International Journal of Earth Sciences Knowledge and Applications (2022) 4 (1) 124-132

IJESKA contribution to science

International Journal of Earth Sciences Knowledge and Applications
journal homepage: http://www.ijeska.com/index.php/ijeska

Research Article

e-ISSN: 2687-5993

Geotechnical Appraisal and Geological Influence on Road Failure: A New Perspective in Geotechnical Engineering

Osakpolor Marvellous Omorogieva[1]*, Isaac Okiti[2]

[1]*Department of Marine Geology, Faculty of Marine Environmental Management, Nigerian Maritime University, Okerenkoko, Delta State, Nigeria*
[2]*Department of Geography, Faculty of Science and Technology, University of Tartu, Tartu, Estonia*

INFORMATION

Article history
Received 15 June 2021
Revised 12 October 2021
Accepted 16 October 2021

Keywords
Road failure
Earth material
Geology
Geotechnical
Incessant

Contact
*Osakpolor Marvellous Omorogieva
osakpolor.omorogieva@physci.uniben.edu

ABSTRACT

Four samples of red tropical soils (RTSs) were obtained were obtained along 164 km Benin-Auchi-Igarra Highway at notable points/places which include Etete (Benin City), Sabo (Auchi), Ikpeshi and Igarra with the aim of determining their geotechnical properties in ascertaining the causes of the incessant road failure often recorded along the road network as well as the geology of the environment. The tests carried out in accordance with the British Standard Institution (BSI), Unified Soil Classification System (USCS)and American Association of State Highway and Transportation Officials (AASHTO) include; Atterberg limits tests, particle size distribution (PSD), specific gravity (Gs), compaction characteristics and California Bearing Ratio (CBR).Based on USCS classification, Etete (Benin City), Sabo (Auchi) and Ikpeshi have high percentage of sand with little silt (silt sand) whereas Igarra soil contains more of silt with little sand (sand silt). Conversely, AASHTO classification puts Etete (Benin) and Ikpeshi as A-2-4, Sabo (Auchi) as A-3 and Igarra as A-2-7, respectively. These classifications are good to excellent but cannot be applied as sub-base nor base course for roads construction because of their mineralogy and or chemical composition. However, they are better material for sub-grade; hence, result values from Benin, Auchi and Ikpeshi can serve as a good sub-grade material, while Igarra soil can serve as a sub-grade material for class S1 road designed to have a minimum thickness of 250 mm. Ultimately, it is advised that soils with low bearing capacity should be stabilized by compaction in order to yield maximum strength on the dry side of their respective optimum moisture content (OMC). The study concludes that the incessant road failure is attributed the wrong uses of TRSs as sub base and base course and non-consideration of the geological influence of the source material.

1. Introduction

RTSs are a highly weathered material from igneous, metamorphic and sedimentary rocks that are rich in secondary oxides of iron, aluminum, or both. It usually occurred within the tropical and sub-tropical climate between latitude 300 North and South of the Equator (Roy Chowdhuby, 1965; Tardy, 1997). It is a common earth material used in engineering works as subgrade, sub base and base course for road construction in the tropics and subtropics where it is in abundance. The weathering process primarily involves the continuous chemical alteration of minerals, the release of iron and aluminum oxides, and the removal of bases and silica in the rocks (Northmore et al., 1992; Cardarelli, 2008). The geotechnical properties of RTSs often called laterite are influenced by climate, drainage conditions, the nature of the parent rock and the degree of laterization of the parent rock (Abebaw, 2005). These factors also differentiate laterite from other soils that are developed in the temperate or cold regions (Jiregna, 2008; Aginam et al. 2015). Some soils are thought to have been transported from their place of origin by wind or water; however, those used for road construction are mainly in-situ (D'Hoor, 1954).

As road construction materials, they form the sub-grade of most tropical and sub-tropical roads, and can also be used as sub-base and base courses for roads that carry light traffic depending on their quality. Understanding soil behaviour, including that of the RTSs a requirement in solving

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engineering problems especially in the area of road construction. Engineering planning, design and construction, must be based on sound knowledge of the geotechnical parameters and engineering properties of the soil and sub-soil condition of the area where application is sort; because failures of engineering structures including road is one of the main causes of accident due to poor soil condition occasioned by the wrong application of constructional materials. We were motivated to undertake this study because of the incessant road failure along Benin-Auchi dual carriage way, as well as Ikpeshi and Igarra road covering a distance of over 164 km, and to understand the influence of geology in the process. RTSs obtained from sedimentary and basement complex terrain formed the sub grade, sub base and sometime base course of the roads found in the area (Okiti, 2018). These areas are within south-western Nigeria belong to the tropical climatic condition characterized by excess rainfall of about 1200 mm and average daily temperature greater than 25 °C (Bello et al., 2010; Omorogieva and Tonjoh, 2020).

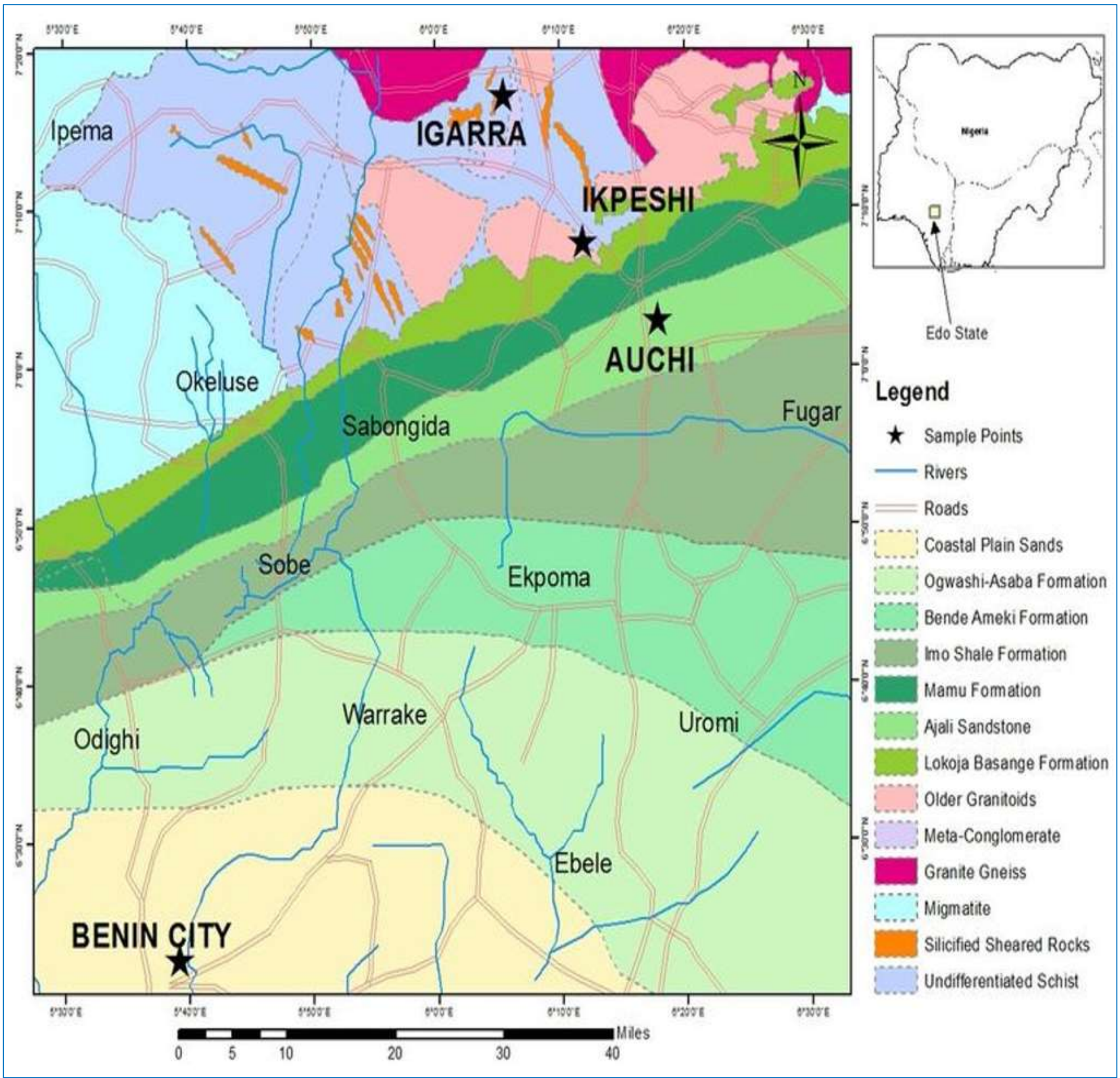

Fig. 1. Geological/sample location map

The study aimed at assessing the geotechnical properties of the four different RTSs obtained across basement complex and sedimentary terrains in Edo State, Nigeria to evaluate their suitability as earth material for road construction while acknowledging the role of the geology in the study area. This is because the usability of soils as pavement material depends on its strength in transmitting the axle-load to the sub-soil or sub-grade (the mechanical interlock). The characteristics and durability of any constructional material is a function of its efficiency in response to the load applied on it AASHTO (2002). To determine the efficiency of RTSs as construction material for road, the geotechnical properties such as the specific gravity, bearing capacity, shear strength, and Atterberg limits need to be analyzed. Thus, failure to investigate the engineering behaviour of soil as pavement material could lead to failure and collapse of several engineering structures including roads leading to economic waste and hardship (Onyeobi 1985; Ogunsenwo, 1989; Pavement Interactive, 2020).

To solve problems associated with road failure, it is imperative to understand the role of underlying geology and mineralogical composition of the soils in the course of road design, nature of the road, the quality of the sub grade, sub base and base courses to be applied as well as the bearing capacity of the soils. Failure to do this, the pavement will certainly fail which will may leads to road accident, economic waste and hardship, heavy traffic on the adjacent roads and increase in crime rate in the affected portion and neighbouring communities. The outcome of the study will provide the relevant information on the soil usability as pavement material in road construction.

2. Geology of Study Area

Etete location one (1) in Benin City is by underlain by sedimentary rock belonging to Benin Formation which has been described severally by Short and Stauble (1967), Ekweozor and Gormly (1983), Akujieze and Oteze (2006). Drifts and soil-cover characterize the formation over lateratized reddish brown clayey sand capping highly porous friable white sands, pebbly sands and clay stringers with basal indurated ferruginous pebbly-coarse grained sandstone (Akujieze, 2004). Benin Formation is poorly bedded and occasionally cross - bedded at greater depths (Akujieze and Irabor, 2014; Maju-Oyovwikowhe and Malomi, 2019). This region falls within the Niger delta sedimentary basin; it originated from the series of tectonic activities that occurred in the south Atlantic region during the Late Cretaceous (Murat, 1972; Edegbai et al., 2019; Short and Stauble, 1967; Edegbai, 2019).

Deposition of sediments in the Niger Delta Basin began in the Tertiary and continued into post Tertiary times till date. The basin consists of Benin, Agbada and Akata Formations which range from Eocene to Recent (Nwachukwu, 1976; Nwajide and Reijers, 1996). It is predominantly made up of sandstones (over 90%) with shale intercalations. Texturally, the grains are coarse, gravelly, locally fine grains and poorly sorted, grey sandy, silty shale with plant fossils in some portion of the basin (Ehinola et al., 2005; Edegbai et al., 2018; Ilevbare and Omorogieva, 2020).

Location two (2), Sabo quarter in Auchi occurs within the Benin flank of the Anambra Basin. The basin is one of the sub-basins in the Benue Trough that began in the Late Jurassic to Early Cretaceous (Reijers et al., 1997; Edegbai and Emofurieta, 2015; Okiotor and Asuen, 2019). The basin is about 40,000 km in length, and is bounded to the west by the Okitipupa Ridge, in the east by Abakiliki basin, and in the south by the Niger Delta basin (Edegbai et al., 2019; Omontese et al., 2019). Its basin fill is estimated to be about 5000-7000 m and contains mainly Cretaceous to Tertiary continental-marine sediments which suggests that sedimentation was tectonically controlled (Obi and Okogbue, 2004; Edegbai and Emofurieta, 2015; Okiotor and Ighodalo, 2020).

Location three (3) and four (4) which include Igarra and Ikpeshi lie within the Pre-Cambrian basement complex of Southwestern Nigeria. The basement rocks notably include migmatite gneiss complex, biotite-hornblende gneiss, metasediments and older granite intrusive (Rahaman, 1976). The metasediments occur as a supracrustal cover on the basement and consist of quartz-biotite, calc-gneiss and marble, met conglomerate and mica schist. This area is underlain mainly with metasediments, commonly referred to as the Igarra Schist Belt, which presumably overlies an older gneiss-migmatite basement, possibly of Liberian age (Ocan et al., 2003). The met sedimentary succession in Igarra area consists predominantly of pelitic to semi-pelitic rocks of low to medium-grade metamorphism such as quartz-biotite schist; mica schist; calc-silicate gneiss, marble and metaconglomerate (Odeyemi, 1990). These supracrustal rocks and the underlying basement were subsequently intruded by Pan African granites such as the Igarra batholiths and other minor intrusive including pegmatite, aplite, dolerite, lamprophyre and syenite.

3. Materials and Methods

3.1. Site description and sample collection

The sites include Etete (Benin City), Sabo (Auchi), Ikpeshi and Igarra in Edo State, Nigeria. The study area is situated within5°44'N and 7'37''N and, 5°44 and 6'43''E, and share common boundaries with neighbouring states of Kogi, Ondo, Delta and Anambra (Omorogieva and Tonjoh, 2020). Benin City is mainly lowlands cover with coastal plain sand and alluvial clay which is underlain by the Benin formation. The area is drained by Ikpoba and Ogba Rivers respectively (Ikhile, 2016). Conversely, Auchi, Ikpeshi and Igarra falls within the Guinea Savannah belt characterized with hills and pockets of valleys and flat plains. The vegetation consists of rain forest in Benin City, low lands and savanna in Igarra and Ikpeshi whereas Auchi is characterized by mosaic forest-grassland. Four samples of RTSs were collected cross the study areas with the aid of soil auger and spade. The samples were kept in a well labeled polythene bag, and afterwards transported to the laboratory for analysis. Samples collected were prepared for each laboratory test in accordance with British Standard 1377 (1990) part one (1). The tests carried out included; natural moisture content (NMC), PSD, Gs, Atterberg Limit Tests which include; liquid limit (LL), plastic limit (PL) and Plasticity Index (PL), standard compaction test (CT) and CBR. The rock types, general geology and the sample location map were designed with ArcGIS version 15.0 and represented in Fig. 1.

4. Results and Discussions

The NMC of a soil is the amount of moisture contained in the soil as at the time it was obtained. It is used to determine the shear strength of a pavement material for construction work. The results of the NMC in this study ranged from 9.05% to 16.8 % (Table 1). The sample from Etete in Benin City has the highest value of 16.80%, whereas in Sabo (Auchi), Ikpeshi and Igarra have 9.05%, 12.3% and 14.60% respectively. The variation in the values could be attributed to the rainfall pattern and the mineralogy of the weathered parent rocks in relation to the geology of the environment. The rainfall observed in the study area decrease from Benin City towards Igarra which is described as Guinea Savannah characterized with hills, pockets of valleys, flat plains and light rainfall compare to Benin City which is best described as tropical rainfall characterized with tall trees and canopy (Ojo and Ologe, 1999; Omorogieva and Tonjoh, 2020).

The NMC of soil is a function of the mineral content of the soil resulting from the weathering process of the parent rock (Tuncer et al., 1977). For example, the release of iron and aluminum sesquioxides increases the loss of silica and the dominance of new clay materials like smectites, allophones, halloysite, and as the weathering progresses, kaolinite is formed from the dissolved materials (Northmore et al., 1992; Omorogieva, 2018). Soils rich in clay minerals have the capacity to retain water than sandy soils because of the voids which are not interconnected and their affinity for water than quartz, the predominant constituent of sand as noted in the study area (Mohammed and Dahunsi, 2012; Chegg, 2020).

In Fig. 2, the relationship between OMC and NMC is shown. From the figure, it is revealed that NMC of Benin sample exceeded the OMC implying that the NMC must be reduced during compaction test to enable it meet the requirement as pavement material for engineering structures.

Table 1. NMC and its average for the study area

Location	Weight of Container	Weight of Container + Wet Soil	Weight of Dry Soil + Container	Weight of Dry Soil	Weight of Moisture	Moisture Content (%)	Average Moisture Content (%)
Benin City (Etete)	13.44	80.87	70.90	57.46	9.97	17.4	16.8
	17.46	82.49	73.44	55.98	9.05	16.2	
Auchi (Sabo)	15.95	81.50	75.71	59.76	5.79	9.70	9.05
	17.79	85.35	80.10	62.78	5.25	8.40	
Ikpeshi	16.53	85.89	78.05	61.52	7.84	12.70	12.30
	13.85	98.78	89.73	75.88	9.05	11.90	
Igarra	16.43	82.60	74.78	58.35	7.83	13.40	14.12
	16.28	85.62	77.04	60.76	8.58	14.12	

Furtherance to the NMC and OMC evaluation in the study, the soils were subjected to Gs. This parameter defines the degree of soil porosity (n) and void ratio (e); these assist in evaluating the quality of a soil as pavement material. The result of the Gs in this study shows that soil sample obtained from Sabo in Auchi axis has the highest Gs of 2.78, whereas Etete in Benin City, Ikpeshi and Igarra recorded 2.77, 2.66 and 2.63, respectively (Table 2).

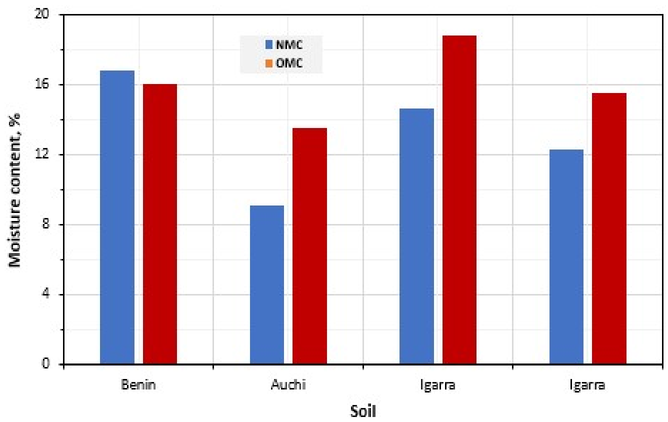

Fig. 2. Comparisons of NMC and OMC

According to Smith (1988), lateritic soil within the range of specific gravity 2.60 - 2.80 is regarded as standard material for pavement. The higher the Gs of a soil, the more resistant it is to erosion. Soils under examination have similar resistance capacities to erosion which is traceable to the geology because Gs is an important index property of soils that is closely linked with mineralogy and/or chemical composition of the soil make up (Maignien, 1966; Smith, 1988; Oyediran and Durojaiye, 2011). The higher the Gs, the higher the degree of laterization. Compaction and or water content test which determine the OMC at which the compacted soils would achieve maximum dry density (MDD) was also carried out. The results shows that the MDD for Benin, Auchi, Ikpeshi, and Igarra are 1.78mg/m3, 1.75mg/m3, 1.76 mg/m^3 and 1.77 mg/m^3 and a corresponding OMC of 16%, 13.5%, 15.51% and 18.81% respectively (Table 3).

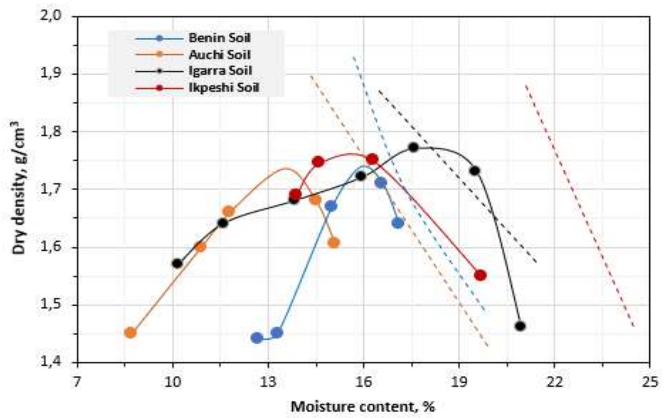

Fig. 3. Compaction curves of soils indicating zero air void lines

The compaction curves (Fig. 3) show that dry density (DD) increases with increasing water content up to a maximum and later decreases. The MDD values obtained in this study are within the range of 1.5-2.5 g/cm^3 specification for standard sub grade pavement material (Ogunsenwo, 1989).

The zero-air void line is a line depicting the points of 100% saturation (S=1), usually drawn on the moisture-density plot. Fig. 3 show the compaction curves with zero air void lines that is, the line, at which each sample becomes completely saturated with water.

Table 4 presents the results for particle size distribution, Atterberg test (LL, PL and PI). From the result, Igarra soil has the highest amount of clay-size particles (12.7%) while Benin, Ikpeshi and Auchi soils have relatively lower values of 6.2%,5.88% and 3.16% respectively. Conversely, Auchi soil has the highest amount of sand fraction (75%) while Benin, Ikpeshi, and Igarra soils have lower values of 64%, 63.2% and 30.66% respectively. The silt fraction ranges from 50.88% for the Igarra soil, 29.8% for the Benin soil, 28.92% for the Ikpeshi soil and 21.84% for the Auchi soil.

Table 2. Soil Gs and its averages for study area

Experiment	Benin City (Etete)		Auchi (Sabo)		Ikpeshi		Igarra	
Bottle Number	1	2	1	2	1	2	1	2
Weight of Bottle W_1	21.33	14.67	18.98	21.53	21.05	16.71	20.40	18.49
Weight of Bottle + soil W_2	52.55	48.22	55.39	56.49	59.80	57.31	45.31	47.77
Weight of Bottle +Soil +Water W_3	88.93	85.42	92.95	94.52	95.41	92.71	83.58	85.93
Weight of Bottle +Water W_4	68.88	64.12	69.51	72.22	70.66	68.04	68.38	667.87
Weight of Water When Full W_4-W_1	47.55	49.45	50.53	50.69	49.61	51.33	47.98	49.38
Weight of Water in Soil W_3-W_2	35.38	36.20	36.56	37.03	34.32	34.41	38.21	38.28
Weight of Soil W_2-W_1	31.22	33.55	36.41	34.96	38.75	40.60	24.91	29.28
Weight of Water Displaced by Soil $W = (W_4-W_1) -(W_3-W_2)$	12.17	13.25	13.97	1366	15.29	16.92	9.77	11.10
Gs of Soil $(W_2-W_1)/W$	2.79	2.74	2.81	2.76	2.77	2.55	2.65	2.61
Gs	2.77		2.79		2.66		2.63	

Fig. 4 shows that the Igarra soil has the highest LL of 43%, PL of 24.55% and PI of 18.45% followed by the Benin soil with LL, PL and PI of 23.45%, 16.49% and 6.96% respectively. On the other hand, Ikpeshi has a LL of 21.4%, PL of 14.4% and PI of 7% while the Auchi soil shows a LL of 19.10% and a PL of 0% signifying a non-plastic soil. To have a clearer picture of the implication of the particle (grain) size distribution, the coefficient of uniformity (Cu) was determined.

Table 3. Summary of compaction test results obtained in the study area

Location	OMC (%)	MDD (Mg/m^3)	Clay content (%)	Fines sand (%)
Benin City	16.00	17.80	6.20	36.00
Auchi	13.50	1.75	3.20	25.00
Ikpeshi	15.50	1.75	5.90	34.80
Igerra	18.81	1.77	12.70	63.50

Table 4. Sieve analysis and Atterberg Limits test results

Location	Benin	Auchi	Ikpeshi	Igarra
Sand (%)	64.0	75.00	64.50	30.70
Silt (%)	29.8	21.80	28.90	50.80
Clay (%)	6.20	3.20	5.90	12.70
Gravel (%)	-	-	0.66	5.80
LL (%)	23.45	19.10	21.40	43.00
PL (%)	16.49	Non-plastic	14.40	24.55
PI (%)	6.96	-	7.00	18.45
D_{60}	0.40	0.15	0.35	0.05
D_{10}	0.01	0.01	0.01	-
$Cu = D_{60}/D_{10}$	66.70	18.80	58.3	-

According to Chegg (2020), Cu is the ratio of the sieve size through which 60% (by weight) of the material passes to the sieve size that allows 10% of the material to pass. The expression is used to determine the gradability of soil particles in relation to engineering application. For example, if the value of Cu equal to 1, it means that the soil consists of only one grain size; in other words, the smaller the Cu, the more uniform the soil particle size would be.

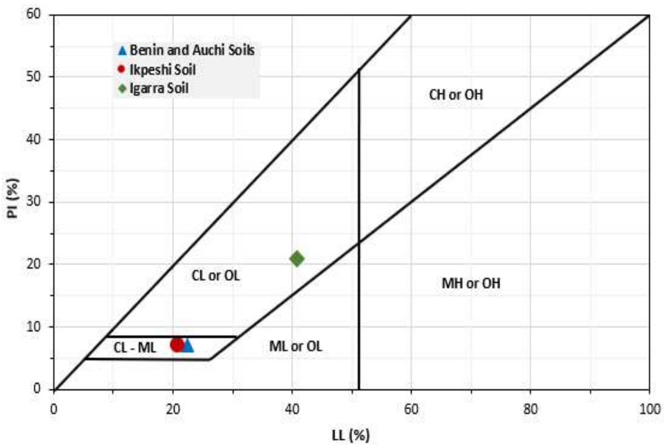

Fig. 4. Plot of soils on the plasticity chart

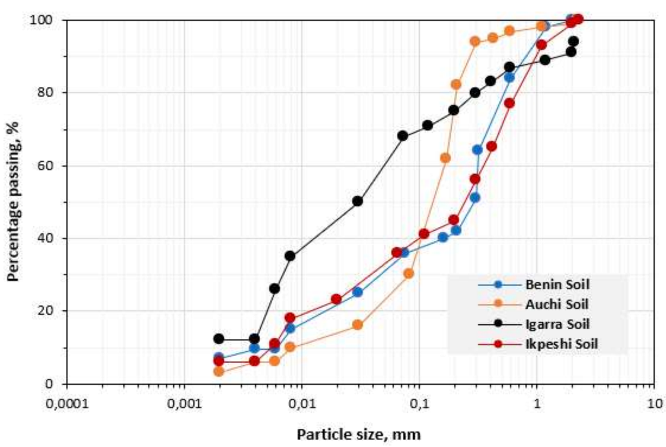

Fig. 5. Particle size distribution curves of soils

In this study, the values obtained for Cu (Table 4) shows that Benin, Auchi and Ikpeshi soils has a value ranging from 18.8 in Auchi to 66.7 in Benin. Auchi soil having a Cu of 18.8 is described as a good and well graded soil, whereas Benin and Ikpeshi with a value of 66.7 and 58.3, respectively means that the difference between the largest and smallest particles is large when compare to the smallest grain size. The variation in the grain sizes in Benin and Ikpeshi is attributed to rock types from which the weathered materials forming the laterite were sourced (Odeyemi, 1990; Akujieze and Oteze, 2006; Tijani et al., 2010).

Fig.5 represents the grading curve of the soils under investigation; by considering particle sizes only, the soil is adjudged a mixture of 30.7% sand, 50.8% silt and 12.7% clay with a little fraction of gravel. The British Standard Institution (1990) suggests that classification for soil samples with higher percentage fines is best carried out by the use of the plasticity chart (Fig. 4).

In view of this, Igarra soil was classified as well graded silty sand with inorganic clays of low to medium plasticity. Etete (Benin), Sabo (Auchi), and Ikpeshi soils sample particle size distribution curves consist predominantly of sand (Table 4) with little percentage of silt and clay. Benin (Etete) and Sabo (Auchi) soils were classified as well graded silty sand while the Ikpeshi sample was classified as well graded sandy silt (Unified Soil Classification System). Aside from the Auchi soil which is non-plastic, Benin and Ikpeshi soils were classified as inorganic silt of low plasticity (Fig. 4).

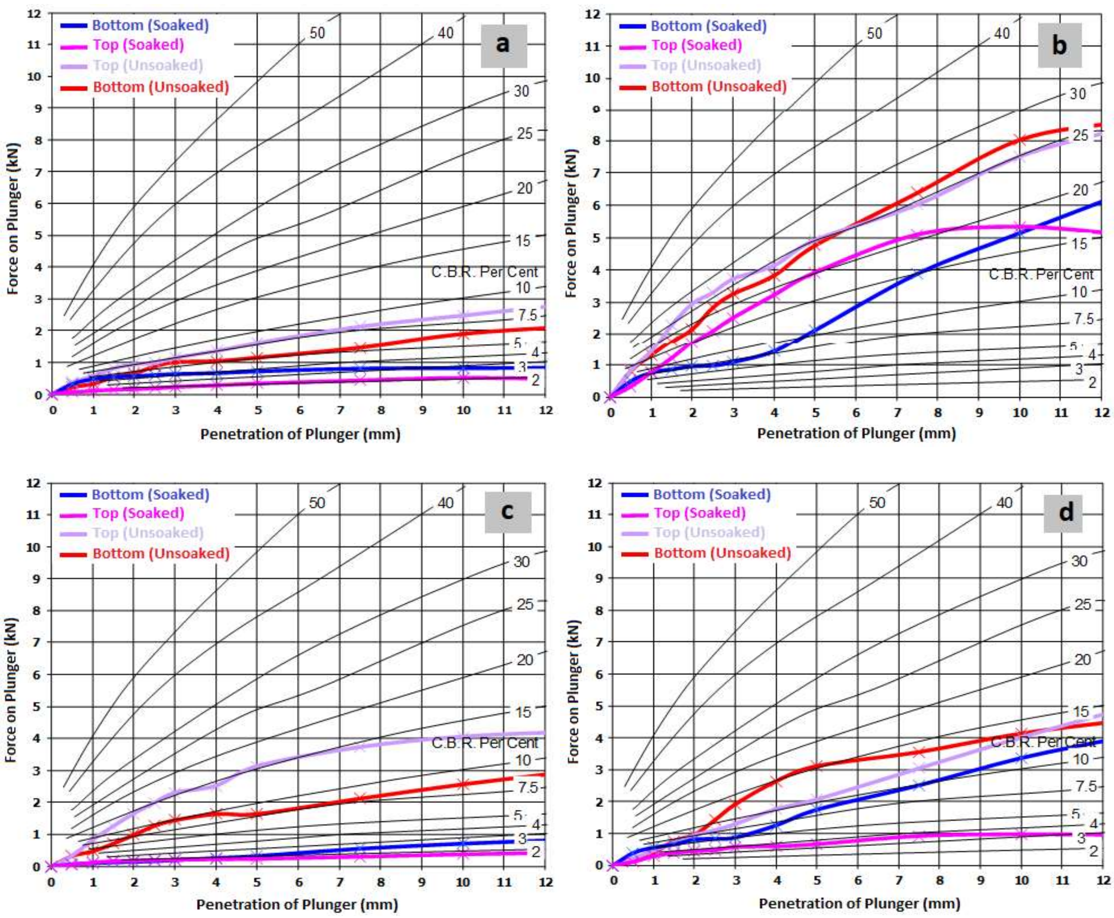

Fig. 6. CBR curve for soils: a) Benin Soil, b) Auchi Soil, c) Igarra Soil and d) Igpeshi Soil

Based on AASHTO, lateritic soil within Sabo in Auchi can best classify under the category of A-3 group whereas Benin, Ikpeshi, and Igarra soils are classify under the A-2-4 and A-2-7 group respectively (Pavement Manual, 2007). This indicates that the materials would likely be unsuitable for use as sub base and base course standard highway pavement material; although they better as an excellent/good sub-grade material. Furthermore, Federal Ministry of Works Nigeria (2013) specified that the LL and PI for sub-grade materials should not exceed 80%. This shows that the soil samples collected for this study satisfy the requirements for sub-grade materials.

Table 5 shows the values obtained from the CBR test carried out for both soaked and unsoaked soils in this study. Sabo (Auchi) soil shows CBR values of 9:24 (%) for soaked and unsoaked respectively. Ikpeshi show a value of 5:13 (%) for soaked and unsoaked, while Etete (Benin) and Igarra show a value of 3:1 (%) and 7:13 (%) for soaked and unsoaked condition respectively (Figs. 6a-d). This shows a reduction in the strength of the lateritic soils on account of soaking with Auchi soil having the highest strength reduction followed by the Igarra, Ikpeshi, and Etete (Benin) soils respectively. According to the Federal Ministry of Works (Nigeria), the standard specification for a material to serve as a sub-grade must have a CBR value of >10% after 48 hrs of soaking. Hence, Auchi and Ikpeshi soil can serve as a good sub-grade material, while Igarra and Benin soil can serve as a sub-grade material for class S1 roads which are designed to have a minimum thickness of 250 mm (Roy, 2016; Tender Documents Specification, 2020).

Stabilization of all soil samples for this study using lime or any other cementing material typically 2 to 5 percent by weight, removal and replacement of soil with better load bearing fill typically 0.3 - 0.6 m (1-2 ft.), bitumen-emulsion of 1.0 to 1.8; marble dust and bamboo leaf ash amongst others is necessary for it to serve as a sub base and base pavement material (Osula, 1991; Okogbue and Onyeobi, 1999; Amu and Adetuberu, 2010; Federal Ministry of Works, 2013; Rodriguez, 2020).

Table 5. Summary of CBR test result

Location	Soaked soil sample (%)	Unsoaked soil sample (%)
Benin City	03	07
Auchi	09	24
Ikpeshi	05	13
Igerra	01	13

When roads are under designed with substandard materials, the road would not last long before it will collapse; consequently, leading to accident of several magnitudes (Imran et al., 2015). To avert the imminent dangers associated with road failure, care must be taken in the use of pavement materials by subjecting it to appropriate test while putting the role of the geology of the area into serious consideration (Onyeobi, 1984; Okigbo, 2012; Justin, 2018).

5. Conclusion

The Gs of the RTS in this study is within the range of soil used as sub base for road construction. However, according to the USCS and AASHTO classification, the soils being silty sand, sandy silt under the category of A-3, A-2-4 and A-2-7 respectively can only best be applied as sub grade material. Based on these classifications, the soils can only be used as sub-grade but not suitable for neither sub-base nor base course for roads construction. Hence, Auchi and Ikpeshi soil can serve as a good sub-grade material, while Igarra and Benin soil can serve as a sub-grade material for class S1 road which are designed to have a minimum thickness of 250 mm. The mineralogy and or chemical composition of the soil material couple with the application of the soil material as sub course and or sub base material as well as constructional problem (s) are responsible for the incessant road failure recorded in the area. Therefore, for the purpose of engineering structures like road, it essential to understand the quality of the soil material to be used as well as the geology of the soil material vis a vise the mineralogy and or chemical composition.

Acknowledgement

Authors appreciate the guidance and input of Professor T.U.S Onyeobi of blessed memory. The laboratory assistants rendered by Mr. Elvis of the Civil Engineering Department; University of Benin is well appreciated.

Compliance with Ethical Standards

There are no conflicts of interest in this article. Dr O.M Omorogieva and Isaac Okiti designed the research in consultation with late Professor T.U.S Onyeobi. Field exercise and sample collection was done by Dr O.M Omorogieva and Mr. Okiti Isaac. The initial manuscript was written by Isaac and edited by Dr. O.M Omorogieva. The final draft was read through by both authors and approved for publication.

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