 0.97) were recorded between the E_{50} and the UCS for the 3 cement types. This implies that UCS had the greatest effect on the E_{50} value and the equations shown in Fig. 12 could predict the E_{50} value accurately for the respective cement types.

Several relationship expressions between the secant elastic modulus and unconfined compressive strength have been suggested in the literature, some of the relationships are expressed in equations 4 - 8 as follows:

Briaud et al. [37]:

$$E_{soil-cement} = 12900q_u^{0.41} \quad (4)$$

Lorenzo and Bergado [35]:

$$E50 = (115 - - 150)qu \quad (5)$$

Dingwen et al. [33]:

$$E50 = (150 - - 275)qu \quad (6)$$

Wahab et al. [32]:

$$E50 = 106.82qu \quad (7)$$

Roshan et al. [7]:

$$E50 = (74.72 - - 135.25)qu \quad (8)$$

Comparison of the equations obtained in this study with the results reported in some other studies in the literature show that there is a wide range of forecasting of the secant elastic modulus. It is obvious from Eq. (5) – 8 that the outcomes of the present study agrees well particularly with the study carried out by Dingwen et al. [33].

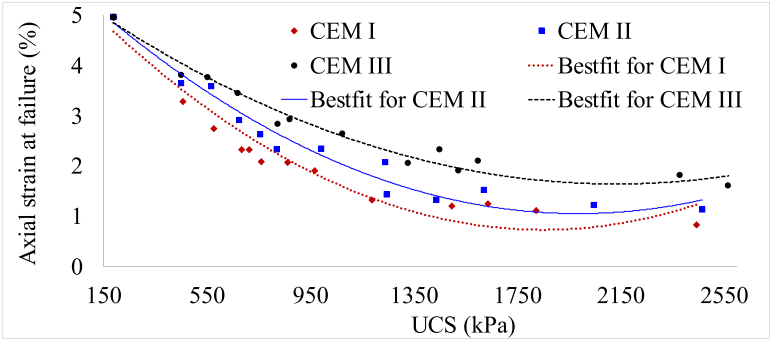
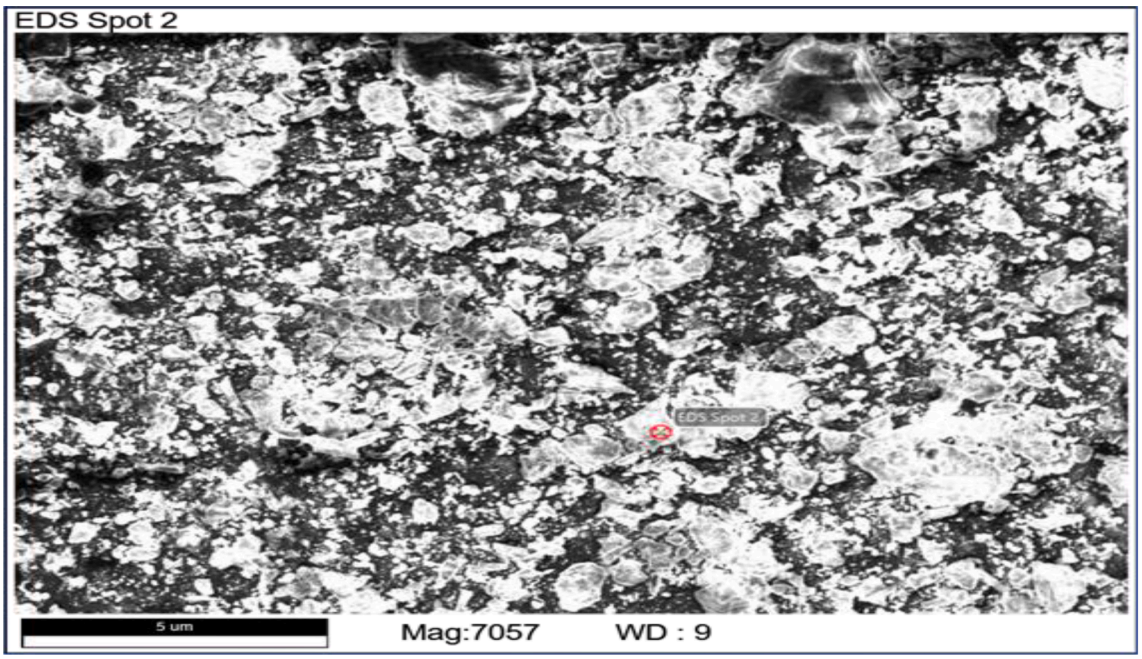
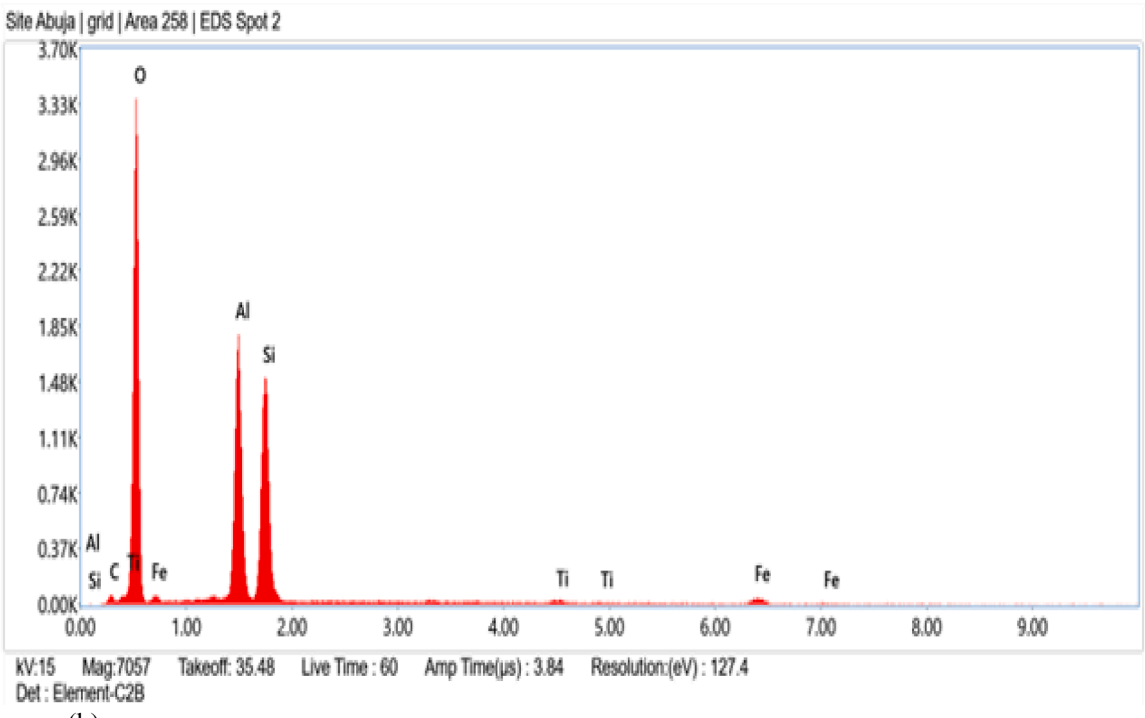


Fig. 9. Variation of Axial strain at failure with compressive strength for the various cement types.



(a)



(b)

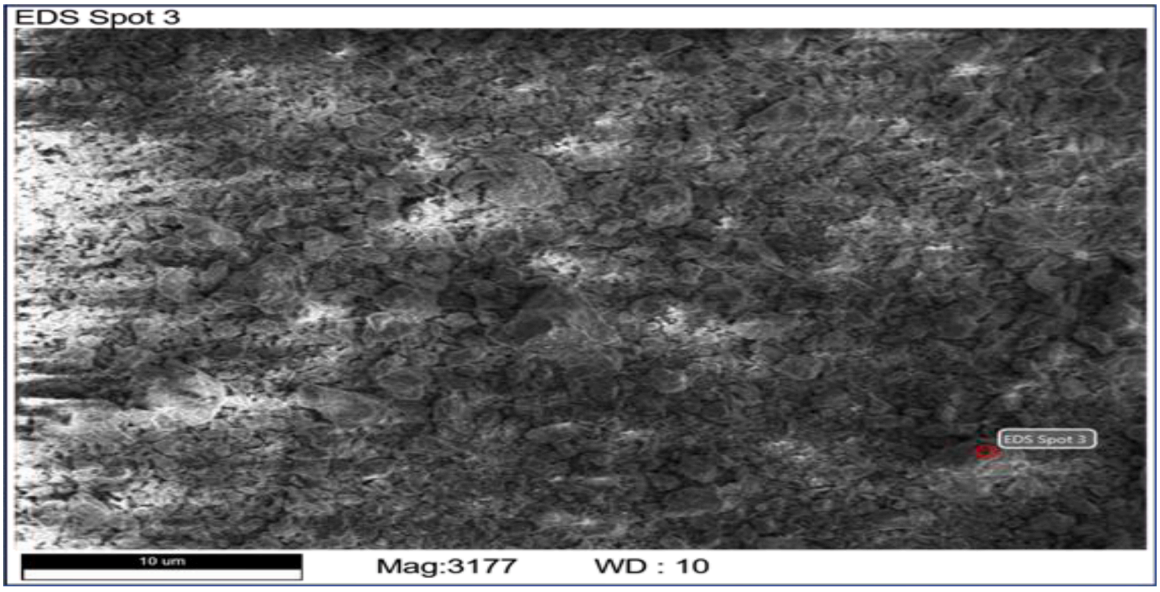
Fig. 10. SEM and EDX results of unstabilized lateritic soil and soil mixtures produced with 12 % of selected cement types at 7-day curing time (a and b) unstabilized soil (c and d) CEM I (e and f) CEM II (g and h) CEM III.

3.6. Practice implications

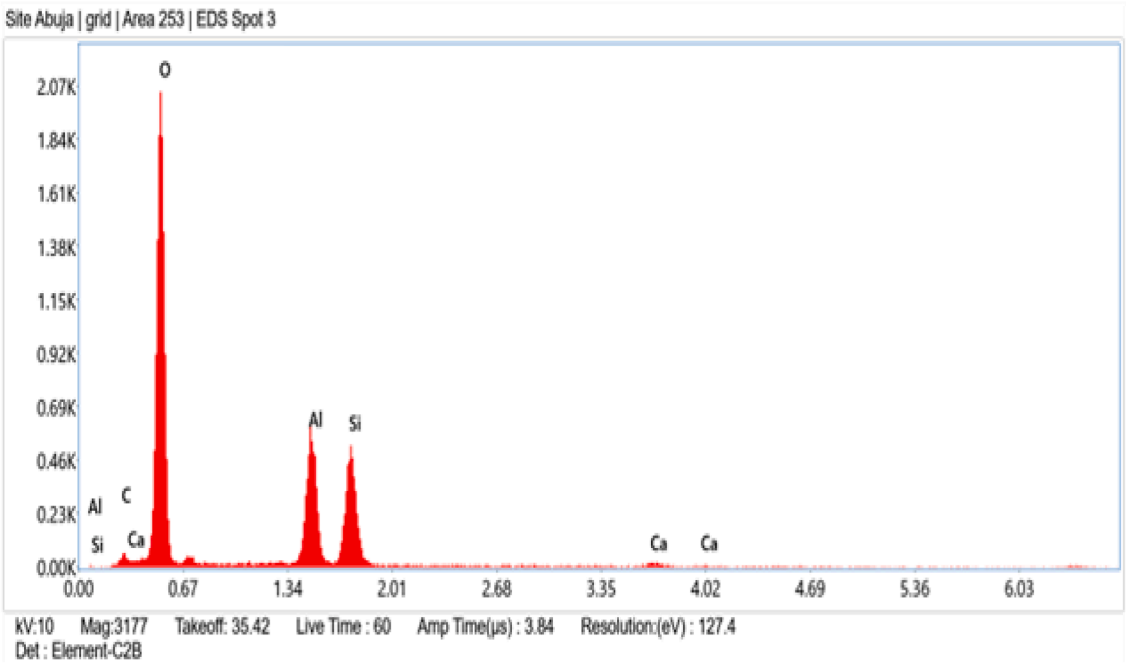
Granted that the threshold strength requirement of cement stabilised soils in applications vary according to standards worldwide, CEM I, CEM II and CEM III cements achieved very high strength values adequate to meet the requirements for most engineering applications.

Furthermore, it can be concluded that soil mixtures containing CEM II and CEM III established higher strength after 90 days of curing which makes it feasible to utilize the studied lateritic soil for engineering works where long term strength development is required.

While the use of CEM I with higher clinker percent achieved the targeted strength quickly, the use of lower clinker cements i.e., CEM II and CEM III in particular for construction is a favourable substitute for the future, as it leads to the lessening of the carbon footprint and reduced



(c)



(d)

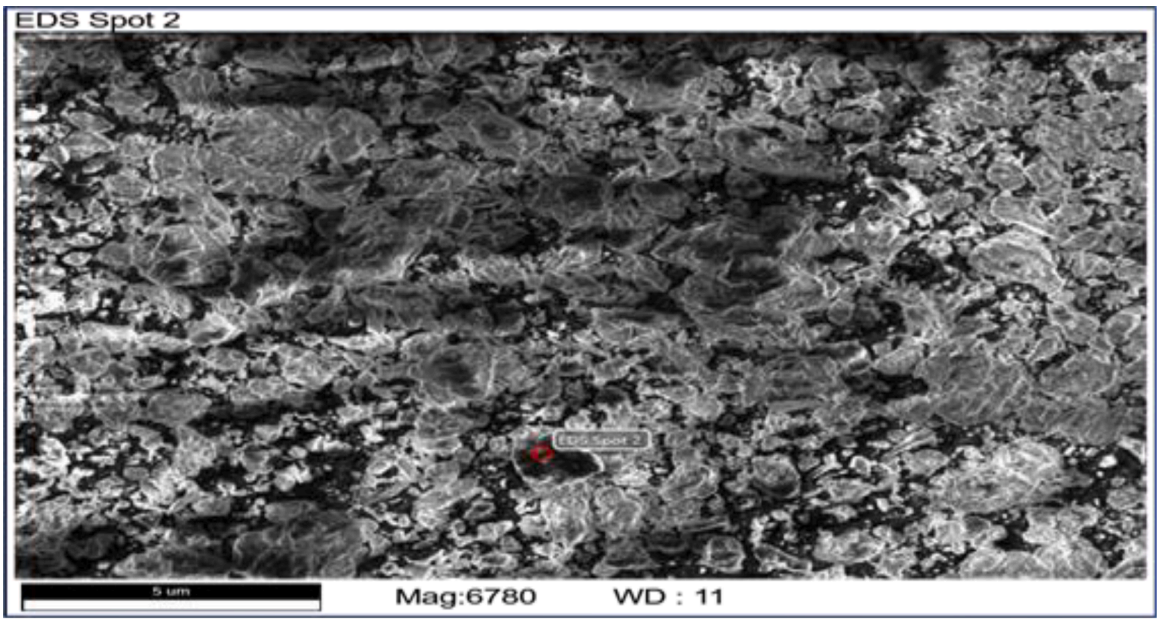
Fig. 10. (*continued*).

carbon dioxide (CO2) emissions. Surveys conducted to analyze CO2 emissions by cement industries revealed that lower clinker cements represent a significant percentage of cement consumption. For example, the clinker-to-cement factor, which could be seen as an indicator of the CO2 emissions of the cement industry, has reduced from 0.86 (2000) to 0.75 (2009) [38,39]. Besides, studies have shown that the production of CEM III/C produces about 10 times less CO_2 than CEM I [40]. Also, the use of waste materials specifically, the fly ash and blast furnace slag without reducing the characteristics of soil-cement mixtures results in increased sustainability. However, maximizing the use of these cements in some countries such as Nigeria remains a major challenge, as the availability of fly ash and slag tends to decline due to decreases in coal power and primary/virgin steel production. This will lead to increasing use of cements with higher limestone content namely CEM II cements.

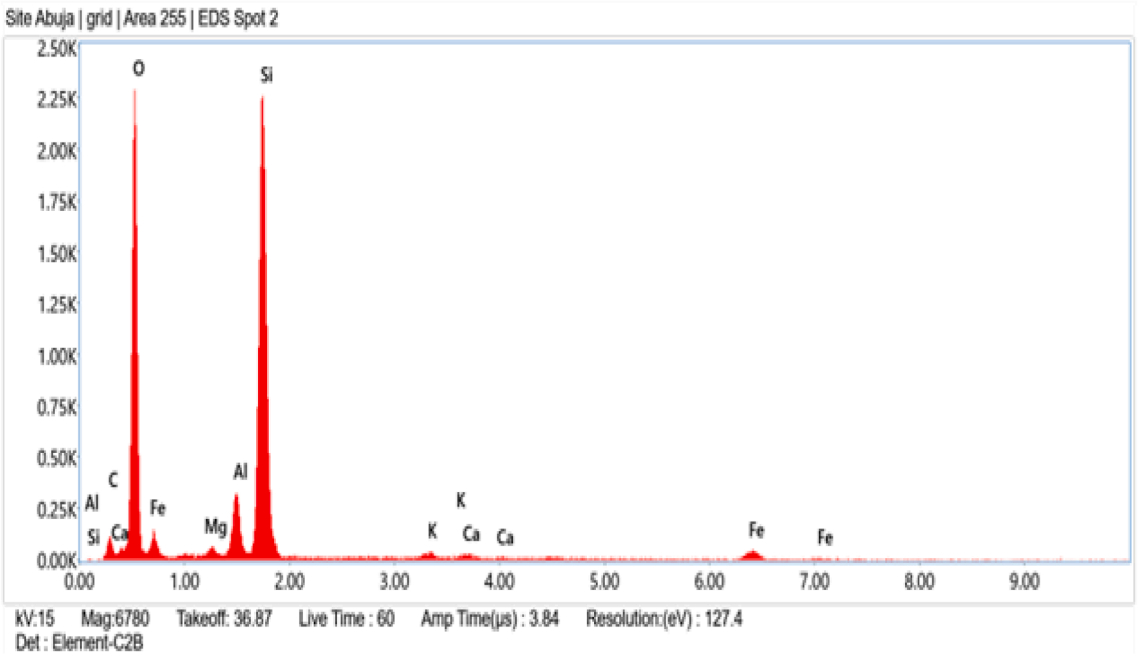
4. Conclusions

Stabilization of a lateritic soil was carried out by using five cement dosages (0, 3, 6, 9 and 12 %) of CEM I, CEM II and CEM III cements. Changes in consistency limits, water content – unit weight relationship, stress–strain behavior, unconfined compressive strength as well as elastic properties were considered. The following characteristics of the stabilized soil were noted in this study:

The results show that treatment of the soil with the three cement types in general indicated an apparent decrease in LL and PI. In contrast, the values of plastic limit (PL) were raised. Specimens stabilized using



(e)



(f)

Fig. 10. (*continued*).

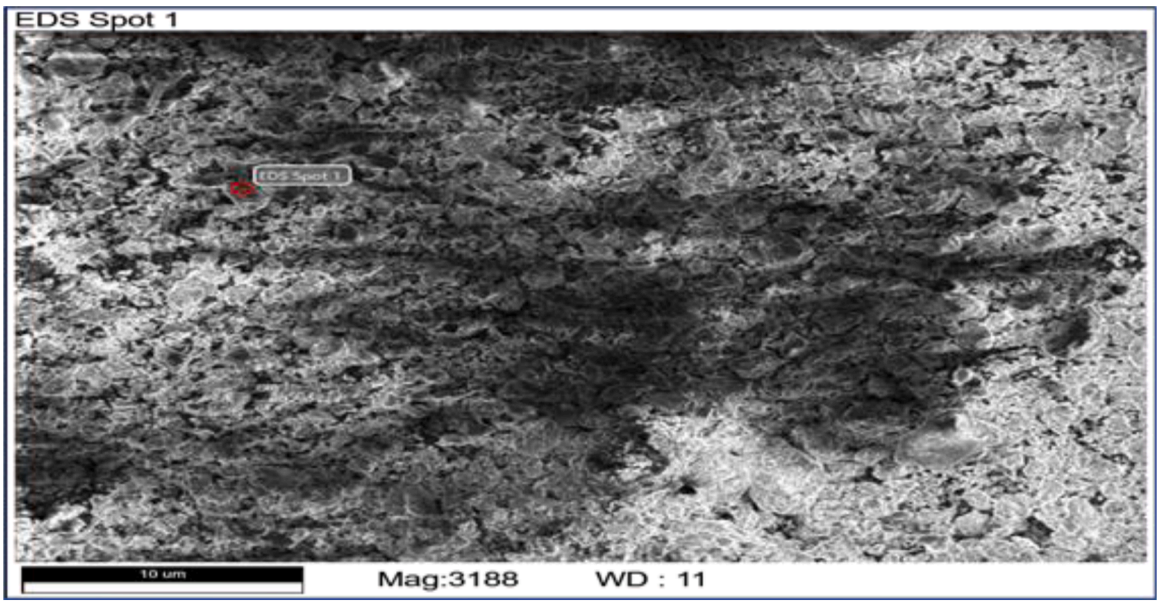
CEM I, however, produced slightly better performance in terms of reduction in plasticity index than CEM II and CEM III.

By increasing the percent of cement, there was increase in the values of both maximum dry unit weight and optimum water content in comparison with the untreated soil by the three cements. Again, the variation in maximum dry unit weight between the three types of cement was not overly large.

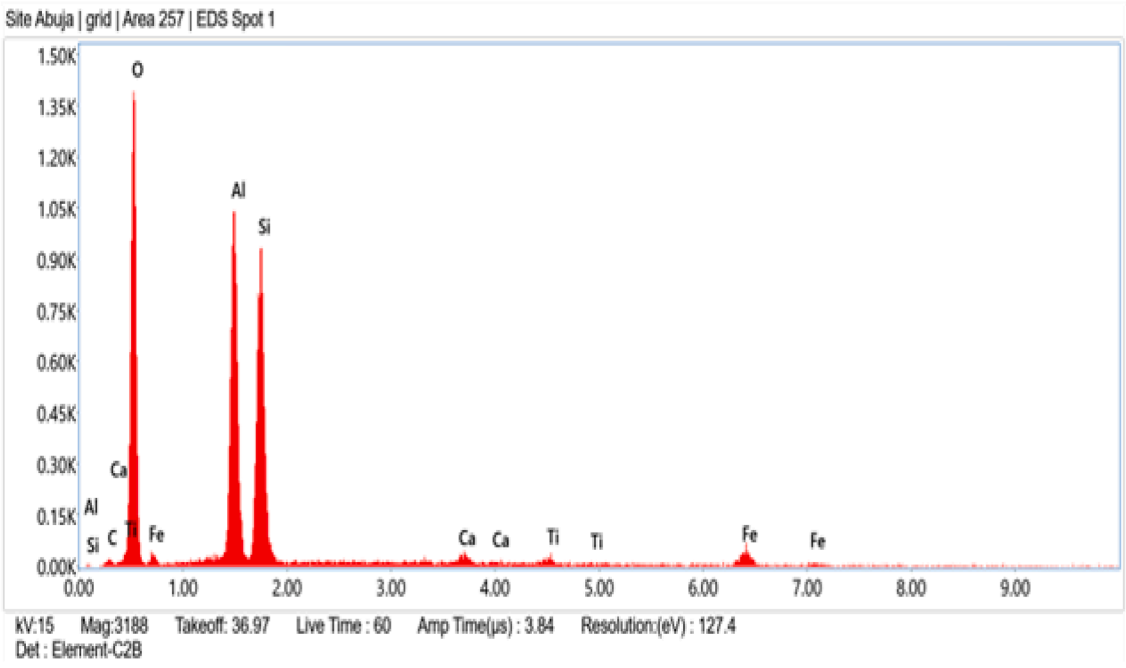
Regardless of the cement type, there was an overall improvement in the strength properties of this grade lateritic soil represented by a range of 11 – 14 times for UCS and 31 - 62 folds for E_{50} at 12 % cement after 90 days curing duration in comparison with the untreated soil. While strength gain is higher in CEM I cement at early ages (7 days), the strengths of mixtures containing CEM II and CEM III cements exceeded the strengths of CEM I mixture with CEM III eventually providing superior strength gains at 90 day curing period. Furthermore, the failure strain (ε_f) which distribute in the range of 0.6 to 4.95 %, basically diminished with the rising cement content as well as the curing duration.

The outcome of analysis of variance (ANOVA) indicate that both cement content and type had statistically significant ($p < 0.05$) effects in the characteristics of liquid limit, optimum moisture content and UCS at 28 and 90 days curing ages of investigated mixtures.

In the study, a grade of lateritic soil classified as MH was used, therefore, the results obtained are only applicable to this grade of lateritic soil. Hence, further research is recommended to investigate the effectiveness of these cement types in other grades of lateritic soil.



(g)



(h)

Fig. 10. (*continued*).

Table 7
EDX atomic and weight concentration of major elements in soil mixtures at 7 days.

Element name/Symbol	Unstabilized soil		CEM I		CEM II		CEM III	
	Atomic conc. (%)	Wt. conc. (%)	Atomic conc. (%)	Wt. conc. (%)	Atomic conc. (%)	Wt. conc. (%)	Atomic conc. (%)	Wt. conc. (%)
Oxygen, O	64.25	55.53	69.44	61.10	56.79	50.03	10.00	47.13
Aluminum, AL	11.03	16.07	10.16	15.07	2.33	3.46	13.55	18.17
Iron, Fe	1.10	3.31	–	–	1.59	4.88	2.67	7.40
Calcium, Ca	–	–	1.14	2.51	0.28	0.61	0.78	1.55
Titanium, Ti	0.31	0.80	9.53	6.29	–	–	0.61	1.45
Carbon, C	12.79	8.31	9.53	6.29	21.97	14.53	10.0	5.97
Magnesium, Mg	–	–	–	–	0.36	0.49	–	–
Silicon Si	–	–	–	–	16.36	25.30	13.13	18.33
Potassium, K	–	–	–	–	0.70	0.33	–	–

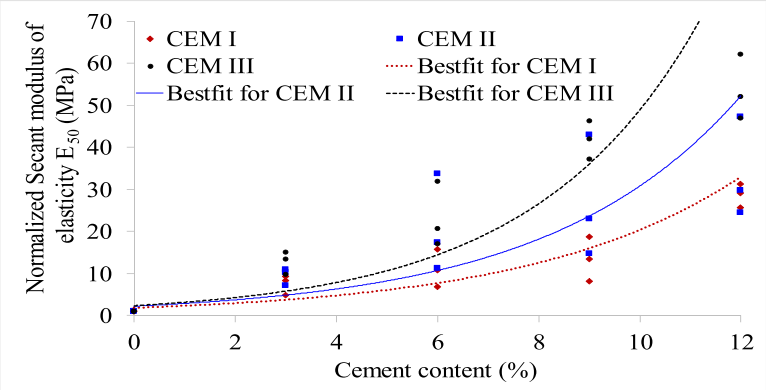


Fig. 11. Variation of normalized secant modulus of soil mixtures with cement content.

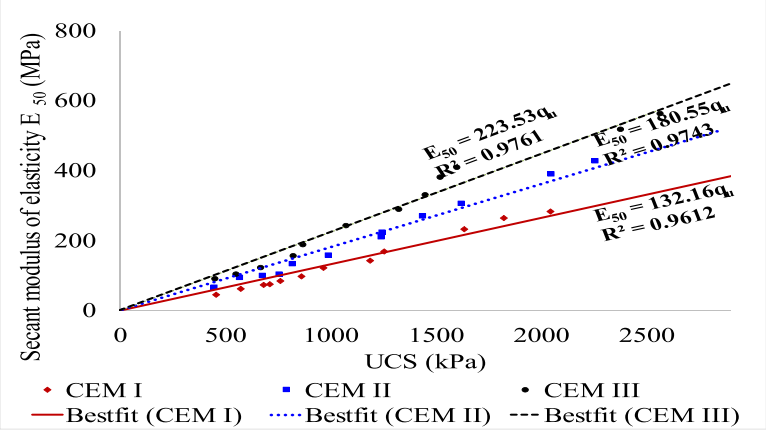


Fig. 12. Relationship between secant elastic modulus (E50) and UCS.

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Code availability

Not Applicable.

CRediT authorship contribution statement

A.A. Amadi: Writing – review & editing, Supervision, Investigation, Data curation, Conceptualization. **S.S. Kolo:** Supervision, Data curation. **A. Yusuf:** Writing – original draft, Data curation. **F.E. Eze:** Writing – original draft, Investigation. **U. Salihu:** Writing – original draft, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] S. Horpibulsuk, A. Suddeepong, P. Chamket, A. Chinkulkijviwat, Compaction behavior of fine-grained soils, lateritic soils and crushed rocks, Soils Found. 53 (1) (2013) 166–172, https://doi.org/10.1016/j.sandf.2012.12.012, 2013.

[2] N.A. Wahab, A.S.A. Rashid, M.J. Roshan, N.H.A. Rizal, N.Z.M. Yunus, M.A. Hezmi, M.Y.M. Tadza, Effects of Cement on the Compaction Properties of Lateritic Soil, in: IOP Conf. Ser.: Mater. Sci. Eng. 1153, 2021 012015, https://doi.org/10.1088/1757-899X/1153/1/012015.

[3] R.K. Etim, D.U. Ekpo, G.E. Udofia, I.C. Attah, Evaluation of lateritic soil stabilized with lime and periwinkle shell ash (PSA) admixture bound for sustainable road materials, Innov. Infrastruct. Solut. 7 (2022) 62, https://doi.org/10.1007/s41062-021-00665-z.

[4] P. Sudla, J. Donrak, M. Hoy, S. Horpibulsuk, Laboratory investigation of cement-stabilized marginal lateritic soil by crushed slag–fly ash replacement for pavement applications, J. Mater. Civ. Eng. 32 (2020) 1–11, https://doi.org/10.1061/(ASCE)MT.1943-5533.0003011.

[5] A.A. Amadi, O. Odedede, Attenuation of contaminants in landfill leachate by lateritic soil enhanced with bentonite, Geomech. Geoeng.: Int. J. 16 (5) (2021) 348–358, https://doi.org/10.1080/17486025.2019.1670872.

[6] R. Kufre Etim, D. Ufot Ekpo, I. Christopher Attah, K. Onyelowe, Effect of Micro sized quarry dust particle on the compaction and strength properties of cement stabilized lateritic soil, Clean. Mater 2 (2021) 100023, https://doi.org/10.1016/j.clema.2021.100023.

[7] M.J. Roshan, A.S.B.A. Rashid, M.A.B. Hezmi, M.N. Nejabi, S.N. Josuh, R. Razali, Evaluation of cement stabilised residual soil on macro- and micro-scale for road construction, J. Eng. Appl. Sci. 69 (2022) 109, https://doi.org/10.1186/s44147-022-00165-6, 2022.

[8] S.M. Lim, K. Yao, Y.B. Jiang, Z.C. Lim, I.H. Baker, Geotechnical characteristics of lateritic clay admixed with biomass silica stabilizer, J. Clean. Prod. 321 (2021) 129008, https://doi.org/10.1016/j.cscm.2022.e00947.

[9] C. Suksiripattanapong, K. Jenpiyapong, S. Tiyasangthong, B. Krittacom, C. Phetchuay, W. Tabyang, Mechanical and thermal properties of lateritic soil

mixed with cement and polymers as a non-bearing masonry unit, Case Stud. Constr. Mater. 16 (2022) e00962, https://doi.org/10.1016/j.cscm.2022.e00962.
[10] E. Mengue, H. Mroueh, L. Lancelot, R.M. Eko, Mechanical improvement of a fine-grained lateritic soil treated with cement for use in road construction, J. Mater. Civ. Eng. 29 (2017) 1–22, https://doi.org/10.1061/(ASCE)MT.1943-5533.0002059.
[11] D.R. Biswal, U.C. Sahoo, S.R. Dash, Fatigue characteristics of cement-stabilized granular lateritic soils, J. Transp. Eng. Part B Pavem. 146 (2020) 04019038, https://doi.org/10.1061/JPEODX.0000147.
[12] P. Chindaprasirt, A. Kampala, P. Jitsangiam, S. Horpibulsuk, Performance and evaluation of calcium carbide residue stabilized lateritic soil for construction materials, Case Stud. Constr. Mater. 13 (2020) e00389, https://doi.org/10.1016/j.cscm.2020.e00389.
[13] N.C. Consoli, D. Párraga Morales, R.B. Saldanha, A new approach for stabilization of lateritic soil with Portland cement and sand: strength and durability, Acta Geotech. 16 (2021) 1473–1486, https://doi.org/10.1007/s11440-020-01136-y.
[14] M. Joel, I.O. Agbede, Mechanical-cement stabilization of laterite for use as flexible pavement material, J. Mater. Civ. Eng. 23 (2) (2010) 146–152, https://doi.org/10.1061/(ASCE)MT.1943-5533.0000148.
[15] S.H. Chew, A.H.M. Kamruzzaman, F.H. Lee, Physicochemical and Engineering Behavior of Cement Treated Clays, J. Geotech. Geoenviron. Eng. 130 (2004) 696–706, https://doi.org/10.1061/(ASCE)1090-0241(2004)130:7(696).
[16] T.A. Biyindi, F.K. Mbakop, E. Toumi, B.W. Etonleu, J. Pondi, Comparative physico mechanical study of cements CEM II 42.5R in Cameroon: case of DANGOTE and CIMENCAM, Open J. Civ. Eng. 9 (2019) 18–34, https://doi.org/10.4236/ojce.2019.91002.
[17] T. Vu, V. Dang, Q. Ngo, L. Ho, Influence of some factors on the mechanical properties of cement-treated clay for shallow mixing in Vietnam: a comparative study, Result. Eng. 17 (2023) 101011, https://doi.org/10.1016/j.rineng.2023.101011. Online publication date: 1-Mar-2023.
[18] EN 197-5, Cement—Part 5: Composition, Specifications and Conformity Criteria for Portland-Composite Cement and Composite Cement, 2021. Available online, https://standards.iteh.ai/catalog/standards/sist/93368845-504d-4e50-bab7-e32d1a6f6d6f/sisten-197-5-2021. accessed on 10 September 2021.
[19] D. Wang, L.L. Olowokere, D. Zhang, Interpretation of soil-cement properties and application in numerical studies of ground settlement due to tunneling under existing metro line, Geotechn. Geolog. Eng. 32 (5) (2014) 1275–1289, https://doi.org/10.1007/s10706-014-9803-2.
[20] S. Pongsivasathit, S. Horpibulsuk, S. Piyaphipat, Assessment of mechanical properties of cement stabilized soils, Case Stud. Construct. Mater. 11 (2019) e00301, https://doi.org/10.1016/j.cscm.2019.e00301.
[21] J. Gu, H. Lyu, J. Yang, C. Zeng, Effects of cement content and curing period on geotechnical properties of cement-treated calcareous sands, Transport. Geotech. 33 (2022) 100732, https://doi.org/10.1016/j.trgeo.2022.100732. Online publication date: 1-Mar-2022.
[22] S.M. Haeri, A. Hamidi, S.M. Hosseini, E. Asghari, D.G. Toll, Effect of cement type on the mechanical behavior of gravely sand, Geotechn. Geolog. Eng. 24 (2) (2006) 335–360, https://doi.org/10.1007/s10706-004-7793-1.
[23] British Standards Institution, BS 1377:1990 British Standard Methods of Test for Soils for Civil Engineering Purposes-Part 7: Shear Strength Test, 1999.
[24] M.A. Ismail, H.A. Joer, W.H. Sim, M. Randolph, Effect of cement type on shear behaviour of cemented calcareous soil, in: J Geotech Geoenviron Eng, 128, ASCE, 2002, pp. 520–529, https://doi.org/10.1061/(ASCE)1090-0241(2002)128:6(520, 2002.
[25] I.T. Jawad, M.R. Taha, Portland cement treated soil: evaluation and conflict results, Civ. Eng. Architect. 11 (2) (2023) 560–568, https://doi.org/10.13189/cea.2023.110203.
[26] F. Sariosseiri, B. Muhunthan, Effect of cement treatment on geotechnical properties of some Washington State soils, Eng. Geol. 104 (1–2) (2009) 119–125, https://doi.org/10.1016/j.enggeo.2008.09.003.
[27] M.S. Al-Zoubi, Undrained shear strength and swelling characteristics of cement treated soil, Jordan J. Civ. Eng. 2 (1) (2008) 53–62.
[28] A. Sharo, A. Alawneh, H. Al zghool, S. Rabab'ah, Effect of alkali-resistant glass fibers and cement on the geotechnical properties of highly expansive soil, J. Mater. Civ. Eng. 34 (2022) 2, https://doi.org/10.1061/(ASCE)MT.1943-5533.0004058. Online publication date: 1-Feb-2022.
[29] X. Wang, X.;. Dong, Z. Zhang, J. Zhang, G. Ma, X. Yang, Compaction quality evaluation of subgrade based on soil characteristics assessment using machine learning, Transp. Geotech. 32 (2022) 100703, https://doi.org/10.1016/j.trgeo.2021.100703, 2022.
[30] T. Rudnicki, The influence of the type of cement on the properties of surface cement concrete, Mater. (Basel) 15 (2022) 4998, https://doi.org/10.3390/ma15144998.
[31] T.O. Ho, W.B. Chen, J.H. Yin, P.C. Wu, D.C.W. Tsang, Stress-strain behaviour of cement-stabilized Hong Kong marine deposits, Construct. Build. Mater. 274 (2021) 122103, https://doi.org/10.1016/j.conbuildmat.2020.122103.
[32] N.A. Wahab, M.J. Roshan, A.S,A. Rashid, M.A.B. Hezmi, S.N. Josuh, Norsyahariati, S. Tamassoki, Strength and durability of cement-treated lateritic soil, Sustainability 13 (11) (2021) 6430, https://doi.org/10.3390/su13116430.
[33] Z. Dingwen, F. Libin, L. Songyu, D. Yongfeng, Experimental Investigation of Unconfined compression strength and stiffness of cement treated salt-rich clay, Mar. Georesour. Geotechnol. 31 (2013) 360–374, https://doi.org/10.1080/1064119X.2012.690826.
[34] H. Cai, C. Chen, S. Wei, S. Zhu, Strength development of cemented soil cured in water-air conditions at varied temperatures: experimental investigation and model characterization, J. Mater. Civ. Eng. 35 (2023) 3, https://doi.org/10.1061/(ASCE)MT.1943-5533.0004631. Online publication date: 1-Mar-2023.
[35] G.A. Lorenzo, D.T. Bergado, Fundamental characteristics of cement-admixed clay in deep mixing, J. Mater. Civ. Eng. 18 (2006) 161–174, https://doi.org/10.1061/(ASCE)0899-1561(2006)18:2(161), 2006.
[36] G.G. Balmer, Shear strength and elastic properties of soil-cement mixtures under Triaxial loading, in: Proceedings of American Society for Testing Materials by Portland Cement Association, Research and Development Laboratories, 1958, pp. 1187–1204.
[37] J.L. Briaud, P. Nicholson, J. Lee, Behavior of a full-scale VERT wall in sand, J. Geotechn. Geoenviron. Eng. 126 (9) (2000) 808–818.
[38] Z. He, X. Zhu, J. Wang, M. Mu, Y. Wang, Comparison of CO2 emissions from OPC and recycled cement production, Constr. Build. Mater. 211 (2019) 965–973, https://doi.org/10.1016/j.conbu ildmat.2019.03.289.
[39] J. Zhang, G. Liu, B. Chen, D. Song, J. Qi, X. Liu, Analysis of CO_2 emission for the cement manufacturing with alternative raw materials: a LCA-based framework, Energy Proced. (2014), https://doi.org/10.1016/j.egypro.2014.12.041.
[40] G. Van Rompaey, Ph.D. Thesis, Université libre de Bruxelles, Faculté des Sciences–Sciences de la Terre et de l'Environnement, Bruxelles, Belgium, 2006.