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Engineering Structural Strength Properties of Lateritic Soil-Cement Mix for Road Pavement Stability

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Abstract

Qualitative construction materials in highway pavement prompted addition of cement at different proportion of 2 - 10% to lateritic soils for enhanced performance. Engineering geological tests were performed on the soil-cement mixture to determine their highway pavement suitability for durable road construction. Furthermore, modelling of the strength characteristics of the mixture presents the correlation between the structural properties and cement mix. Thus, increase in soil-cement California bearing ratio (CBR) and unconfined compressive strength (UCS) values with higher cement mix of 8%, revealed enhanced soil improvement. The soil strength is also affected by the curing period. Better quality strength characteristics obtained decreases pavement thickness with reduced cost in road construction. Relationship between the soil strength properties and cement mix content are represented by polynomial model. This reveals stronger bearing capacity of soil cement mix cured in 14 days with R2 ≥ 0.8. The lateritic soil cement mix at 8% cement content could serve as highway subbase and base construction materials. Cement mix having positive effects on soil geotechnical properties are indication of its effectiveness in enhancing volume stability of different soils. Prolong curing time is essential for compacted soil cement mix for enhanced geotechnical engineering properties and to improve the quality of lateritic soil used as road construction materials. Thus, cement-stabilized lateritic soil reduces cost of road construction, its persistent failure, human and environmental losses.

Keywords: Crushed rock, Curing period, Highway construction, Lateritic soil cement, Soil improvement, Structural properties.

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Ethical: This study followed all ethical practices during writing.

Contents

Contribution of this paper to the literature:
This study unravels the intrinsic reasons for failure of engineering structures constructed with lateritic soil prior the expiration of the design age. The soil inconsistent engineering properties necessitated its stabilization with cement for improved quality soil suitable for durable and sustainable road pavement construction. Bearing capacity of the soil-cement mix improved with prolong curing time.

1. Introduction

Construction of civil engineering works on geomaterials (soil or rock) dictates its structural performance. Soils support structures, pavement for highways, airport and dams. Some existing soils may be used in their natural state, while others may require stabilization which modifies its engineering properties, producing better breed of construction materials capable of meeting the specific requirements. Lack of standard construction materials has necessitated the search for local alternatives. In tropical and subtropical areas, lateritic soils rich in aluminium, iron appear as surface soil deposits formed from physical and chemical weathering of pre-existing rocks. Laterites in Nigeria serve as foundation materials in construction of civil engineering works without due consideration to its geotechnical behaviour and site performance. Poor subsoil engineering structural characteristics accounts for unstable highway sections in Nigeria [1]. The inconsistency of soil engineering properties prompted consistent soil test for update subsoil information to establish the most suitable soil stabilization method prior highway design and construction. Utilization of soils for a particular purpose depends on factors affecting their performance and in-depth knowledge of their geotechnical properties. Engineering structures constructed with lateritic soil experience failure before the expiration of the design age and this has necessitated soil stabilization for quality soil. Commonly used additives to enhance soil quality are lime, cement, fly ash, cement kiln dust, rock flour and other forms of stabilizers. Clay swells in water, shrinks when dry and thrives in freezing conditions. This makes them unnoticeable when used [2]. Most lateritic soils contain high proportion of clay, thus, their properties should be improved. Soil modification requires different methods of improving engineering performance of soil for suitability for different construction purposes. Cement and lime are major additives for improving granular and fine-grained soils, weak/soft soils, problematic soils and generally poor properties soils. Despite this, the use of cement as a stabilizer is well-known than lime due to factors of its availability, cost and strength that are attainable using cement. Higher strength is attained using cement than using the same quantity of lime [3]. Recently, in an attempt to achieve an economically effective modification of deficient soils, available locally generated waste materials are utilized to strengthen weak soil for appropriate performance. This form of soil stabilization emphasizes best use of local materials to minimize civil engineering construction cost as well as reducing the environmental hazards they cause. However, most of these materials do not have adequate cementation property required to bind the materials to an acceptable performance for sustainable road pavements as cement. Hydration reaction associated with cement enables the improvement of soil properties. Soil and rocks, under load beyond their bearing capacity fail [4]. Natural resources depletion as a result of consistent exploration has prompted the usage of readily available construction material for conservation of these resources. Road pavement construction with quality materials results in high cost of construction. Thus, this research investigates engineering properties improvements of lateritic soil cement mix with intent to establishing its suitability in road pavement construction.

2. Study area Location and Geology

The study area (Ibadan-Iwo-Osogbo highway and its environs) lies in the southwestern part of Nigeria, lies between 7° 37.50' N to 7° 48.18' N latitudes and 4° 10' E to 4° 30' E longitudes. The road trends southwest to northeast direction and spreads approximately 86 km (Figure 1). Settlements around this major highway are linear, drained by many rivers and their tributaries with dendritic drainage pattern [5]. The aquiferous units of the area and typical basement geologic setting are weathered layer and the fractured bedrock. The area witnesses dry and rainy seasons of annual rainfall of 1,600 mm. The area undergoes undulating topography and is characterized by rain forest tropical zone with evergreen forest type of vegetation.

The area of study falls in the Precambrian geological complex terrain of Nigeria with diverse rock types encompassing migmatite gneiss in the age of 2700 Ma (Archean) to 2000 Ma (Proterozoic) [6]. Geologic rock units of this complex terrain is dominated in a triangular segment that forms the African crystalline basement rocks affected by geotectonic activities [7]. This extends to part of West African Craton. The rock units of the area are within the migmatite-gneiss-quartzite complex, characterized majorly by ultramafic, felsic and charnockitic rocks [8]. These rock types have undergone series of deformation and metamorphism from 2000 Ma (Early Proterozoic) to approximately 600 Ma [9]. The highway cuts through major noticeable rock types in the area as shown in Figure 2. Migmatite gneisses in the area are mostly differentiated by medium grained well classified bands of diverse mineralogical composition [10]. In the area, weathering of gneiss, migmatite and granite resulted into formation of lateritic-soil with quartz, hornblende, biotite, microcline and plagioclase feldspars as the major mineralogical composition. The formation and composition of the lateritic soil varied over the parent rocks. The clay minerals constituents present in lateritic soils are kaolinite, montmorillonite and chlorite. Other non-clay minerals present are quartz, feldspar, mica and goethite [11]. The presence of clay minerals derived from underlying rocks also necessitates the modification of the soil with cement for improved performance in road construction.

3. Materials and Study Methods

3.1. Soil-Cement Mix Materials

The soil-cement mix materials are cement, lateritic soil and water. They are the three basic materials needed to produce soil-cement mixture.

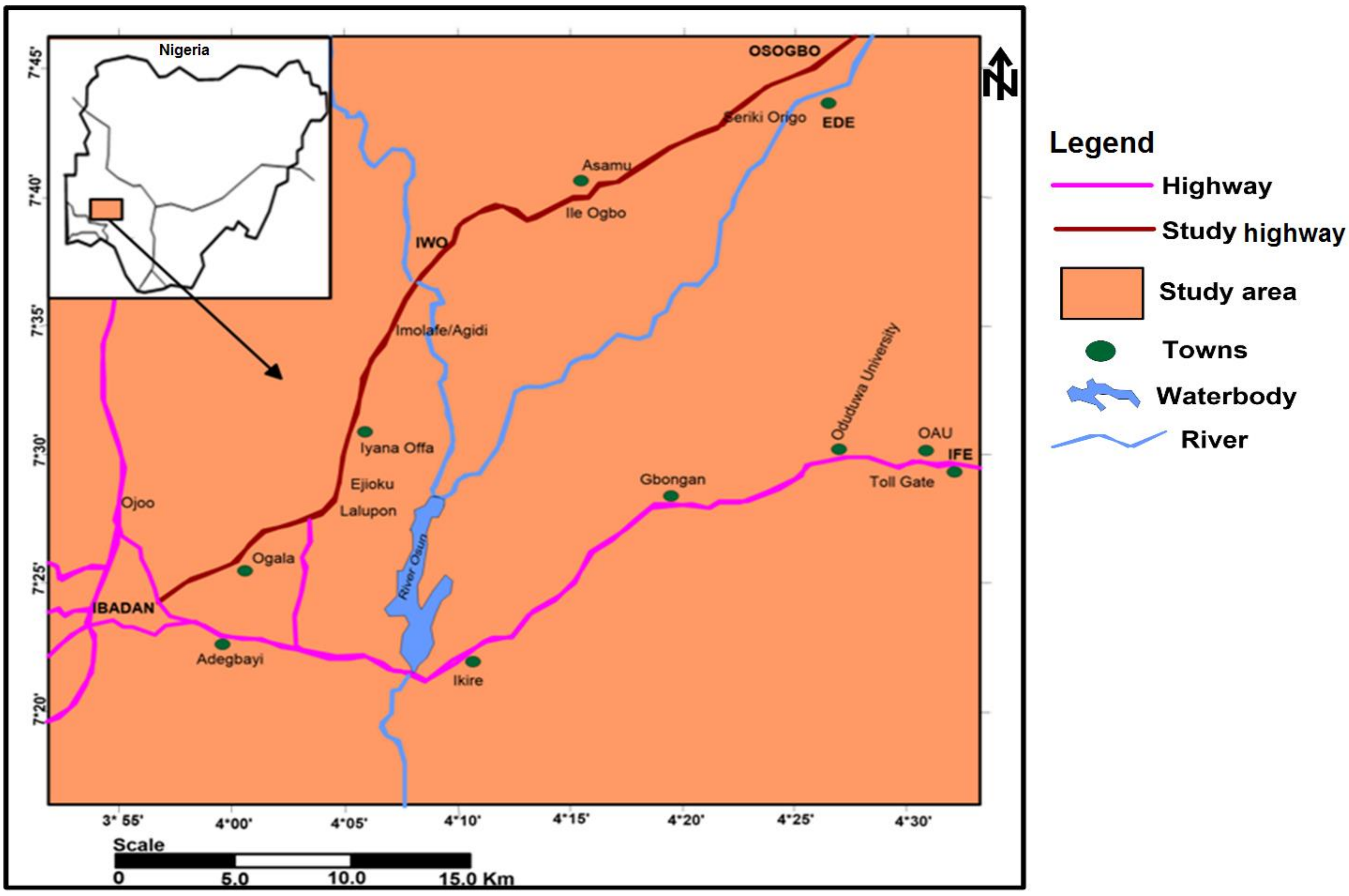


Figure 1. Location map of area of study.

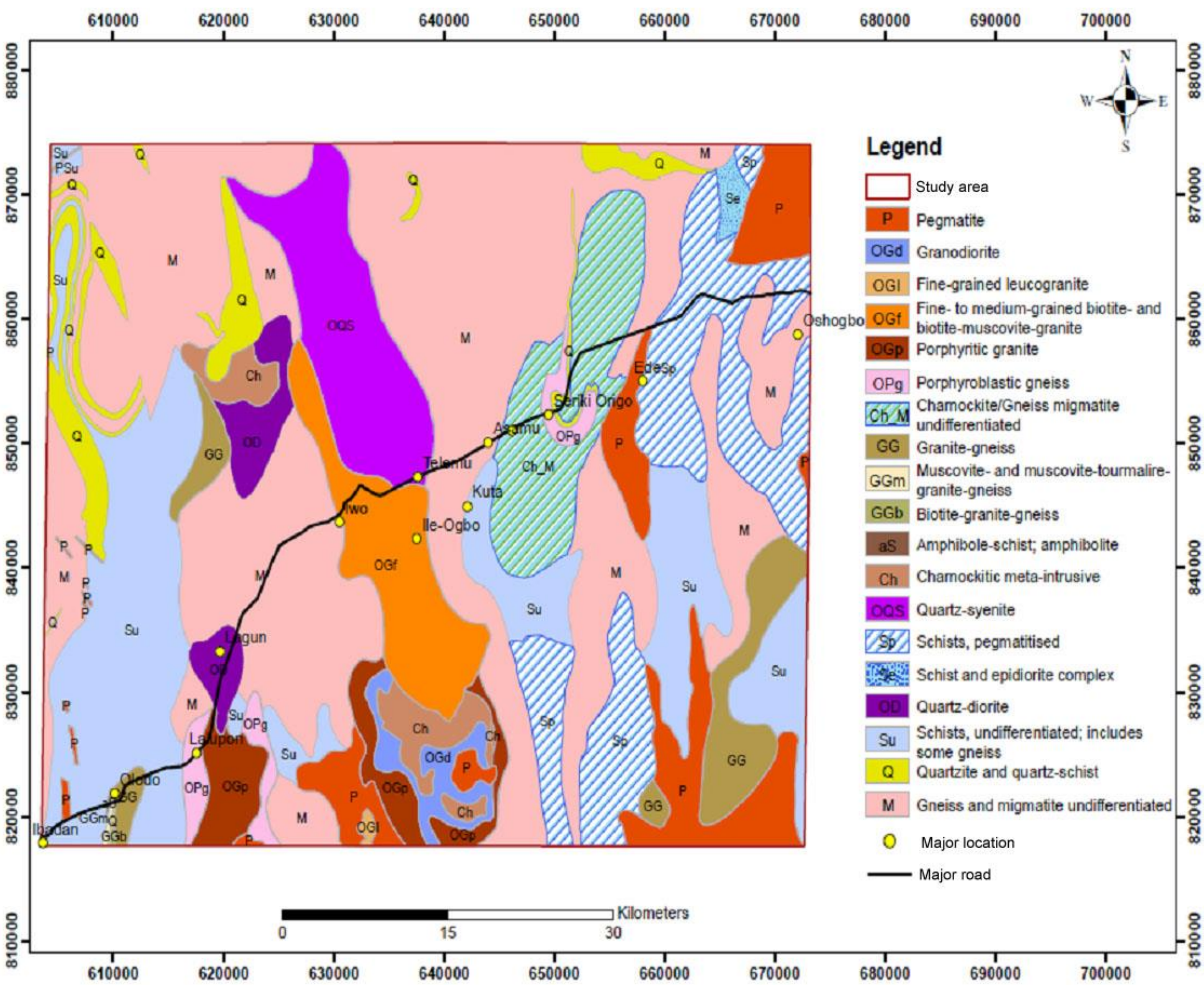


Figure 2. Ibadan-Iwo-Oshogbo Highway and environs geological map.

3.1.1. Lateritic Soils

They are weathered, decomposed residual soils, which occur as surface deposits. They are distinguished by aluminum and iron oxides. Lateritic soils may contain clay minerals; but they tend to leach out silica by water passing through the soil. Lateritic soils have high clay content and lower cation exchange capacity. They have high clay content, thus, with water retention capacity. Their formation from intense and prolonged weathering of the underlying parent rocks under strongly oxidizing and leaching conditions make them consist of less minerals and organic materials. Formation of laterites under continuously wet regions characterized them with moist and irretrievable alteration when dried, while, those formed in regions of alternating wet and dry seasons have low plasticity, moisture content, cemented and compaction horizons. Engineering properties of this soil are influenced by presence of sesquioxides (iron and aluminum oxides) thereby coating the soil particles. The research was carried out on ten bulky samples of lateritic soil collected from different parts of the area with each sample at depth range of 1.5 - 2 m. This is to ensure true representation of subsoil beneath this highway in a systematic order to reflect full coverage of the entire area. Global positioning system (GPS) was employed to record the coordinates and elevation of all sampling points. All samples obtained were cautiously labelled for laboratory analysis. The lateritic soil properties are presented in Table 1.

Table 1. Lateritic soil properties.

Soil properties		Outcome
Soil colour		Brown to reddish brown
Specific gravity		2.68 ± 0.04
Clay content (%)		30.7 ± 7.7
Moisture/water content (%)		6.6 ± 1.3
Plasticity limit (%)		20.9 ± 2.3
Liquid limit (%)		32.0 ± 6.0
Soil plasticity index (%)		11.2 ± 4.3
American association of state highway and transportation officials (AASHTO) classification		A-2-4 till A-7-6
Unified soil classification system (USCS)		CL–ML and CL or OL
Soil optimum moisture content		15.30 ± 3.10 (%)
Soil maximum dry density		1.87 ± 0.11 (Mg/m³)
Soil California bearing ratio	Unsoaked	40.8 ± 18.6 (%)
	Soaked	28.5 ± 12.8 (%)
Unconfined compressive strength (kN/m²)		145.7 ± 19.0

3.1.2. Portland Cement

Portland cement was employed in this work as binder in soil stabilization. This conformed to British Standard Code of Practice BS 12 [12] standard as stabilizing agent. It was examined from different engineering tests for road pavement suitability. The soil response to varying cement content is the focus of this study. It attempts to establish the effects of cement content increase on the soil strength characteristics.

3.1.3. Borehole Water

Borehole water in line with British Standard Code of Practice BS 3148 [13] standard was utilized in this study.

3.1.4. Soil-Cement Mixtures

Soil cement is a combination of Portland cement, powdered soil and water. Soil-cement mixtures were formed by carefully mixing dry pulverized soil and cement to a required homogeneous paste with cement content in the range 2 – 10% of the dry soil. Measured water from moisture-density analysis was added to the dry soil cement mix (paste) for compaction. 8% quantity of Portland cement is required to adequately improve and harden the lateritic soils.

3.2. Test Methods

The soil water content was determined at the laboratory and thereafter dried for further analysis. Lumps in the soil were pulverized after two weeks of drying. This was intended to allow them retail their initial grain sizes. Geotechnical tests were carried out on soil samples following British Standard (BS) 1377 [14] test procedures. Soaked soil samples in weak Calgon solution helps separate the soil grains in the process of wet sieving. Soil sedimentation test was performed using hydrometer method by Stokes law.

3.2.1. Atterberg Limits Test

The soil samples were subjected to Atterberg limit tests; plastic limit (PL), liquid limit (LL), and plasticity index (PI) in order of ASTM D4318 [15] standard technique. The Casagrande method was employed in determining the values of liquid limit (soil change from liquid to plastic form) corresponding to water content arising from change in volume of soil behaving as in liquid form. Likewise, plastic limit (PL) determination corresponds to water content at point of soil change from flexible plastic to semi-solid form. The soil at this point rolled in a form of threads of diameter of about 3 mm and crumbled. The plastic limit is also the crumbling point where the moisture content of crumbled soil placed in a moisture container was determined. Water content range between liquid limit and plastic limit represents the plasticity index, which specifies the extent of soil plasticity.

Linear shrinkage (LS) is the reduction in soil sample length when dried from its original state. It aids in evaluating soil suitability as construction material in roads, building foundations and other civil engineering works. A pycnometer was used in determining the soil specific gravity values.

$$\text{Linear shrinkage (LS)} = (L_o - L_1)/L_o \times 100\% \quad (1)$$

Where L_o = initial soil length, while L_1 = final dry soil length.

3.2.2. Compaction Test

This test determines the soil maximum dry density (MDD) and optimum moisture content (OMC) according to ASTM D698 [16] testing procedure, using standard Proctor energy level. These tests were performed on natural and stabilized soils at different percentages of cement mix content. In these tests, weight of the compaction mould and soil compacted were noted. From the test, moisture content was derived from top and bottom compacted soil samples. This was done repeatedly for the unstabilized soils and those stabilized with 2%, 4%, 6%, 8% and 10% cement upon which their MDD and OMC were established.

3.2.3. Unconfined Compression Test

Stabilized soil strength was achieved by performing unconfined compressive strength (UCS) test. Thus, characteristics of structural load distortion can be measured in determining its strength. These natural and stabilized soils were compressed in moulds of 1000 cm^3 at their OMC values. Unconfined compressive strength tests performed on the compacted soil samples from the moulds were cured for 7 and 14 days respectively according to ASTM D2166 [17] stipulations in a triaxial machine. At expiration of curing, the samples were de-waxed and centrally positioned at the compression testing machine lower plate and subjected to a compressive force at 1%/min strain control. The soil UCS was thereafter noted and recorded from the stress–strain curve at the point where failure occurred. Load and deformation were then measured and this gives insight into the relationship between stress-strain.

3.2.4. CBR Test

CBR (California bearing ratio) a penetration test for assessing strength of road subgrade and pavements. It is carried out on soil samples (soaked and unsoaked) with their OMC and MDD respectively as stipulated by ASTM D1883 [18] testing procedures.

4. Results of Study and Discussion

4.1. Index Properties of Soil

Grain size distribution analysis of the lateritic soils showed gravel content in the range 1.3 – 28.7 % Table 1. Sample 3B is characterized with highest gravel content and lowest fines. Despite the pressure heave characterized by clay-rich soil [19] with clay amount of about 30.7 ± 7.7% Table 1 70% of lateritic soils analyzed are within acceptable range of Nigerian General Specifications for highways [20] of not exceeding 35% clay content. The soils specific gravity is in the range 2.64 – 2.75 with an average of 2.68 ± 0.04 Table 1. The values are within 2.60 and 2.80 standard range [21]. Coarse soil is characterized by lower specific gravity, while fine grained soil is of higher values. The specific gravity of soils in this area exceeds the recommended [20] value of 2.2 for bridges and roads.

Atterberg limit values shown in Table 1 is consistent with the classification of soil and determines the shrink/swell potential as well as clay mineralogy of a soil [22]. The liquid limit ranged from 24.0 – 40.8% with mean value of 32.0 ± 6.0%, the plastic limit ranged from 17.4 – 24.1% with mean value of 20.9 ± 2.3% and the plasticity index of the soils is in the range 7.0 – 17.5% with mean value of 11.2 ± 4.3% Table 1. Some of the samples (samples 1A, 1C, 8A and 8B) are not suitable for subbase while most of them are unsuitable for base course materials due to their high liquid limit values greater than 35% and 30% maximum recommended for subbase and base course materials respectively [20]. The lateritic soils range in the group A-2-4 to A-7-6 classification of American Association of State Highway and Transportation Officials (AASHTO) [23] classification system rated as excellent to good and fair to poor subgrade highway materials. This implies that the soils (A-2) have clayey or silty gravel and sand proportion rated quality road construction materials and clayey soils (A-7) rated as poor construction materials (Table 2). Plasticity index of some of the soils are above 12%, which means they are unsuitable for road construction [20] thus, the need for soil stabilization. Based on the plasticity chart (plot of plasticity index versus liquid limit) as illustrated in Figure 3, the soils are inorganic in nature with low - medium plasticity. They fall in the category of CL and CL–ML (inorganic clayey/silty soil of low to medium plasticity) in line with Unified Soil Classification System.

Table 2. Soils classification and its aggregate mix.

General classification	**Granular materials (35% or less passing No. 200)**							**Silt-clay materials (More than 35% passing No. 200)**			
Group classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5' A-7-6
Sieve analysis, % passing:											
No. 10 (2.00 mm)	50 max	…	…	…	…	…	…	…	…	…	…
No. 40 (425 µm)	30 max	50 max	51 min	…	…	…	…	…	…	…	…
No. 200 (75 µm)	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing											
No. 40 (425 µm):											
Liquid limit	…		…	40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
Plasticity index	6 max		N.P.	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min[A]
Usual types of significant constituent materials	Stone fragments, gravel and sand		Fine Sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General rating as subgrade				Excellent to good				Fair to poor			

Note: [A] Plasticity index of A-7-5 subgroup is equal to or less than LL minus 30. Plasticity index of A-7-6 subgroup is greater than LL minus 30.

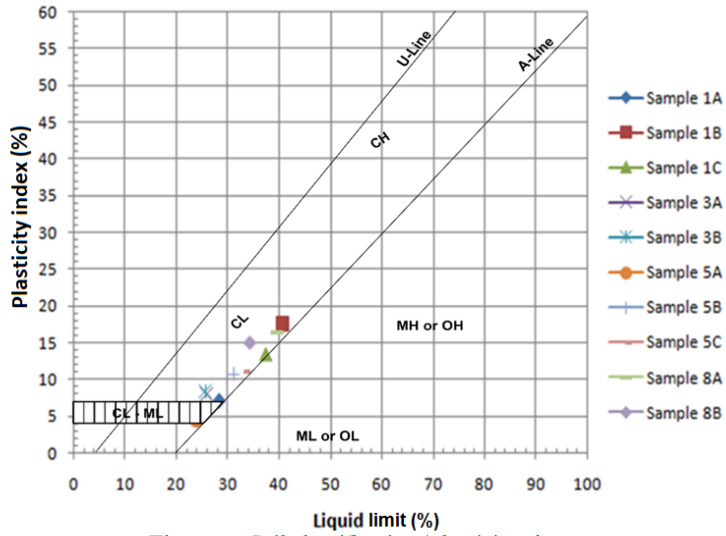


Figure 3. Soil classification/plasticity chart.

4.2. Compaction

Optimum moisture content (OMC) and maximum dry density (MDD) of compacted soils with addition of the different content of cement are shown as curves in Figure 4 and Figure 5. The addition of 2% cement resulted in MDD increase for all soils tested except for sample 3B, while increase from 4% to 10% cement content led to reduction in MDD of the soils. This indicates MDD reduction with corresponding cement increase in the soil above 2%. Reduction in MDD could be ascribed to soil coating by cement which act as soil void filler. Dry density increase is an indication of soil improvement, but in this case, reduction in dry density indicates the need for low compactive energy to achieve maximum dry density. OMC increases with increase in cement content from 8.99% to 16.07%, thus, reflects clay reduction, establishing coarser grains with bulky surface area. it can also be ascribed to more water in the flocculant soil matrix from the reaction of cement.

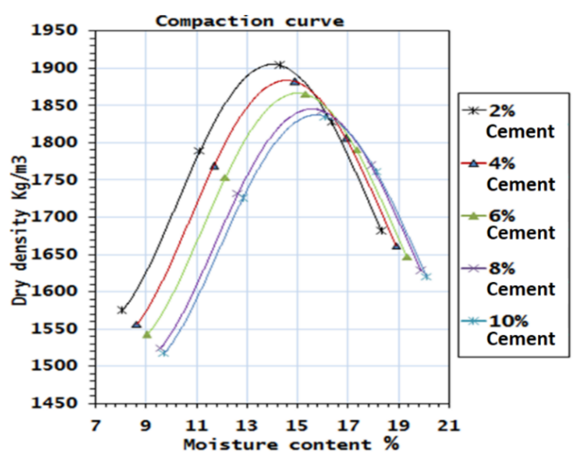


Figure 4. Soil sample 1A compaction curve.

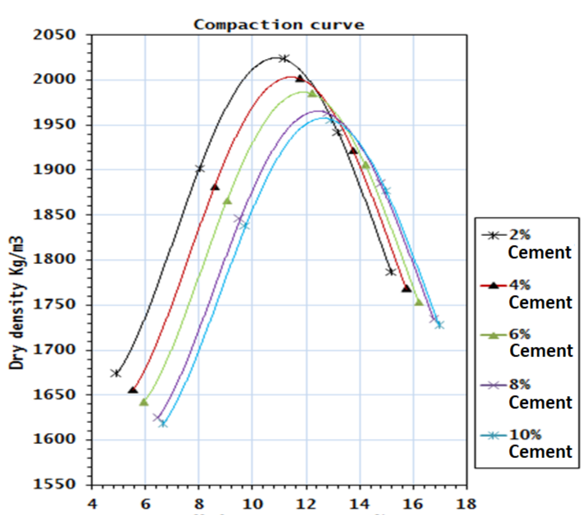


Figure 5. Soil sample 3B compaction curve.

4.3. CBR Result

Results of the unsoaked and soaked CBR values at 7 and 14 curing days for the lateritic soils stabilized with cement are illustrated in Figure 6a, 6b, 7a and 7b. They displayed CBR increase with increase in cement content. Chemical reaction between soil grains and cement results in an increase in CBR coupled with the soil compaction. Generally, there is increase in CBR (soaked and unsoaked) values with cement content increase from 0% till 8% for sample of soils cured for 7 and 14 days. Addition of cement content exceeding 8% resulted into CBR reduction, thus 8% cement soil mix is considered optimal for improved state of the soil.

From the results, cement soil mix cured in 14 days have stronger effect on soil bearing capacity/strength for road pavement construction. Addition of cement has improved soils to attain the requirements for subgrade and subbase in road construction [24]. This improvement reduces cost of road construction as thickness of pavement reduces.

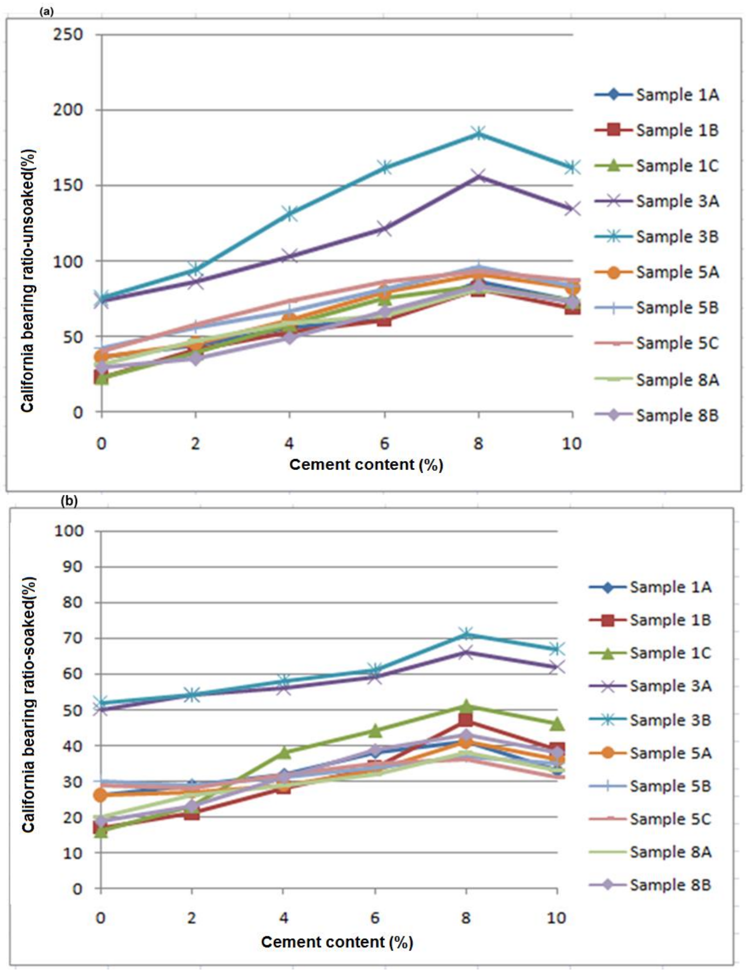


Figure 6. Cement content effect on unsoaked (a) and soaked (b) CBR cured soils in 7 days.

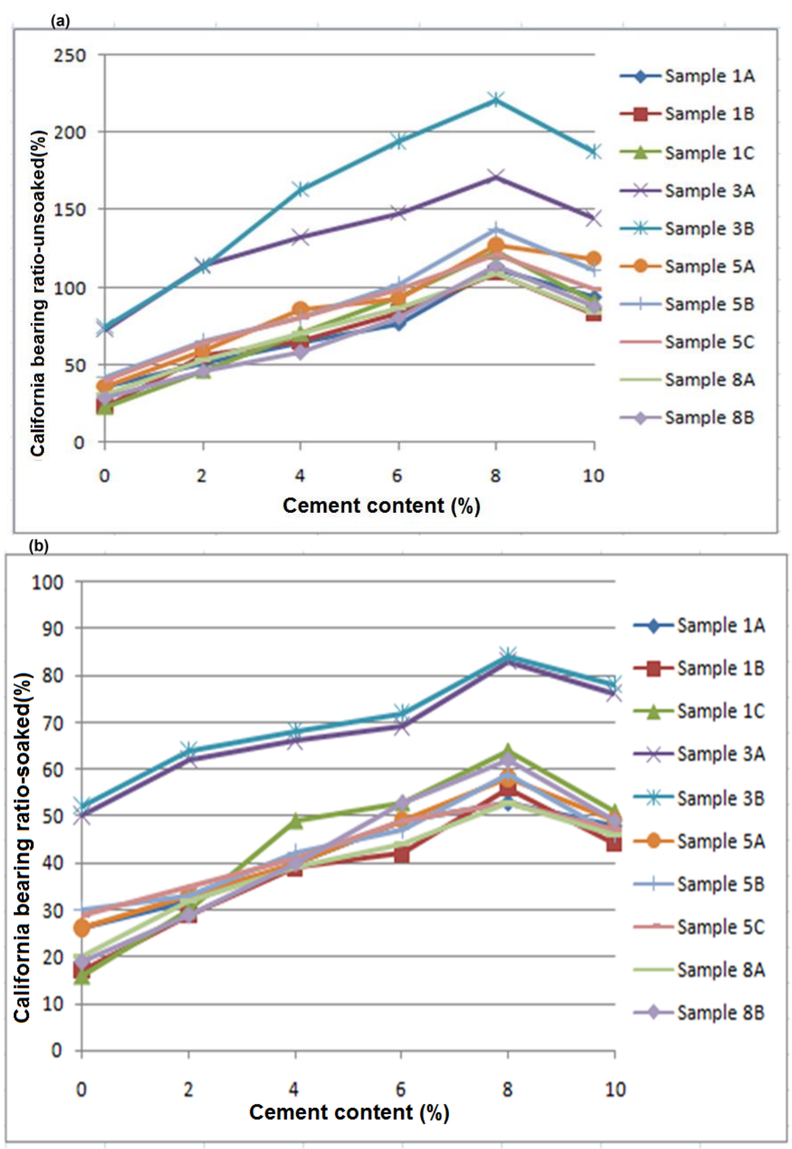


Figure 7. Cement content effect on unsoaked (a) and soaked (b) CBR cured soils in 14 days.

4.4. Unconfined Compression Test

The effect of curing on UCS values are pronounced as shown in Figure 8a and 8b. Cementation of the grains of soil led to increase in UCS as cement content increases. Also, increase in UCS values with cement content increase from 0% till 8% for sample of soils cured in 7 and 14 days. Addition of cement content exceeding 8% resulted into UCS reduction, thus 8% cement soil mix is considered optimal for improved state of the soil. Stronger effects are achieved with soil cement mix cured in 14 days than that of 7 days, which shows that soil strength is improved for better quality performance with respect to cement content and curing period. UCS values increase could be ascribed to cement solidification property that enables compaction of soil mass with resultant increased strength. The UCS values of soil cement cured in 14 and 7 days (845.5 – 1011.6 and 761.7 – 872.1 kN/m^2) are within the 750 – 1500 kN/m^2 stipulated Nigerian General Specifications for highways [20] at 8% cement content. The results show that the strength structural properties (CBR and UCS) of the soil is improved on addition of 8% cement content. It also confirms proper curing of soil cement mix in 14 days with increased strength and as effective stabilizer.

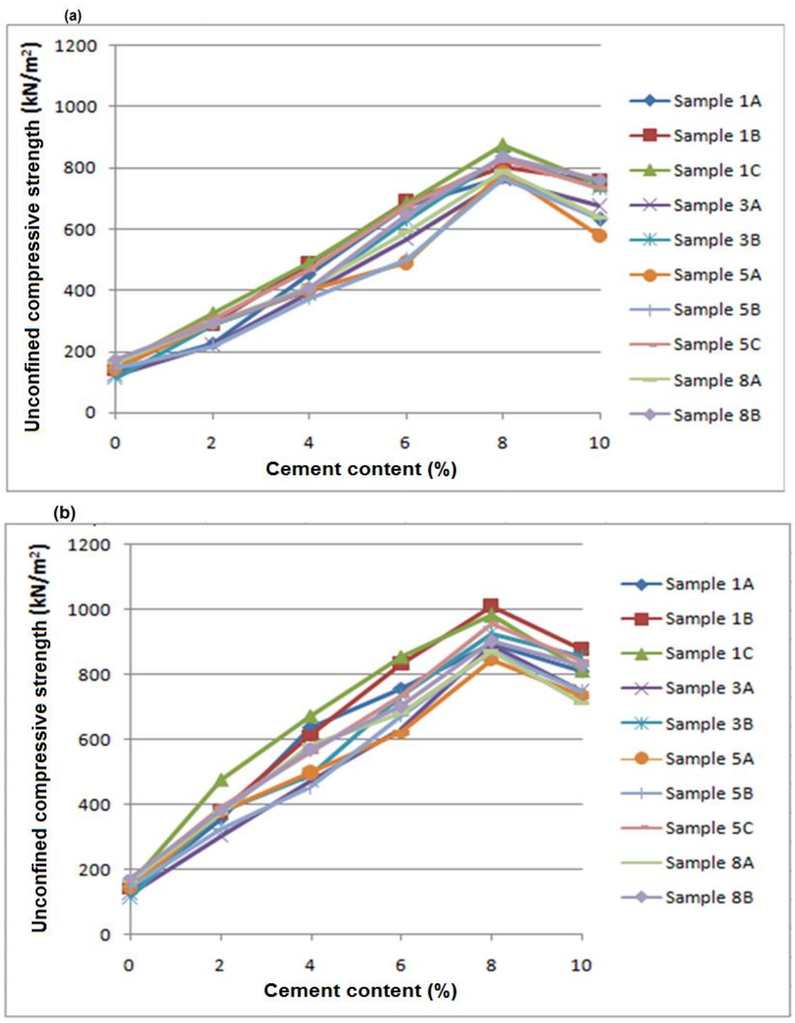
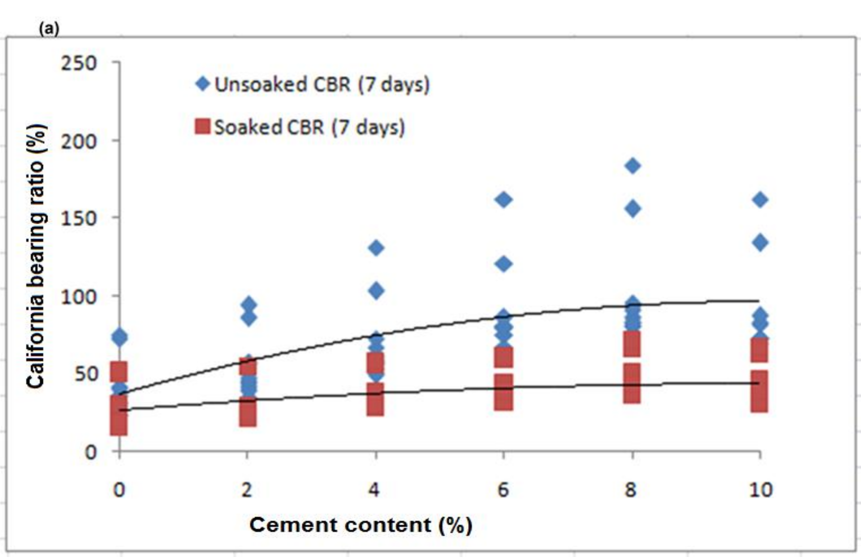


Figure 8. Cement content effect on cured soils UCS in 7 days (a) and 14 days (b).

Modelling of structural strength properties of soil cement mix as revealed in Figure 9 and 10 and illustrated with Equations 2 – 7 with their corresponding R^2 values revealing the correlation extent between the strength properties and cement contents. Curing period was observed to have impact on the soil strength planned for road construction sustainability. Strong relstionship exist between the strength indices of soil cement mix cured in 14 days with values of $R^2 \geq 0.8$. This reveals that prolong curing time is essential for compacted soil cement mix for enhanced geotechnical engineering properties and to improve the quality of lateric soil used as road construction materials.



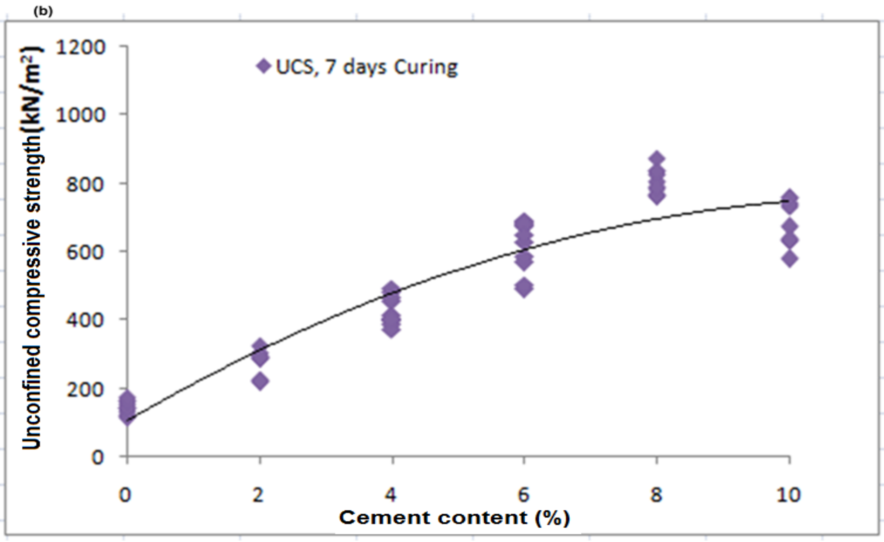


Figure 9. CBR/ UCS $_{7\ days}$ Vs Cement content; (a) CBR $_{7\ days}$ Vs Cement content (b) UCS $_{7\ days}$ Vs Cement content.

CBR $_{7\ days}$ Vs Cement content Figure 9a
CBR/ UCS $_{7\ days}$ Vs Cement content model

$$7\ days\text{-}CBR_{Unsoaked} = 0.567\ \%Cement^2 - 11.55\ \%Cement + 37.42 \qquad (2)$$

$R^2 = 0.570$

$$7\ days\text{-}CBR_{Soaked} = 0.157\ \%Cement^2 - 3.272\ \%Cement + 27.11 \qquad (3)$$

$R^2 = 0.413$

UCS $_{7\ days}$ Vs Cement content Figure 9b

$$7\ days\text{-}UCS = 4.823\ \%Cement^2 - 112.3\ \%Cement + 107.5 \qquad (4)$$

$R^2 = 0.90$

Where: 7 days-$CBR_{Unsoaked}$, 7 days-CBR_{Soaked} and 7 days-UCS are: CBR and UCS of soil cement mix cured for 7 days. %Cement is cement content.

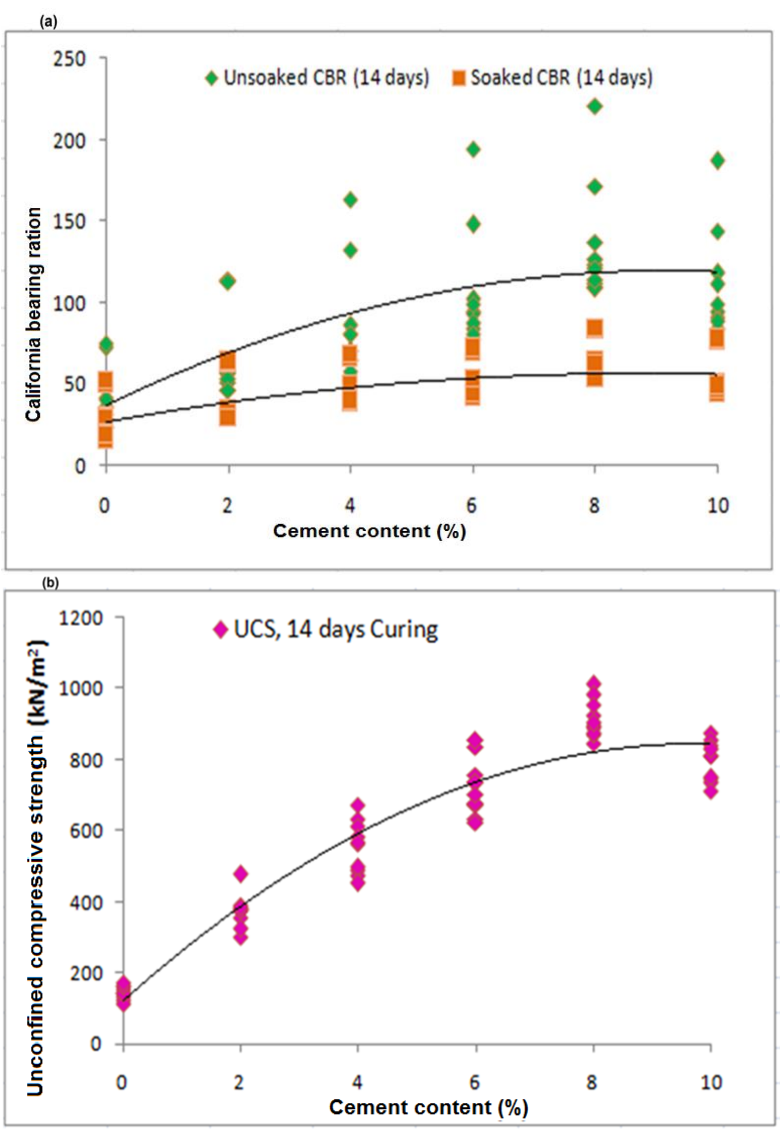


Figure 10. CBR/ UCS $_{14\ days}$ Vs Cement content; (a) CBR $_{14\ days}$ Vs Cement content (b) UCS $_{14\ days}$ Vs Cement content.

CBR $_{14\ days}$ Vs Cement content Figure 10a
CBR/ UCS $_{14\ days}$ Vs Cement content model

$$CBR\ unsoaked_{14\ days} = 0.98\ \%Cement^2 - 17.89\ \%Cement + 37.2 \qquad (5)$$

$R^2 = 0.776$

$$\text{CBR soaked}_{14\ days} = 0.39\ \%\text{Cement}^2 - 6.82\ \%\text{Cement} + 27.08 \quad (6)$$

$R^2 = 0.753$

UCS $_{14\ days}$ Vs Cement content Figure 10b

$$\text{UCS}_{14\ days} = 7.53\ \%\text{Cement}^2 - 147.20\ \%\text{Cement} + 124.0 \quad (7)$$

$R^2 = 0.93$

Where: 14 days-$CBR_{Unsoaked,}$ 14 days-CBR_{Soaked} and 14 days-UCS are: CBR and UCS of soil cement mix cured for 14 days. %Cement is cement content.

5. Conclusion

Index properties of the soils reveal its unsuitability as road construction materials, thus necessitated its enhancement for such purpose. Reduction in dry density indicates the need for low compactive energy to achieve maximum dry density with reduced cost of construction. The strength properties of the compacted cured soil cement mix improve with cement content increase from 0% till 8%. Addition of cement content exceeding 8% resulted into soil strength reduction, thus 8% cement soil mix is considered optimal for improved state of the soil. Enhanced strength condition of the soils has guaranteed its usefulness in flexible road pavement construction. Prolong curing period of 14 days is confirmed necessary for soil cement mix planning to be used in sustainable civil engineering works as maximum load bearing capacity of the soil depend not only on increase cement content but curing time. Improved soil bearing capacity offer reduction in pavement thickness with reduced/low construction cost. Cement exclusively stabilize the soil on its addition of 8% with improved strength properties. Soil cement mix could serve as alternative road construction material and cost-effective substitution for building construction mining and river sands. Soil cement mix would minimize continuous exploration of natural resources for construction, civil engineering work failures, cost of construction, human and environmental losses. Curing period was observed to have impact on the soil strength planned for sustainable road construction, as strong relstionship exist between the strength indices of soil cement mix cured for 14 days with $R^2 \geq 0.8$.

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