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Evaluation of the Geotechnical Properties of Residual Soils in Two Different Basement Complex Areas of Nigeria

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Authors' contributions

This work was carried out in collaboration among all the authors. All authors read and approved the final manuscript.

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ABSTRACT

Rocks from the Basement Complex areas of Nigeria weather to produce residual soils of varying geomechanical properties. Two such soils from the zone of accumulation were collected from Ore (Ors) and Abuja (Abs). The soils were understudied for their suitability for use as construction materials by subjecting to geotechnical analyses in order to evaluate their index and engineering properties. Ors with clays, silts, sands and gravel of (17, 22, 60 & 01) % respectively, and specific gravity of 2.57 g/cm^3 is classified as a silty sand with clays whereas Abs is clayey sands with gravels. Their index properties are in the order: LL, (43.45 & 51.7) %; PI, (12.14 & 31.57) %; linear shrinkage, (8.57 & 12.1) %;

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free swell, (11.1 & 22.5) %; liquidity index, (-1.10 & -0.09); group index, (3.30 & 9.54); and plasticity plots, (ML & CH) for Ors and Abs respectively. Similarly, their engineering characteristics are as follows: maximum dry density, (1.52 & 1.49) g/cm^3; optimum moisture content, (22.0 & 22.5) %; change in void ratio, (0.18 & 0.39); change in porosity, (0.05 & 0.10); cohesion (20.65 & 31.65) KN/m^2; shear strength, (86.63 & 88.9) KN/m^2; and CBR, (27.86 & 26.79) % respectively. Overall, this study shows that whilst Ors has superior analytes properties, both soils can be used as subgrades in flexible pavement design as well as for many other common construction purposes.

Keywords: Cohesion; geotechnical; residual soils; shear strength; subgrade.

1. INTRODUCTION

In-situ weathering of bedrocks produces residual soils, which may also contain organic material derived from plants and animals living in the area. The associated humus in soils are to be avoided as they impact weaknesses to engineering soils. All Engineering structures are erected on a substructure (foundation). The rigidity and safety of the super structure subsist in part, on the constituent and consistency of the substructure. Geotechnical methods have been used in assessing the strength of materials for the support of infrastructures such as roads, buildings and dams [1,2]. The significance of geotechnical tests on soils cannot get excess mention given its immense relevance for construction purposes. Designing structures on a soil material without prior knowledge of its engineering behaviour and competence based on geotechnical tests may prove costly in terms of capital, labour, and human misery in the event of failure. The main thrust of this work is to understudy Ore soil (Ors) and Abuja soil (Abs) by subjecting them to geotechnical analyses in order to evaluate their index and engineering properties, and therefore determine their suitability for use as construction materials.

2. LOCATION AND GEOLOGY OF THE STUDY AREAS

The sample from Abuja (Abs) was collected at latitude 9.1335°N and longitude 7.22288°E along Daura Road in the Kubwa area of the FCT (Fig. 1). It is a residual soil formed from Zuma rock. The Zuma rock is an igneous intrusion composed of gabbro and granodiorite. The soil colour is dark brown. It is coarse and very plastic with angular grains, some containing quartz and incompletely weathered feldspars. The Ore soil sample (Ors) was collected off the Ore-Ondo Road (some distance from the Benin- Sagamu expressway) at a depth of 1.2m with geographical co-ordinates of 6.7758° N and 4.8755° E. It is a light reddish brown soil with mottled yellow, and gritty with grains fragments thought to be derived from migmatitic rocks within the Basement Complex (Fig. 2).

The Nigerian Basement Complex lies within the Pan-Africa mobile belt to the east of West Africa Craton and North West of the Congo Craton. It can be divided into two provinces. The Western province is approximately west of Latitude 8° E and is characterised by N-S trending to low grade schist belt in a predominately migmatite gneiss Older Basement introduced by Pan Africa granitic plutons. The eastern province comprises mainly migmatite gneiss complex introduced by larger volume of Pan- Africa granites and the Mesozoic ring complexes of central Nigeria. The most obvious tectonic effect of the Nigerian Basement Complex is the Pan- African Orogeny [3].

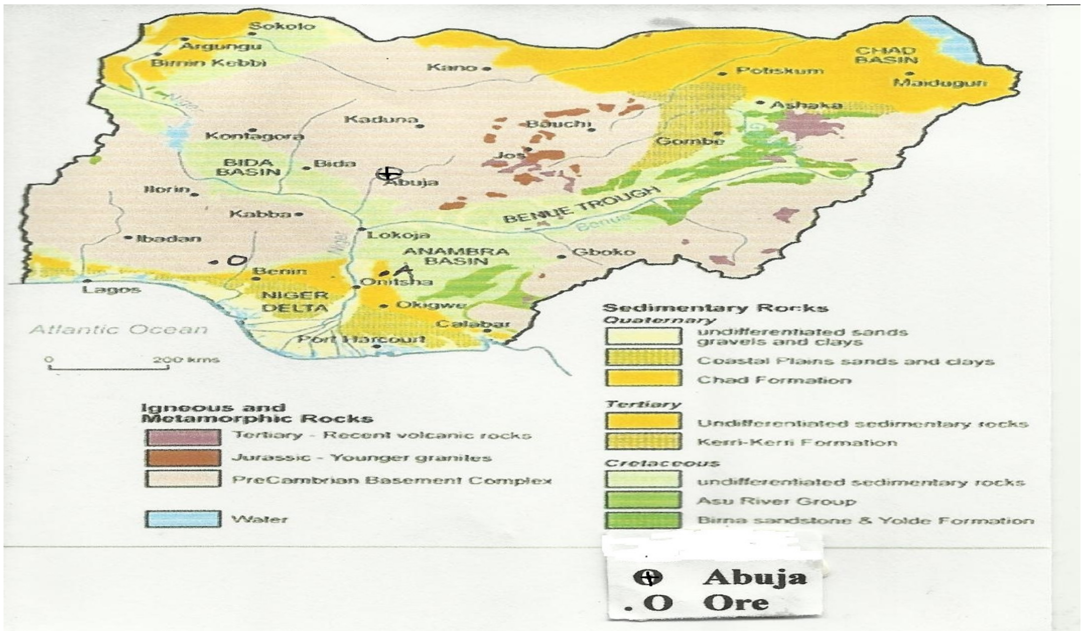

Fig. 1. Simplified geological map of Nigeria showing study areas

3. FIELD PROCEDURES AND METHODOLOGY

A quick reconnaissance study of the sample area was made on reaching the field. The soil profile after observation, was sketched and described together with the soil characteristic, in a field notebook.

The observed colour at in-situ moisture content was recorded, since colour is dependent on moisture content. Soil description aids the development of a feel for soil behaviour. It also helps in interpretation of the results obtained and checks laboratory classification against that made in the field.

A measure of the plasticity of the soil was obtained by noting how much working on the soil between the fingers was required to dry it; from the wet state, near the liquid limit, to the crumbling state, near the plastic limit. The greater the plasticity the longer the kneading time required. The zones containing humus were not sampled, since humus impacts weaker strength to engineering soil. Ample quantity of representative soil was collected (about 25 kg per location) for required laboratory test. Some of these were placed in cellophane bags for moisture content determination.

Series of tests were conducted on the soil samples in accordance with BS-1377 [4]. These included: natural moisture content determination, Atterberg or consistency limit, free swell linear shrinkage, particle size analysis, determination of the colloidal activities of fine – grained fractions, specific gravity determination, standard compaction, California Bearing Ratio, unconfined compressive strength test and direct shear test.

All the laboratory tests were carried out in the geotechnical laboratories of the Departments of Geology, and Civil Engineering in the University of Benin, Nigeria.

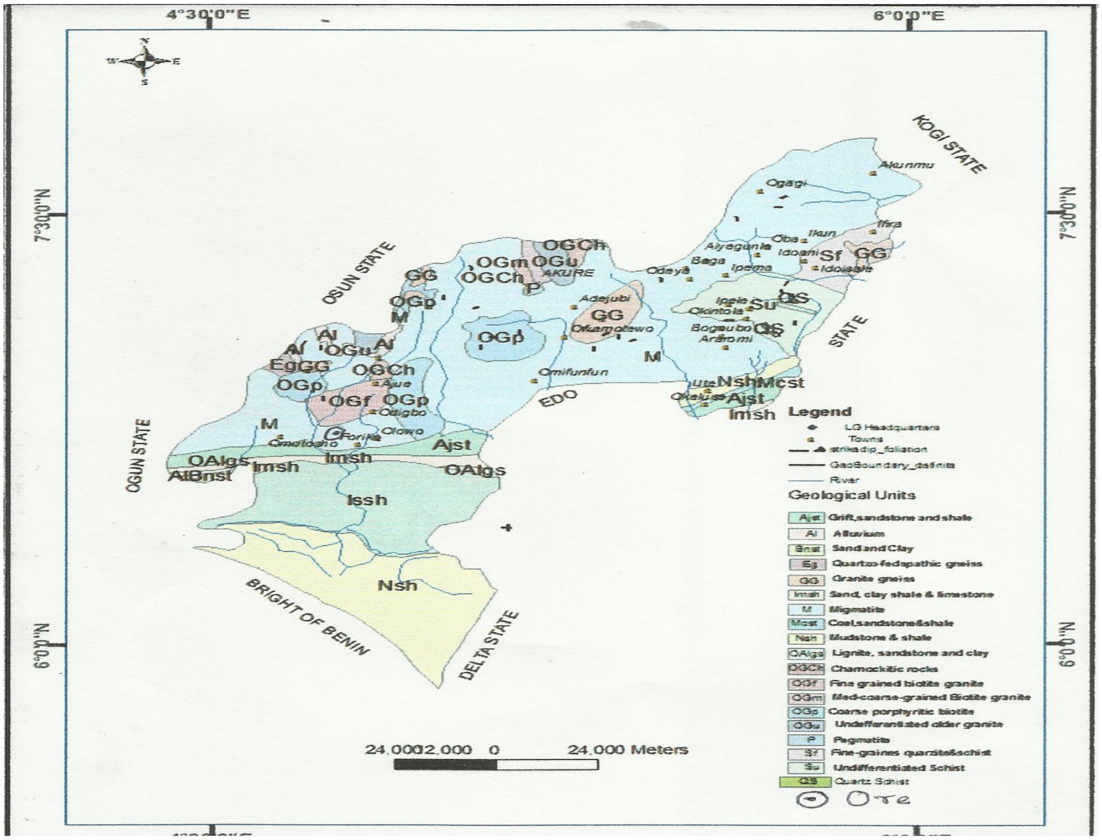

Fig. 2. Geological map of ore and environs

4. RESULTS AND DISCUSSION

The samples were collected at about the same depth and time during the dry season and the measured natural moisture content values are consistent with their percentage of fines (the influence of temperature and humidity being almost negligible). Ors has slightly higher natural moisture content (w) with a value of 17.85% as compared to 17.24% of Abs (Fig. 3). This is understandable given probable dispersed moisture emanating from a proximal spring.

Abs has more clays than Ors (27% vs. 17%) but lower fines than Ors (37% vs. 39%). However, Ors has more silts and sands and is therefore expected to be less plastic with a slightly lower specific gravity (2.57 vs. 2.6) g/cm^3. Overall, Ors is thus designated as silty sand with clays while Abs is clayey sand with gravels. Both soils are well graded.

Therefore, the inference is that the Ore clay will be the least plastic (considering its percentage of clays) since at lower moisture content the soil becomes more friable. In the same vein, Abuja soil will be more plastic than the Ore soil. It also shows that the Ors will attain greater strength assuming the same quantity of water content is abstracted from both soils. However, considering the granular percentages; Ore soil may not give the best shear strength parameters even under effective drainage. Besides, the presence of feldspar in it makes it more susceptible to weathering.

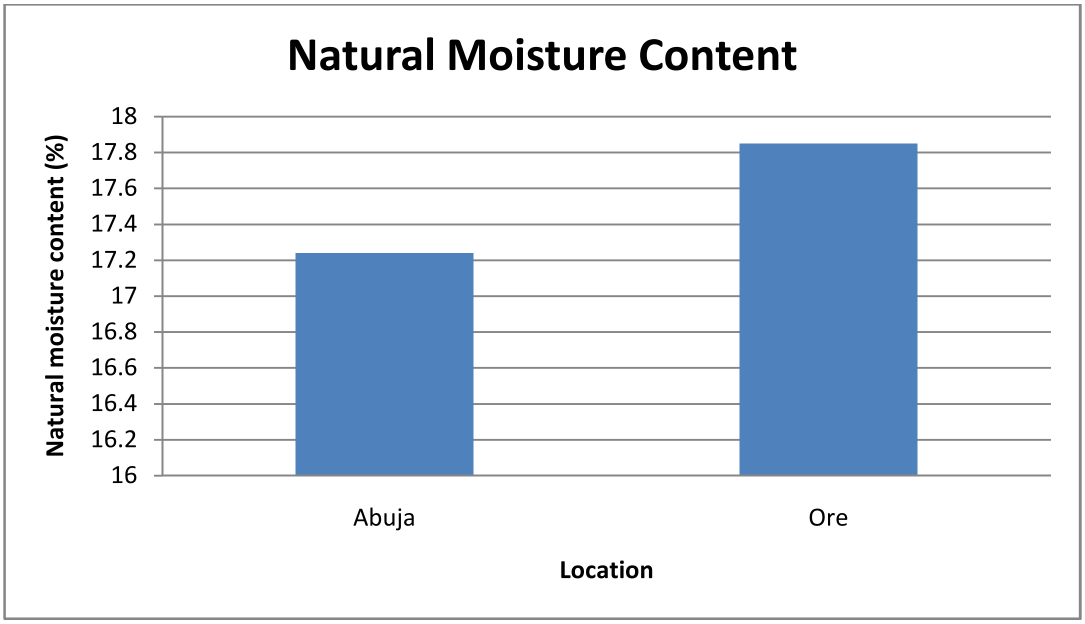

Fig. 3. Natural moisture content of the sampled areas

The liquid limit (LL) is the lowest water content above which soil behaves like liquid. Normally, this is below 100. This represents the minimum moisture content at which soil will flow under its own weight. Empirical analyses reveal that a disturbed soil at liquid limit has shear strength around 1 KN/m^2 [5]. However, for the present discourse, it is convenient to regard the liquid limit as the water content corresponding to shear strength of about 2.5 KN/m^2 [6]. Ors and Abs have LL of (43.4 & 51.7) % respectively as shown in (Fig. 4). The use of the cone penetrometer gives slightly higher values as shown in (Fig. 5).

With reducing moisture content from the liquid limit, the soil becomes stiffer and less plastic and finally emerges into a semi-solid state. The moisture content at which this change occurs is called the plastic limit (PL). The lowest water content at which soil behaves like a plastic material is normally below 40. Ors and Abs have PL of 31.26 and 20.13 respectively. Whatever the structural status of water and the nature of the inter-particle forces, the plastic limit is the lower boundary of the range of water content within which soil exhibits plastic behaviour. That is, above the plastic limit, the soil can be deformed without volume change or cracking and will retain its deformed shape [7].

The plasticity index is derived from the difference between LL & PL and is an important indicator of the surface chemical activity of the fine soil fraction of the material. It refers to the soil itself and is the change in water content required to increase the strength of disturbed samples a hundred times [5].

Abs with about 27% of clays and 10% of silt has a higher PI value of 31.57% and is more plastic when compared with Ors with 17% clays, 22% silt and PI of 12.14%. A measure of consistency and strength is deduced from the liquidity index (LI). LI is given by (w-PL)/PI. The LI values for Ors and Abs are -1.10 & -0.09 respectively and indicates that both soils are semi-solid to stiff since LI <0 [8,9].

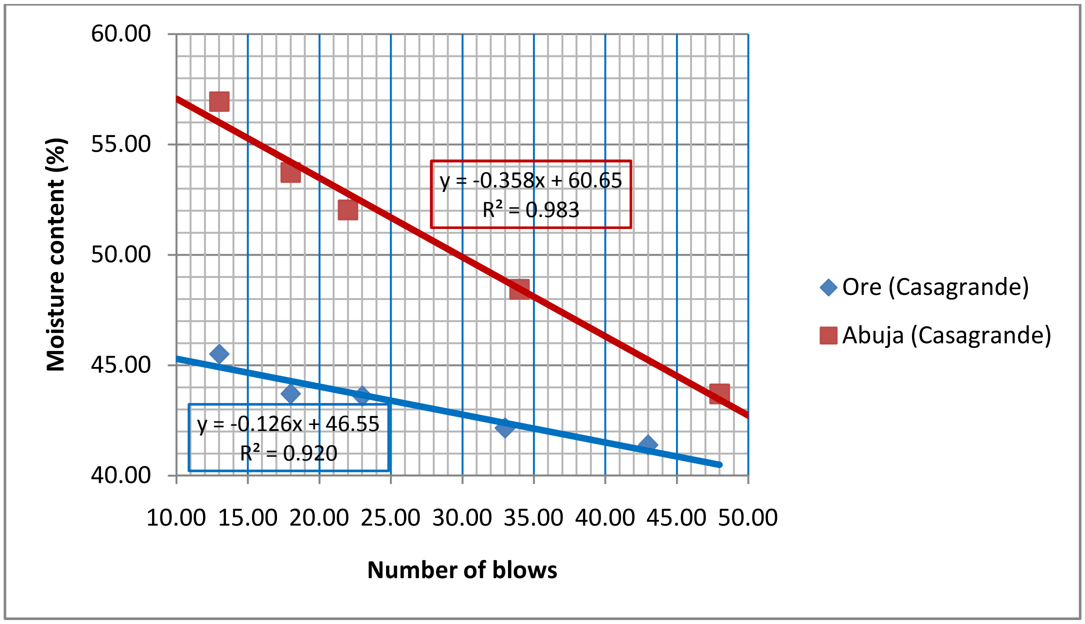

Fig. 4. Determination of LL in the sampled areas using the casagrande device

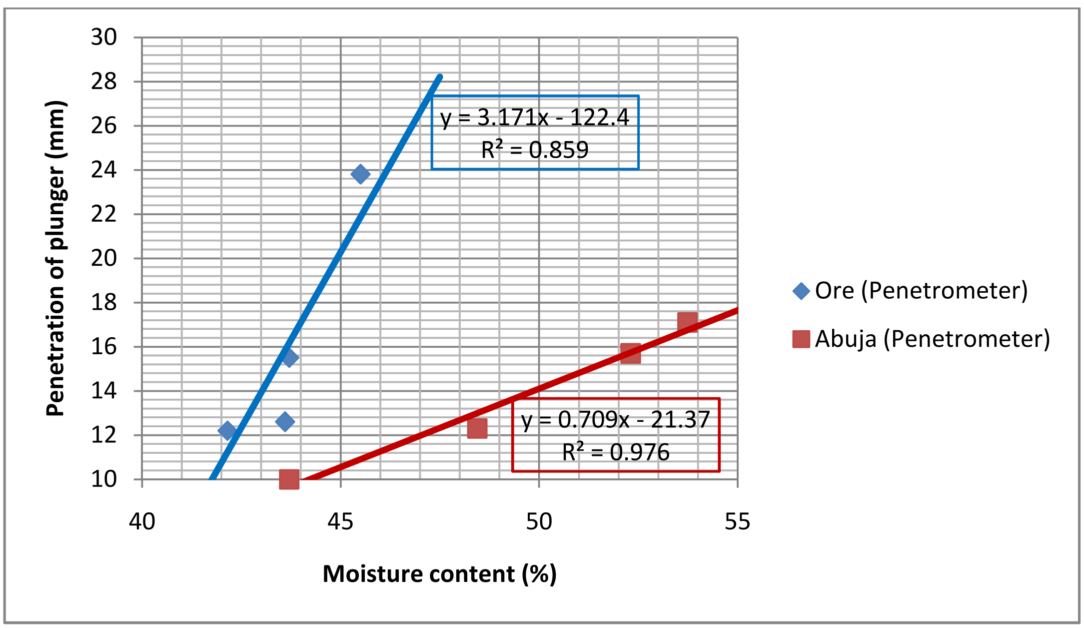

Fig. 5. Determination of LL in the sampled areas using the cone penetrometer

A collaborative measure is also inferred from the consistency index, CI (which is derived from (LL-w)/PI). The CI values are 2.10 and 1.09 in the aforementioned order. Similarly, because CI is > 1, it buttresses the previous deduction. Also their colloidal activity values of 0.71 & 1.17 infers that the clays are normal clays since these values are lower than the > 1.25 designated for chemically reactive clays. Ors has a better soil group index (GI) with a value of 3.30 whereas that of Abs is 9.54. In general, the rating for a pavement subgrade is inversely proportional to the group index, GI. The closer the soil GI is to zero or negative values, the better it is in terms of its suitability for use as subgrade. The compressibility of the sampled clays according to Terzaghi & Peck [10], and then according to NAVFAC [11] are 0.3 & 0.38; and 0.16 and 0.41 for Ors & Abs respectively.

Swelling may cause building foundation to heave to such an extent that building are damaged. However, given their marginal free swell values of 11.1% and 22.5% for the Ore and Abuja clays respectively, none of the tested soil exhibited such critical swelling since soils with a free swell value below 50% will not have appreciable volume change when loaded [6]. The Ore soil clay mineral could be kaolinite derived from the weathering of feldspars and micas within the migmatitic body present in the Basement Complex from where the sample was collected. The clay mineral in the Abuja soil could also be kaolinite from the weathering of rocks containing more feldspars and micas in the Basement Complex. It is known that it is the clay fraction in a soil that will respond to swelling and shrinkage because they are expandable and compressible. The silt and sand fraction are predominantly made up of quartz, which are physico-chemically inert.

Whereas Abs plots above the ‘A’ line of the Casagrande plasticity chart, Ors plots below (Fig. 6). Essentially the fines in Ors are silts of low plasticity whereas Abs has clays of relatively higher plasticity.

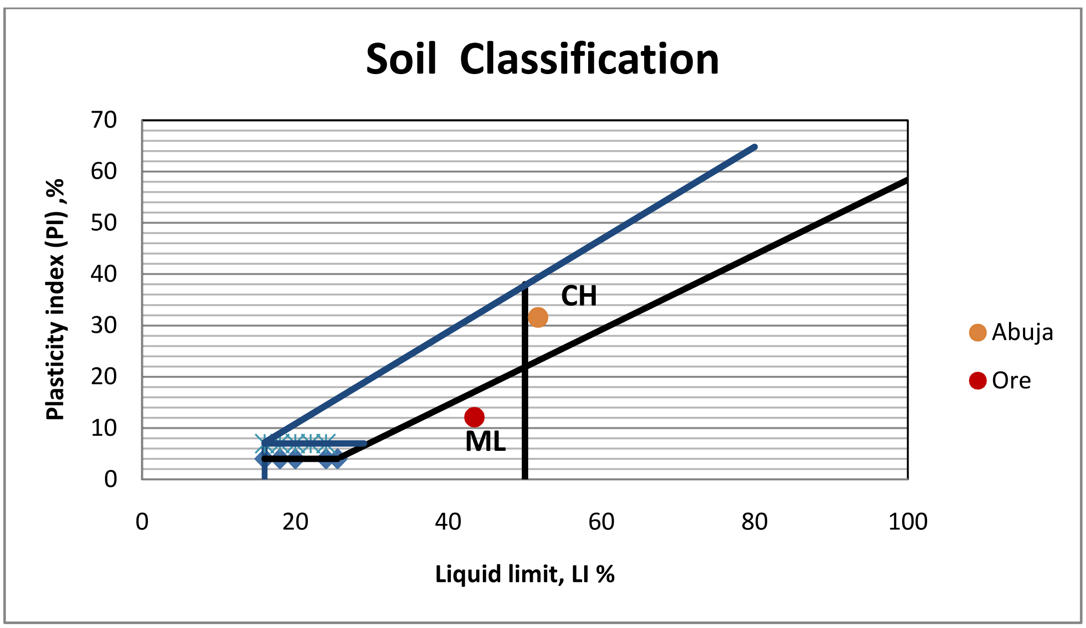

Fig. 6. Classification of the sampled soils based on index properties

The purpose of the laboratory compaction test in this work was to determine the proper amount of mixing water to use when compacting the soil in the field and the resulting degree of denseness which can be expected from compaction at this moisture content. Compaction is the process by which the bulk density of an aggregate of matter is increased by driving out air. For any soil, for a given amount of compactive effort, the density obtained depends on the moisture content. At very high moisture contents, the maximum dry density is achieved when the soil is compacted to nearly saturation, where (almost) all the air is driven out. At low moisture contents, the soil particles interfere with each other; addition of some moisture will allow greater bulk densities, with a peak density where this effect begins to be affected by the saturation of the soil. The bulk density or dry density of soils is not a constant value; it could be changed in relation with the moisture content of soils and the compactive effort (Fig. 7).

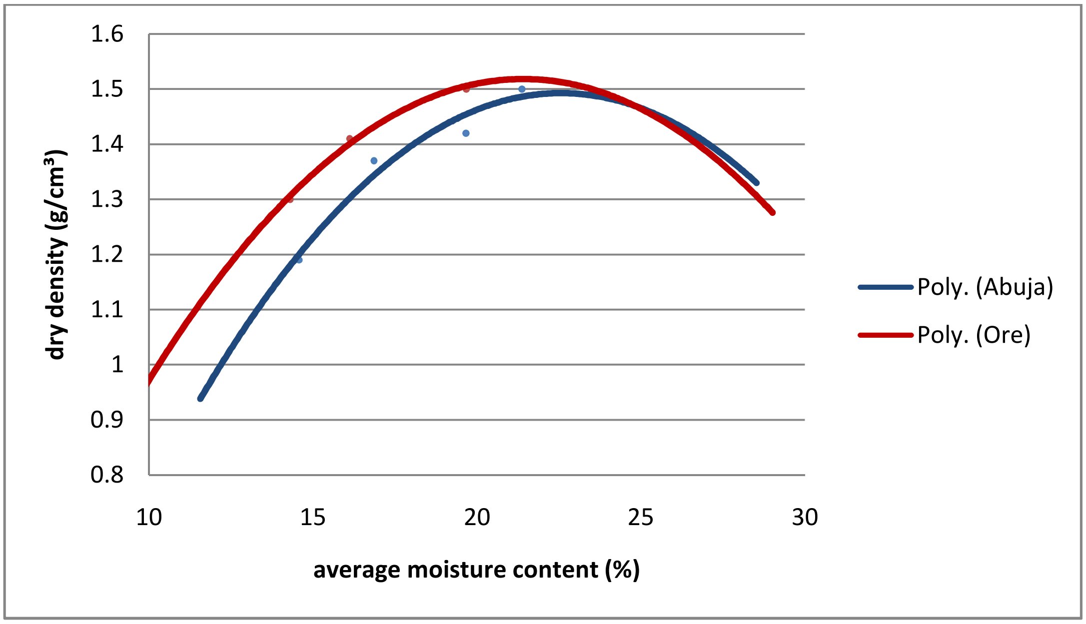

Fig. 7. Determination of maximum dry densities and optimum moisture contents

From (Figs. 7 & 8), it is easy to discern that as compaction commences, the dry density increases whereas the void ratio reduces as air is expelled. Similarly, there is an inverse relationship between bulk density and porosity. The changes in void ratio and porosity in the course of standard compaction of Ors and Abs were (0.18 & 0.39) and (0.05 & 0.10) respectively. Both soils also share close maximum bulk & dry densities, and optimum water contents of (1.86 & 1.84) g/cm^3, (1.52 & 1.49) g/cm^3, and (22 & 22.5) % for Ors and Abs in the regular order. The optimum moisture content is the water content that results in the greatest dry density for a specified compaction effort. Compacting at water contents higher than the optimum water content; results in a relatively dispersed soil structure (parallel particle orientations) that is weaker, more ductile, less pervious, softer, more susceptible to shrinking, and less susceptible to swelling than soil compacted dry of optimum to the same density. The soil compacted lower than (dry of) the optimum water content typically results in a flocculated soil structure (random particle orientations) that has the opposite characteristics of the soil compacted wet of the optimum water content to the same density.

Knowledge of density is essential in all problems where the body of the strata is an important factor, e.g. stability of slopes of earth dams; earth pressure on retaining walls, tunnel linings and timbering of excavation. The method of designing inverted fillers for dams, levees etc. uses the particles size distribution of the soils involved. This method is based on the relationship of grain size to permeability, along with experimental data on the grain size distribution required to prevent the migration of particles when water flows through the soil.

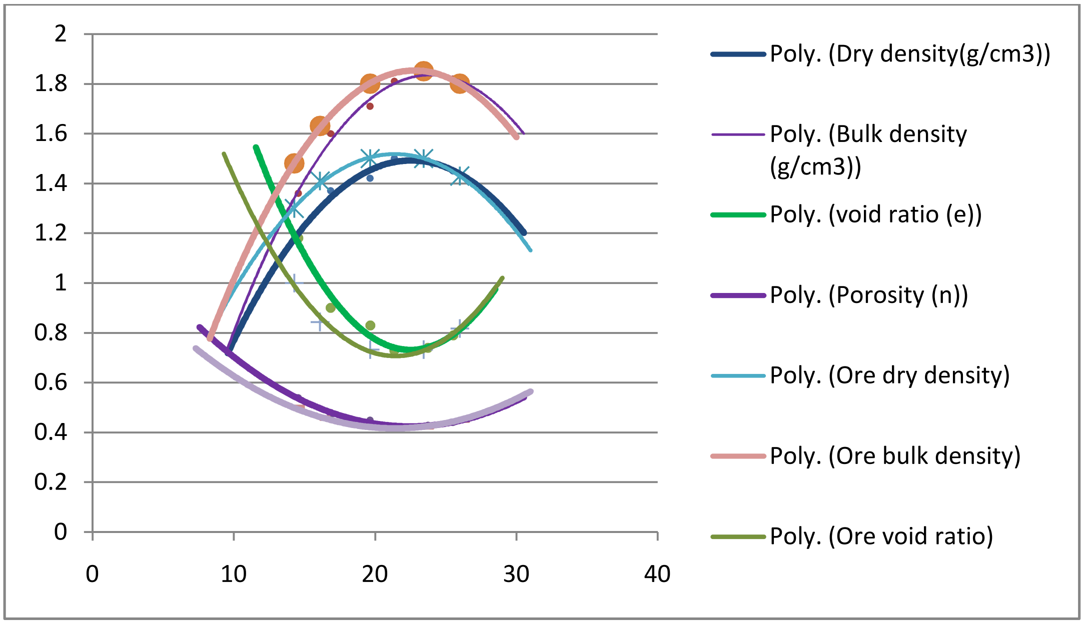

Fig. 8. Determination of various compaction indices and ratios

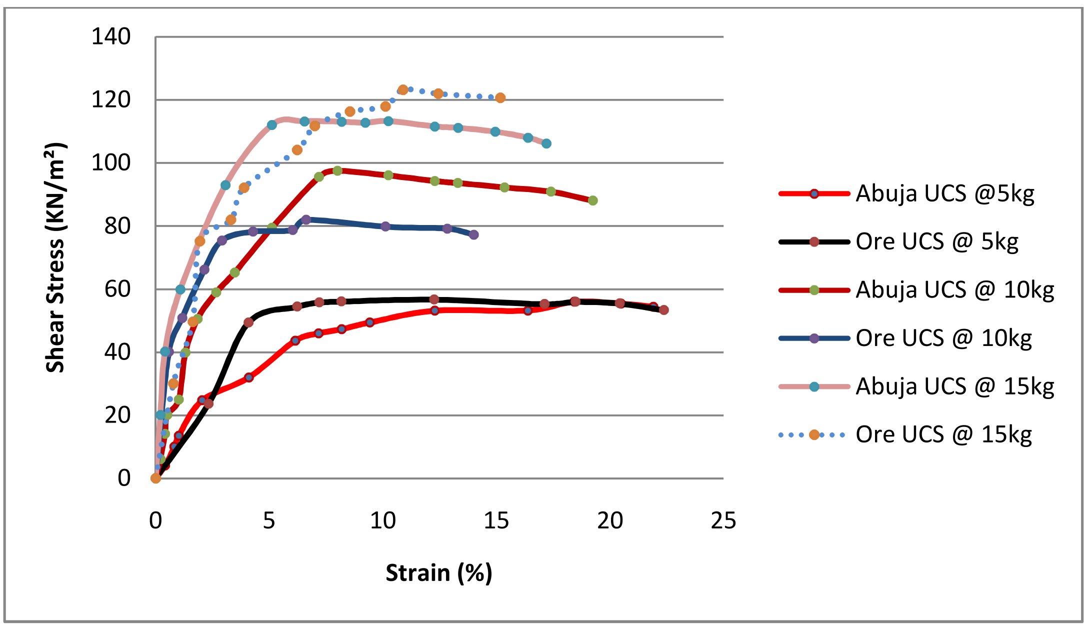

Fig. 9. Determination of unconfined compressive strength in the sampled soils

Shear strength is a term used in soil mechanics to describe the magnitude of the shear stress that a soil can sustain. The shear resistance of soil is a result of friction and interlocking of particles, and possibly cementation or bonding at particle contacts. Due to interlocking, particulate material may expand or contract in volume as it is subject to shear strains. Using the Tresca criterium, both soils are stiff soils because the shear strengths are between 75-150 KN/m^2 (Fig. 9). This is as previously deduced from the index parameters (a summary of the geotechnical results of both soils is given in Table 1). The Tresca criterium (also known as the maximum shear stress criterium of material failure) is one of the two main failure criteria commonly used to predict the yielding of ductile materials. Yield in ductile materials is usually caused by the *slippage* of crystal planes along the maximum shear stress surface. Therefore, a given point in the body is considered safe as long as the maximum shear stress at that point is under the yield shear stress. Otherwise, yield (failure) occurs which may lead to plastic flow.

Table 1. Summary of geotechnical results

Properties	Sample		Reference limit (BS-1377)
	Ors	Abs	
Granulometry:clay(%)	17	27	Part 2
:Silt (%)	22	10	Part 2
:Sand (%)	60	45	Part 2
:Gravel (%)	1	18	Part 2
Specific gravity (g/cm^3)	2.57	2.60	Part 2
LL (%)	43.45	51.57	Part 2
PI (%)	12.14	31.57	Part 2
Linear shrinkage (%)	8.57	12.10	Part 2
Free swell (%)	11.10	22.50	Part 2
Liquidity index	-1.10	-0.09	Part 1
Group index	3.3	9.54	Part 1
Plasticity plots	ML	CH	Part 1
Max dry density (g/cm^3)	1.52	1.49	Part 4
Optimum moisture content (%)	22.00	22.50	Part 4
Change in void ratio	0.18	0.39	Part 4
Change in porosity	0.05	0.10	Part 4
Cohesion (KN/m^2)	20.65	31.65	Part 7
Shear strength (KN/m^2)	86.63	88.90	Part 7
CBR (%)	27.86	26.79	Part 4

Ors has slightly lower shear strength and cohesion with values of (86.63 & 20.65) KN/m^2 respectively (Fig 10). Though it has higher silts and sands, it has a lower granular interface of about 61%. More importantly, it bears just a percentage of gravel as against 18% offered by Abs. It is known that more compact masses offers better shearing strength. If soil expands its volume, the density of particles will decrease and the strength will decrease; in this case, the peak strength would be followed by a reduction of shear stress. The stress-strain relationship levels off when the material stops expanding or contracting, and when inter-particle bonds are broken. The volume change behaviour and inter-particle friction depend on the density of the particles, the inter-granular contact forces, and to a somewhat lesser extent, other factors such as the rate of shearing and the direction of the shear stress. The average normal inter-granular contact force per unit area is called the effective stress.

The stress-strain relationship of soils (and therefore the shearing strength), is affected by such factors as: the soil composition (mineralogy, grain size and grain size distribution, shape of particles, pore fluid type and content, ions on grain and in pore fluid.); initial state (defined by the initial void ratio, effective normal stress and shear stress (stress history)); structure (arrangement of particles within the soil mass; cementation, etc) [12].

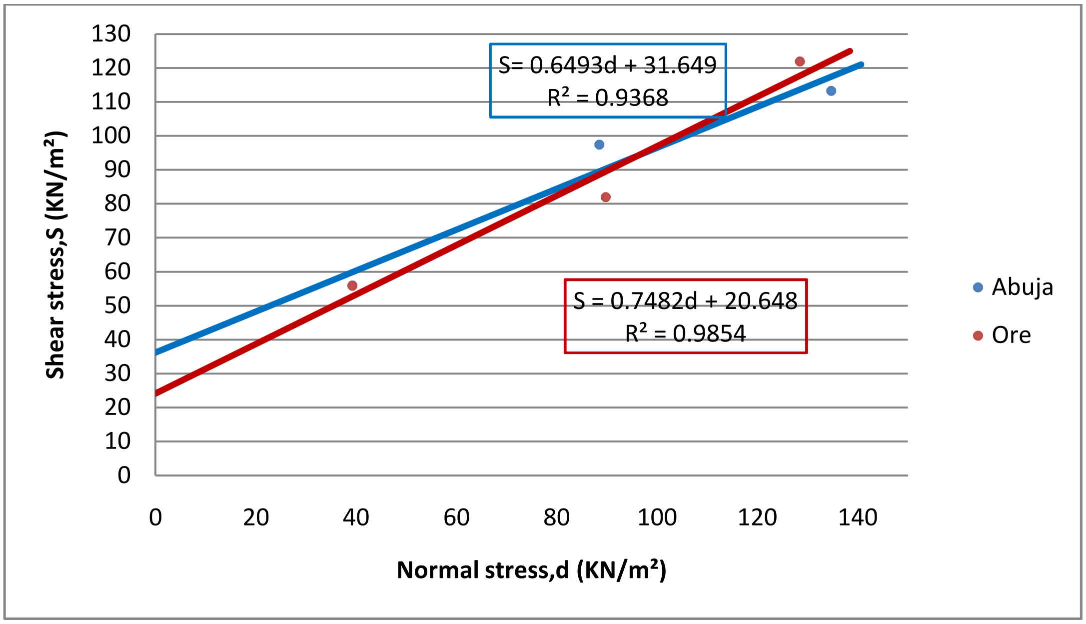

Fig. 10. Determination of shear strength and angle of friction using direct shear test

A granular soil has no shearing resistance at a free surface but it increases rapidly with increase of depth because of the appreciable internal friction. Since the shearing strength of cohesive soil is usually derived almost entirely from the cohesive strength, and very little or none from internal friction, the strength of a cohesive soil of constant water content increases very, little with the increase of depth [6].

When a load is applied to a confined mass of soil, failure will eventually occur when the individual soil grains begin to move relative to each other, i.e. when sliding or shearing will take place along a shear plane. When this "plastic" state of stress is reached the soil mass will be unable to support any additional load. The strength of a soil is therefore dependent on its shearing resistance.

The purpose of compacting the disturbed samples used for this test was to improve the strength and durability of the soil. Soaking was done to stimulate highly unfavourable moisture condition of the prototype soil. The problem of whether or not to soak the samples for a specific design is one of the most controversial features of the CBR design procedures. Studies reported by the Corps of Engineers (U.SA), indicates that moisture accumulated in cohesive soils even in arid climates. The response of Ors to CBR tests was quite consistent with its aforementioned properties and indicates its suitability for common construction purposes requiring the use of soils as it is reasonably more tolerant to imbuement with moisture.

Based on the standard CBR designing curves for roads, Ors with a slightly higher CBR value (27.86%) may require a marginally lower pavement thickness than Abs with CBR of 26.79% (Figs. 11 & 12). Unlike materials like steel, most of the soils are visco-elastic, meaning the failures are time dependant. Higher CBR reading of a soil (>15%) denotes suitability for use as subgrades. With stronger subgrade, the road pavement thickness is reduced thereby saving capital. Experience has shown that the largest percent of pavement failures is due to poor subgrade condition and excessive subgrade deformation. The improvement of subgrade support by good compaction close to the optimum moisture content can be the most economical measure to take for increased load capacity [13].

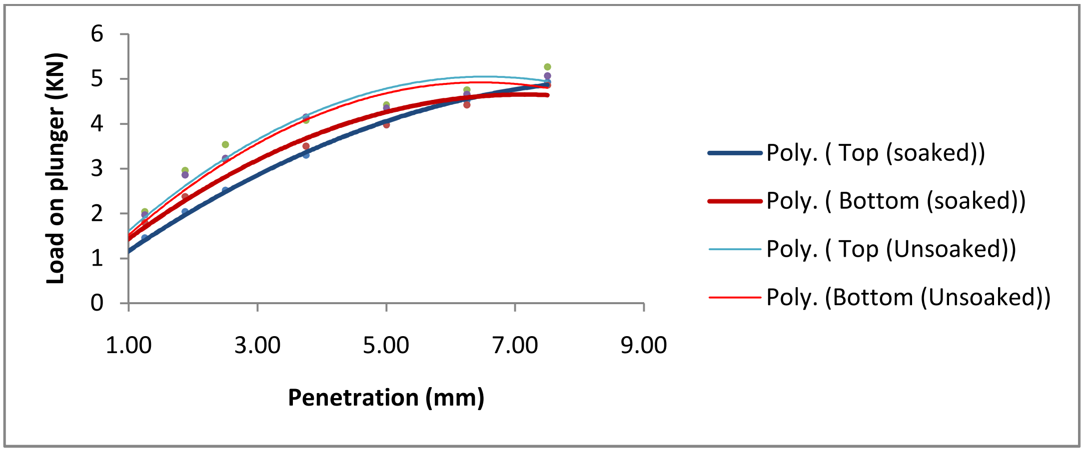

Fig. 11. CBR plots for Abs

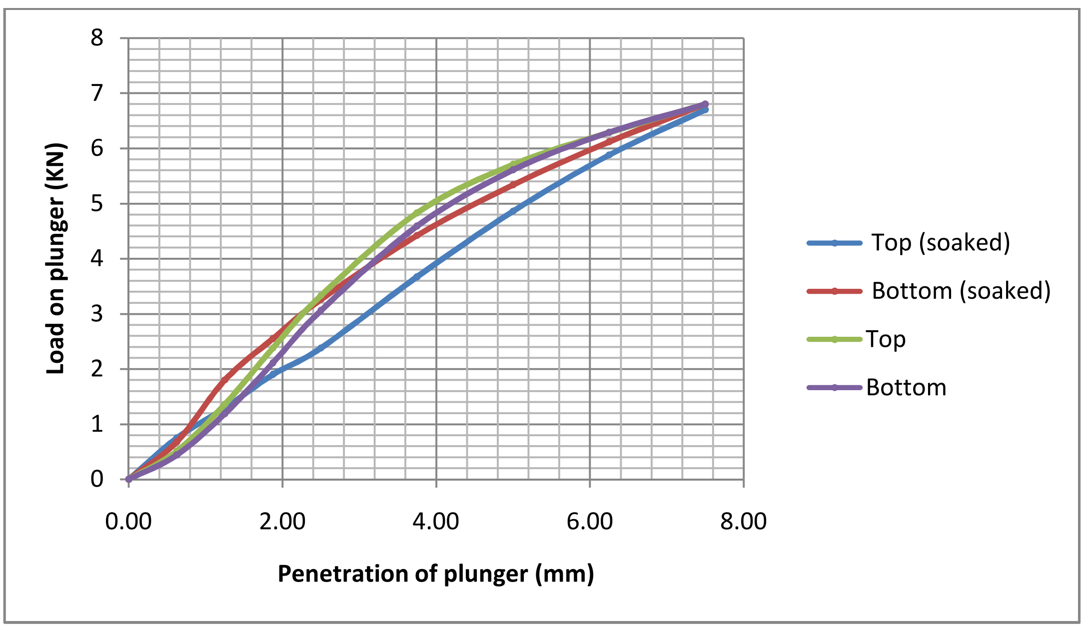

Fig. 12. CBR plots for Ors

Stability in ground water level will maintain the effective weight of the material that it saturates without increasing pore water pressure. Unfavourable conditions can be checked if effective sub drainage systems are put in place for both soils. This will help to reduce maintenance and early replacement problems. Consequently, engineers resort to subdrainage whenever needed to assure maximum service and long life of the embankment or pavement with minimum maintenance and disruption of traffic. For example, unstable soils require the most efficient drainage for railway, municipal and airport application. In addition, the use of perforated steel pipe subdrains for the upstream side of levees and the downstream slope of earth and rock dams is considered good engineering practice. The purpose it to relieve the groundwater pressure of accumulating seepage.

Subgrade performance is a function of a soil's strength and its behaviour under traffic loading. The subgrade should be sufficiently stable to prevent excessive rutting and shoving during construction, provide good support for placement and compaction of pavement layers, limit pavement rebound deflections to acceptable limits, restrict the development of excessive permanent deformation (rutting) in the subgrade during the service life of the pavement and minimise effect of changes in moisture level.

5. CONCLUSION

The soils tested are admixtures of fine and granular materials. Their geotechnical properties reflect the combined effects of these fractions with moisture. In terms of fines, Ors is silt of low plasticity whereas Abs is clay of high plasticity. This suggest that Abs will be more resistant to erosion given similar volume of saturation as it has more significant cohesion due to some form of weak bonds between its particles.

Furthermore, as compaction commenced, the dry densities of both road subgrades increased whereas the void ratios reduced as air was expelled. Similarly, there is an inverse relationship between bulk density and porosity. Using the Tresca criterium, both soils are stiff soils because the shear strengths are between 75-150 KN/m^2). Ors has slightly lower shear strength and cohesion. Based on the standard CBR designing curves for roads, Ors with a slightly higher CBR value (27.86%) may require a marginally lower pavement thickness than Abs with CBR of 26.79% with relative capital savings**.** However, it is instructive to note that unlike materials like steel, the soils are visco-elastic, meaning the failures are time dependant. Higher CBR reading of a soil (>15%) denotes suitability for use as subgrades. Overall, this study shows that whilst Ors has slightly better geotechnical properties, both soils can be used as subgrades in flexible pavement design as well as for many other common construction purposes.

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COMPETING INTERESTS

Authors have declared that no competing interest exists.

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