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Evaluation of Swelling and Slaking Characteristics of Shales from Okigwe Area, Southeastern Nigeria

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Abstract The swelling and slaking characteristics of shales from Okigwe area, Southeastern Nigeria were investigated and evaluated in this study. Two (2) rock samples were collected (one from Leru to represent Mamu Formation and the other from Ihube-Okigwe to represent Nsukka Formation). The samples were subjected to field observations and laboratory measurements of geotechnical properties including Atterberg Limits, Linear Shrinkage, Free Swell, Slake Durability and mineralogical composition. Results of the study show that samples from Mamu Formation and Nsukka Formation have Liquid Limit of 59% and 40%, Plastic Limit of 28.1% and 18.6%, Plasticity Index of 30.1% and 21.4%, Linear Shrinkage of 16% and 10%, Free Swell of 60% and 40% and Slake Durability Index of 44.4% and 41%, respectively. The results indicated that the sample from Mamu Formation (Leru) has high Swelling potential, high degree of expansion and low Slake durability while the sample from Nsukka Formation (Ihube-Okigwe) has medium swelling potential, low degree of expansion and low Slake durability. X-ray diffraction analysis indicated the presence of Smectite (montmorillonite) as the major clay mineral which is responsible for swelling and slaking of the soils. Leru shales have more expansive minerals than Ihube shales. Based on the geotechnical and mineralogical evaluation, Leru Shales (Mamu Formation) are more expansive than Ihube-Okigwe Shales (Nsukka Formation) because they have higher swelling potential. Many failures of roads and building foundations in the area are believed to be caused by the presence of these swelling soils/rocks. The two rock formations exhibit similar degree of expansion (in terms of low degree of expansion) and low Slake Durability Index.

Keywords Swelling, slaking, shales, minerals, Okigwe

1. Introduction

Shales are fine-grained laminated or fissile clastic sedimentary rocks with predominance of silt and clay as the detrital components [1]. They are formed from silts and clays that have been deposited and compacted or hardened into rocks. On the basis of texture therefore, the most common types of shales are silty shale (silt dominant) and clay shale (clay dominant). These two types of shales are also called argillaceous. Occasionally, shales may also contain appreciable amounts of sands in which case they may be called sandy shale (arenaceous shale). Black shales with high proportion of organic matter content are called carbonaceous or bituminous shale. Shales that contain high amount of lime are known as calcareous shale [2].

Shales are the most abundant of all sedimentary rocks (constituting about 60%) and are distributed in wide range of geologic ages from Paleozoic to Cenozoic [3-4]. Their colours may range from white through green to grey and black depending on their composition and environment of deposition. It is obvious from the above that shales are highly varied in nature and composition.

Shales and the soils derived from them are some of the most troublesome materials to build on. They are subject to changes in volume and competence that generally make them unreliable construction substrates. The clay minerals in some shale-derived soils have the ability to absorb and release large amounts of water. This change in moisture content is usually accompanied by a change in volume which can be as much as several percent. These materials are called "expansive soils". When these soils become wet, they swell and shrink when dry. Buildings, roads utility lines or other structures placed on or within these materials can be weakened or damaged by forces and motion of volume change. Shale is the rock most often associated with landslides.

In this study, the swelling and slaking characteristics of shales from Leru (Mamu Formation) and Ihube-Okigwe (Nsukka Formation) in Okigwe, South-eastern Nigeria were investigated. The geotechnical properties of the shales obtained from the study were also used to classify the shales in terms of swelling potential and degree of expansion.

2. Location and Geology of the Study Area

Okigwe lies between latitude 5°46'-5°56'N and longitude 007°18'-007°25'E with an altitude of about 300m above sea level. It is located in Imo State at the south-eastern region of Nigeria. The area shares common boundaries with some other states of the nation like Enugu and Abia State. The major towns in the area are Okigwe Town, Ihube-Okigwe Nkoto-Okigwe, Umulolo, Anuro- Okigwe, Leru, Lokpaukwu, Lekwesi and Ubaha towns (Fig.1). The areas can be accessed through Enugu-Port Harcourt Expressway, Umunze-Okigwe road with other secondary and minor roads.

The area is largely drained by Imo Rivers with a dendritic drainage pattern. The topography of the area is gently undulating and punctuated by a few low hills, some of which are relics of sandstone and siltstone deposits that are more resistant to denudation than the surrounding shales. There are two distinct seasons in the area, the rainy season that lasts from April to October and the dry season that lasts from November to March. The average annual rainfall in the area is 2000mm (Nigeria Meteorological Agency, 2007). The area has humid tropical climate a mean annual temperature range of 27° – 28°C [5] while the average air pressure is about 1050 millibars.

Okigwe area, geologically, lies within the Anambra Sedimentary Basin, which constitutes a major depocenter of clastic sediments in the southern portion of the lower Benue Trough [6-7]. The Benue Trough is a rift basin in Central West Africa that exceeds NNE-SSE from about 800km in length and 150km in width [8]. It is a major structural feature in Southeastern Nigeria and was developed during the separation of South America and opening of South Atlantic Ocean at the site of RRR triple junction [9-11]. The geologic formations of Anambra Basin are Nkporo Formation, Mamu Formation, Ajali Formation, Nsukka formation Imo Shale, Ameki Formation and Ogwashi Asaba Formation [12-18]. Table 1 shows a generalized stratigraphic sequence of sedimentary rock in the study area.

Table 1: Generalized stratigraphic sequence in Okigwe Area [Modified from Reyment [13], Offodile [14], Mode [6] and Ofoegbu, [16])

Age	Formation	Lithological Characteristics
Paleocene (55-65 m.y.)	Imo Formation (Imo Shale)	Blue to dark grey shales and subordinate sandstone member (Umuna and Ebenebe sandstone)
Maestricitian (65-68 m.y.)	Nsukka Formation	Alternating sequence of sandstone and shale with coal seams
Maestricitian (65-68 m.y.)	Ajali Formation	Friable sandstone with cross bedding. Alternating sequence of sandstone, siltstone, shale and claystone with coal seams
Campanian (68-78 m.y.)	Mamu Formation Nkporo Formation (Enugu Shale)	Shale and mudstone with sandstone lenses

This work focuses on the Leru and Ihube-Okigwe area which represents the Mamu Formation and Nsukka Formation respectively. The Nsukka Formation was deposited during the Upper Maestritchian, it consists of alternating succession of sandstones, dark shales and sandy shales with thin coal seanms at various horizons and was formally known as "Upper Coal Measures" [19-20]. It is overlain by the Paleocene Imo Shale and lies comformably on the Ajali Sandstone, it transgresses directly into the Precambrian in the Okiti-pupa area of western Nigeria. Tattam [19], Simpson [21], Reyment [13], Reyment and Barber [20], Kogbe [22], Obi et al [23], noted that Nsukka Formation consist of an alternating succession of sandstone, dark Shale and sandy shale, with thin coal seams at various horizons. Fragmentary plant remains are abundant in the Nsukka Formation and where the carbonaceous shales have been ferruginised in the zone of laterization, leaf impressions are preserved. Mamu Formation was deposited during the Maestritchian and was previously known as the "Lower Coal Measures", it consists of sandstones, shales, mudstones and sandy shales with coal seams at several levels. It overlies the Nkporo Shale without evidence of break in sediment. The shale and mudstones are dark blue to gray and grade into sandstones [12]. Tattam [19], Reyment [13], Murat [24], Dessauvagie [25], Obi et al [23], Oboh-Okuenobe et al [26] described that Mamu Formation contains a distinctive assemblage of Sandstone, Shale, Mudstone and Sandy Shale, with Coal Seams at several horizons. The sandstones which are fine to medium grained and white or yellow in colour, are normally well-bedded and occasionally cross-bedded. They are regarded as the lower coal measures.

Shaley formations of most rocks originates from marine depositional environment and are likely to contain significant amounts of montmorillonitic clay mineral, a swelling clay mineral that will also cause the swelling of any soils that they are associated with [27].

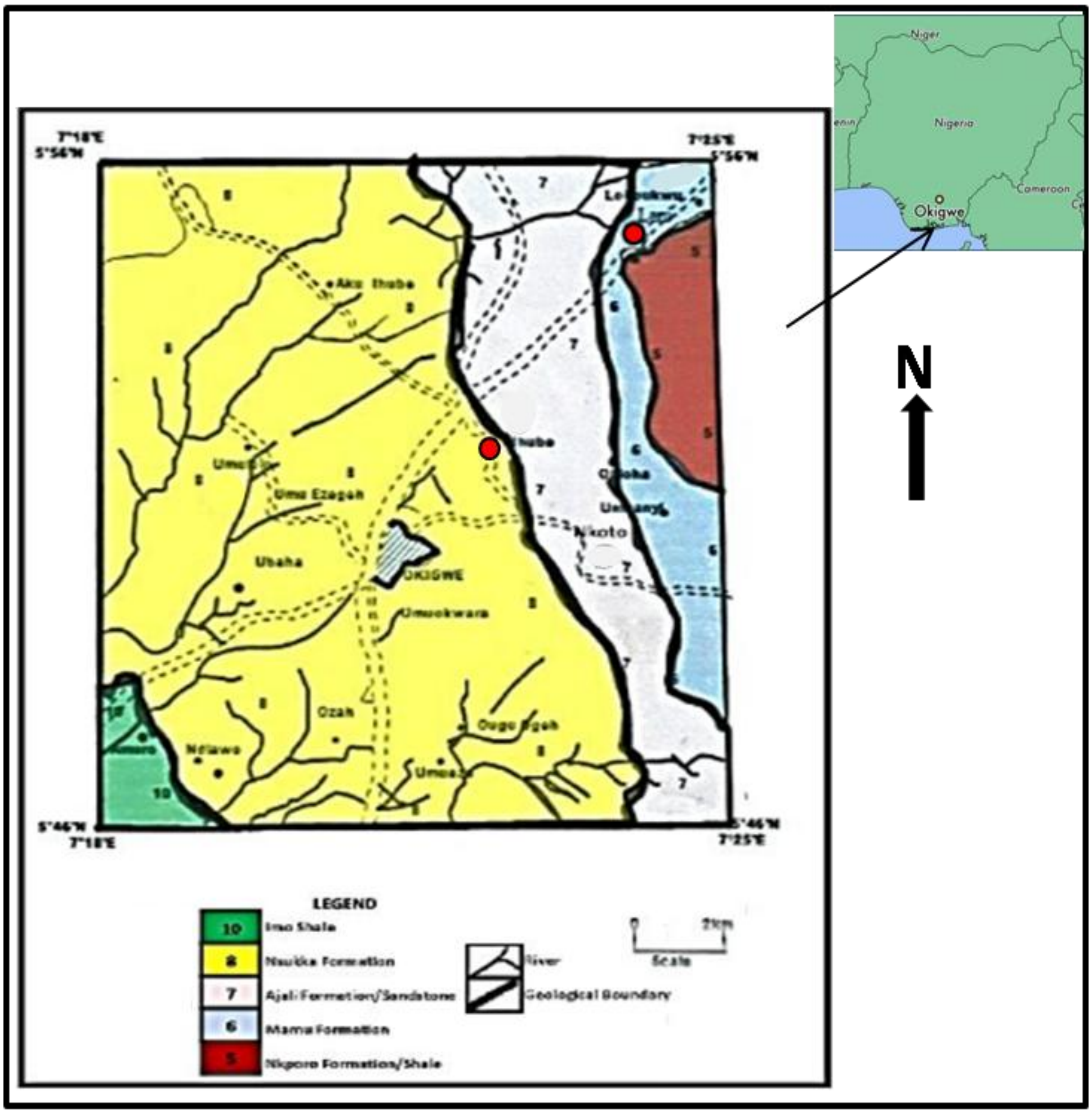

Figure 1: Geologic map of the study area (Okigwe) and locations of sampling points (Adapted from Uduji et al. [28])

3. Materials and Methods

3.1. Field Studies and Sample Collection

The field studies were carried out to identify the presence of suspected expansivity of samples, their parent rocks from which they are derived and their destructive effects on nearby engineering structures. Two samples (shale) each weighing about 500gm were collected from Leru and Ihube areas of Okigwe (as shown in Fig. 1) to represent Mamu Formation and Nsukka Formation respectively in the study area. Table 2 shows the description of sampling locations. The shale samples were therefore collected by shovels from the exposed outcrops, bagged in clean sample bags immediately for preservation of their moisture content, labeled and taken to the laboratory for various tests and analysis.

Table 2: Location of Sampling Points for Shales Used in the Study

S/No.	Location	Geologic Formation/ Parent Rock	Location Coordinates		Location Description
			Latitude	Longitude	
1	Leru	Mamu Formation	5°52'N	007°24'E	Km 20, Okigwe-Enugu Express Road
2	Ihube-Okigwe	Nsukka Formation	5°52'N	007°22'E	Km 4, Okigwe –Enugu Expressway

3.2. Laboratory Tests

The shale samples were subjected to mineralogical (x-ray diffraction analysis) and geotechnical tests such as Atterberg limits, free swell and slake durability tests.

3.2.1. Free swell test

Free Swell test was performed on about 200g of each sample from Ihube and Leru to evaluate the swelling potential of the soil in the Okigwe area of Southeastern Nigeria. About 200g of the sample was dried in an oven at about 100-110°C after which it was passed through a 425 micron sieve. Samples of about 100g were placed in a cylinder filled with 400ml of water and the other 100g placed in a container filled with 400g of kerosene. Entrapped air bubbles were removed by stirring with clean glass rod. The samples were both left to settle for 48 hours. The final constant volume of the samples was taken in both containers. Since kerosene is a non-polar liquid causing very little or no swelling of the soil(control experiment) and read as the original volume of sample while the volume of the second cylinder containing distilled water is taken as the free swell level.

3.2.2. Slake durability test

In order to assess the resistance offered by the samples to weathering and disintegration (durability) when subjected to at least two standard cycles of wetting and drying [29], the Slake durability test was carried out with approximately 400g of the sample fraction, passing the 19mm mesh sieve and retained on the 12.5mm mesh sieve and dried at temperatures 110°C ± 5°C. The sample was then placed in the Franklin's apparatus (a steel mesh drum of 2mm mesh size). The drum was then placed in a container filled with water to a level 2mm below the drum axis and rotated at a 20 revolutions per minutes (20 rpm) for 10 minutes. The samples was then removed and dried in an oven at about 110°C ± 5°C.this completes one cycle, this procedure is then carried out for two or more cycles of alternate rotating in wetting and drying for each of the samples.

3.2.3. Atterberg limit test

The moisture content of a soil at the points where it passes from a stage to the next are known as consistency limits. These consistency limits are based on the concept that a fine grained soil can exist in any four stages depending on its water content. Three of the tests were carried out within the scope of this work.

3.2.3.1. Liquid limit (WL or LL)

The Cassangrade apparatus method was used to determine the liquid limit of the samples. The air dried soil was sieved through an ASTM sieve No. 40 (0.43mm opening). Distilled water was added to about 200g of the sample and mixed thoroughly to a uniform paste. A portion of the paste was placed in the Cassangrade and leveled off to a maximum depth of 1cm. then the grooving tool was drawn through the sample along the axis symmetrical to the cup (from the center of the hinge). The tool was held perpendicular to the cup at the point of contact. The handle was turned at a constant rate of blow per second until two part of the soil come in contact at the base of the groove (the number of blows at which this is achieved was recorded). Approximately 10g of the sample or less was taken near the closed groove for moisture content determination. The tasted sample was then removed and remixed. Changing of the water content of the soil and repeating steps 3-5 were used to obtain four water content determinations within the range of 10 – 15 blows. The samples were drier at the start for convenience and the values were obtained with increasing water content. The moisture content was then plotted against the number of blows. The water content that corresponds to 25 blows on the graph is termed the Liquid Limit.

3.2.3.2. Plastic limit (WP or PL)

About 20g of the sample used in the liquid limit was mixed with distilled water t form a uniform paste. A portion of the sample was used to mould a thread. The thread was rolled on a glass plate until it attained a diameter of 3mm when cracks were seen on it. It the thread is less than the desired 3mm in diameter and does not crack, it indicates that the sample is wetter than the plastic limit. It shows a crack when it's still greater than 3mm, that means is drier than the plastic limit. The moisture content of the 3mm diameter threads are then determined. The steps 1-4 were repeated to obtain three or more determinations and the average of the values of the moisture content which gives the plastic limit of the soil.

3.2.3.3. Linear shrinkage (LS)

A thin film of grease was applied to the linear walls of the mould to prevent the sample from sticking to it. About 150g of the samples were mixed to a homogenous paste with moisture content approximately close to the liquid limits of the samples. The homogenous paste was placed in the mould with the aid of a palate knife. The samples adhering to the sides of the mould were wiped off with a damp cloth. The samples were then air dried until it has shrunk away from the walls of the mould. Then it was transferred to an oven to complete the drying at about 60-50°C it shrinkage has ceased, then at 105-110°C to complete the drying. The mould and samples were allowed to cool, and then the mean length of the sample bar was measured. The linear shrinkage of the soil is calculated as [33]:

$$\% \; Linear \; Shrinkage = \frac{Initial \;\; length \; of \; sample \; - Length \; of \; oven \; dry \; sample}{Initial \;\; length \; of \; sample} \; x \; 100$$

3.2.4. X-ray diffraction test

The XRD was performed with PW 1800 goniometer supply diffractometer with Cuk radiation generation at 40KV and 30mA, as specified by Brindley [30], Carroll [31] and Velde [32]. In this technique, about 10 grams of the air dried sample passing 0.063mm sieve were gently ground in an agate mortar to avoid possible contamination with other materials. Preparations of the powdered soil samples were then made for X-ray runs. This was done by filling a thin-walled glass capillary tube (about 1cm length) with powdered sample and fixing the wax-scaled tube to the end of a brass rod. A scanning rate of 2 degrees/minute from 0 to 60 was used to identify the clay minerals and non-clay minerals (bulk of random analysis).

The diffractogram obtained for the samples were quantitatively interpreted by comparing the peaks/counts of the diagnostic d-value (D)/2 of equivalent minerals as established by Joint Committee on Powder Diffraction Standards [34]. A computer program attached to the instrument records automatically the peaks/concentration of the various minerals at various d-value (D)/2 angles in the samples.

4. Results and Discussion

4.1. Results

The results of geotechnical analysis which include Atterberg Limit, Free Swell and Slake durability tests are shown in the Table 3 below. Fig. 2 and 3 are X-ray diffraction results for Leru and Ihube.

Table 3: Results for Various Geotechnical Analysis

Parameters (%)	Nsukka Formation (Ihube)	Mamu Formation (Leru)
Natural moisture content	10	22.5
Liquid Limit	40	59
Plastic Limit	18.6	28.1
Plasticity Index	21.4	30.1
Linear Shrinkage	10	16
Free Swell	40	60
Slake durability index	41	44.4

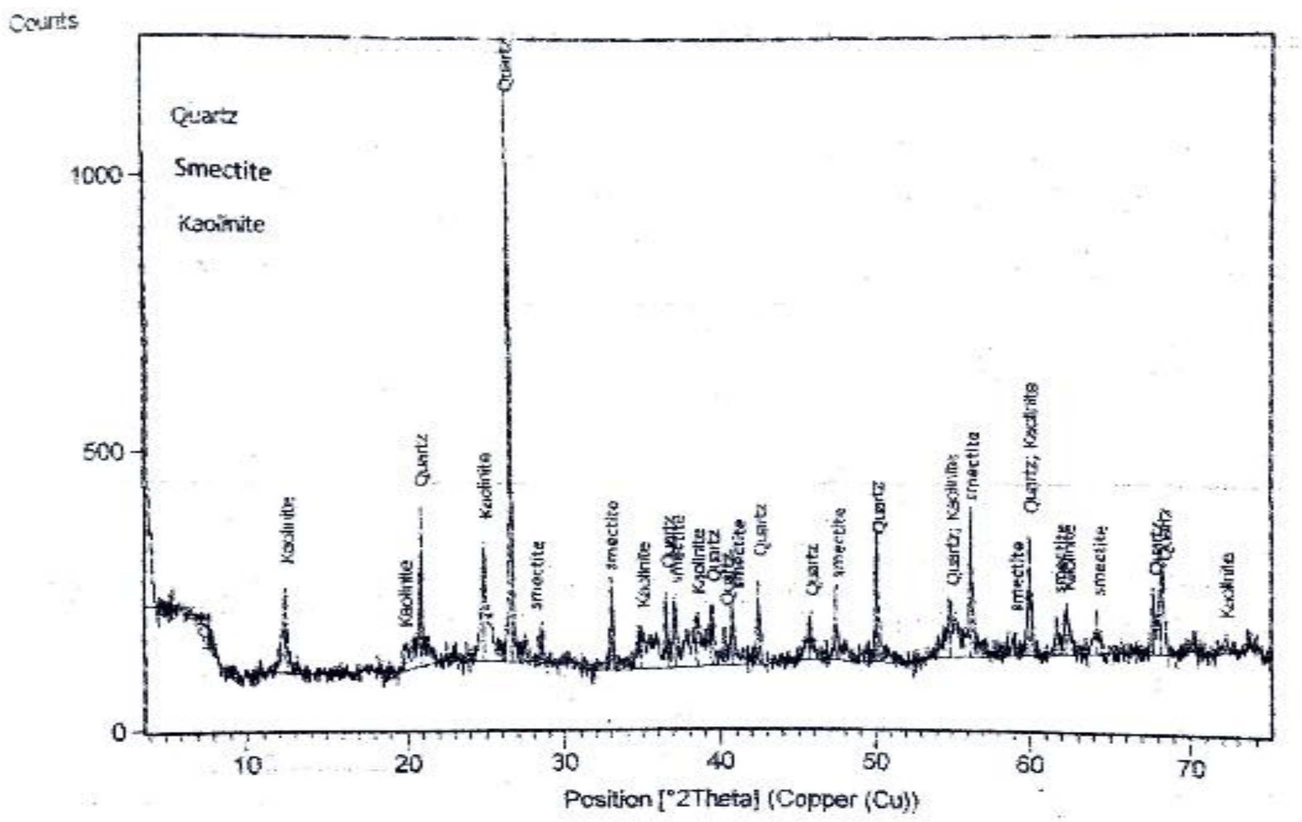

Figure 2: X-ray diffraction result for Leru shale (Mamu Formation)

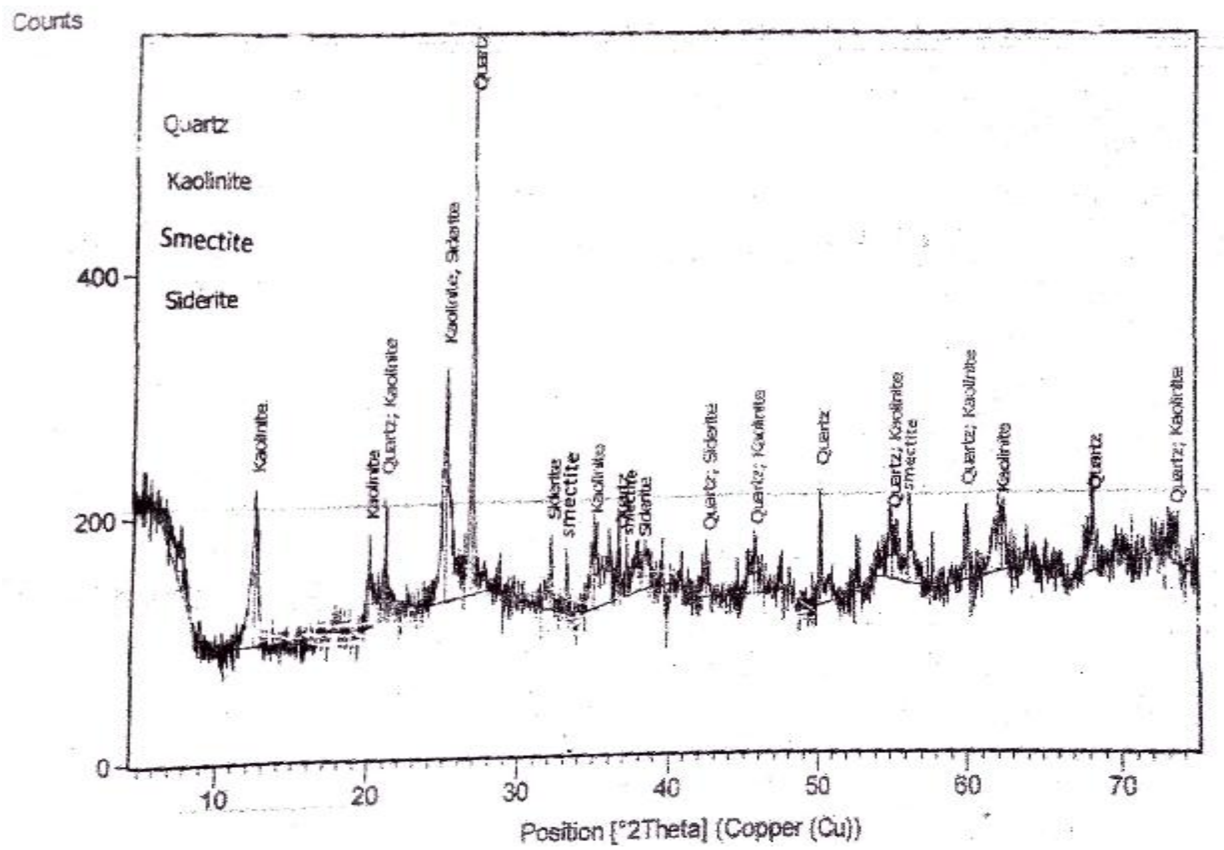

Figure 3: X-ray diffraction result for Ihube-Okigwe shale (Nsukka Formation)

4.2. Discussion

4.2.1. Atterberg limit

A relationship between Atterberg limits and linear shrinkage was established by Heidema [35] who noted that the relationship is more defined with plasticity index than with liquid limit. Ola [36] created a table showing these relationships for soils in Nigeria as shown below:

Table 4: Relationship between Plasticity Index (PI) and Swelling Potential [36]

Plasticity Index (PI)	Swelling Potential
> 1	Low
15 – 25	Medium
25 – 35	High
> 35	Very high

The Plasticity Index of the samples from Leru and Ihube are 30.1 and 21.4 respectively as shown in the result and according to the above table, their swellings potential are medium and high respectively.

4.2.2. Free swell

Dawson [36] also correlated the degree of expansion of some Nigeria soils with their free swell values. He related as high degree of expansion such soils where free swell is above 50 and low degree of expansion such soils where free swell is below 50. The relationship between the differential free swell and degree of expansion is shown in the table below.

Table 5: Relationship between Free Swell and Degree of Expansion [36]

Free Swell %	Degree of expansion
< 50	Low
> 50	High

The samples from Leru (Mamu Formation) with 60% free swell posses a high degree of expansion and Ihube-Okigwe (Nsukka Formation) with 40% free swell posses a low degree of expansion according to the above table.

4.2.3. Slake durability

Generally, the slaking behavior of shale and other argillaceous rock is a reflection of their slake durability index. Based on this fact, Franklin and Chandra [29] suggested a method of classification and characterization on the bases of their durability characteristics.

Table 6: Classification and characterization of Durability (after Franklin and Chandra [29])

Classification of Durability		Slake Durability Index
Soil-like	Very low	0 – 25
	Low	25 – 50
	Medium	50 – 75
	High	75 – 90
Rock-like	Very high	90 – 95
	Extremely high	95 – 100

From the table above, it is seen that Mamu Formation shale has SDI value of 44.4% and Nsukka formation shale has SDI value of 41% which can be formed as soil with low durability. Because of the SDI, the two samples behave more like soil.

4.2.4. X-Ray diffraction (XRD)

Typical diffractogram of the Okigwe area shales of Ihube and Leru shows prominent quartz, kaolinite and mixed layer peaks. The prominent basal reflections of the 'mixed layer' clay minerals, kaolinite, Smectite, siderite and quartz, as indicated by the strong and sharp peaks which are indications of moderate to well crystalline mineral components as opposed to poorly crystalline and disordered, evidence by blunt peaks [38]. The clay mineral assemblage therefore, comprises kaolinite, vermiculite-montmorillonite mixed layer clay. Quartz is the main iron clay mineral detected from the XRD traces. From Fig. 2 and 3, it was seen that samples from the two locations contains expansive minerals such as Kaolinite and Smectite. Leru shales have more expansive clay minerals than that of Ihube shales.

5. Conclusion

The geotechnical investigations and mineralogical identification of both Leru and Ihube shales to represent Mamu Formation and Nsukka Formation respectively show that both samples are expansive with free swell of 60% and 40%, slake durability index of 44.4% and 41% and plasticity index of 30.1% and 21.4% respectively. The Leru shales (Mamu Formation) have higher swelling and shrinking capacity than that of Ihube shales (Nsukka Formation). The x-ray diffraction analysis on the samples confirms the presence of Kaolinite and Smectite (Montmorillonite) as the dominant constituent and the most expansive clay mineral contents of the studied samples.

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