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GEOTECHNICAL ASSESSMENT OF RESIDUAL CLAY IN ZARIAGI, LOKOJA, NORTH-CENTRAL NIGERIA: IMPLICATION FOR INDUSTRIAL APPLICATIONS

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ABSTRACT

Clay is one of the world's most important and oldest building materials but also poses some challenges for civil and geotechnical engineers. Hence, understanding its geotechnical properties is key to the determination of their industrial applications. The geotechnical characteristics of six residual clay samples from the crystalline basement rocks in Zariagi, Lokoja, north-central Nigeria, were evaluated to determine its suitability for construction and civil engineering. Parameters assessed included particle size distribution, consolidation, specific gravity, Atterberg limits, linear shrinkage, loss on ignition, compaction, and permeability. Grain size analysis and Atterberg limit tests classified the samples as clayey. Liquid limit ranged from 36% to 37%, indicating low plasticity. The plastic limit ranged from 33.38% to 34.66%, and the plasticity index from 2.14% to 2.71%, suggesting the clay exhibits low to medium swelling potential when wet and can withstand volumetric shrinkage when dry, meeting the requirements for barrier soils. Compaction tests revealed an optimum moisture content (OMC) of 14.90% to 18.50% and maximum dry density (MDD) of 1270 kg/m³ to 1320 kg/m³, indicating suitability for building construction. Linear shrinkage percentages ranged from 2.86% to 4.29%, indicating moderate linear and low volumetric shrinkage. Loss on ignition values from 3.74% to 4.49% suggested low organic matter content and the absence of swelling clays. Permeability values ranged from 0.000133 cm/sec to 0.000140 cm/sec, suggest moderate permeability. The results suggest the Zariagi clay is suitable for barrier soil and building construction applications.

Keywords: Residual clay, Geotechnical assessment, Lokoja, North-central Nigeria

INTRODUCTION

Prior to the emergence of petroleum in the mid-1970s, the solid minerals sub-sector was second only to agriculture in generating export earnings. Since Nigeria's economy depends mainly on oil and gas (Shuwa & Sabiu, 2019) and with the fluctuating global oil prices and a downturn in the Nigerian economy, there is a need to develop strategies that can take advantage of the opportunities in the nation's industrial mineral resources within a diversified economy. Clay minerals, one of the oldest and most abundant industrial materials globally, are notable for their versatility, with a projected global market value of USD 5.87 billion by 2030 (Grand View Research, 2020). However, they present challenges for civil and geotechnical engineers.

Clay refers to a variety of fine-grained, earthy materials that become plastic and tenacious when wet and harden permanently when baked or fired (Alege et al., 2014). Studies have shown that many natural resources in Nigeria, especially clay, have not received sufficient attention (Aaron & Ishmael, 2015) and hence the need to explore the rich local clay deposit within Nigeria and their industrial/relevant applications. It is common practice to assess materials like clay for suitability by considering their specific and general properties for design and construction purposes. In a similar study, Shuaib-Babata et al. (2016) investigated the suitability of using Ado Ekiti, Akerebiata (Ilorin), and Birni Gwari (Kaduna) clays for the production of household ceramic water filters. For effective material usage, engineers must fully understand the various properties of these materials. Reliable information on material characteristics can be obtained from physical and mechanical tests, aiding in their optimal and appropriate application.

Geotechnical investigation of clay soil is crucial before constructing any structure, as the load of the structure is eventually transferred to the underlying soil. For the structure's stability, the soil must withstand the load. The foundation transmits the structure's loads to the underlying material. Therefore, understanding the geotechnical properties of clay soils is essential for determining their industrial applications. Research has shown that the geotechnical properties of soils play a crucial role in determining the stability of construction materials and civil engineering structures. Some structures, such as buildings and roads, fail prematurely due to insufficient consideration of subsurface soil layers, leading to collapses (Ashioba & Udom, 2023).

This study tends to bridge that gap by considering the geotechnical characteristics of the residual clay derived from the crystalline basement rocks underlying Zariagi area in Lokoja, northcentral Nigeria, using parameters like particle size distribution, consolidation, specific gravity, Atterberg limits, linear shrinkage, loss on ignition, compaction, and permeability with a focus on uncovering it suitability in construction and civil engineering works.

Description of the Study Environment

Geographic Location, Geomorphology and Geology

Lokoja, where the Niger and Benue rivers meet, is situated between latitudes 7º45' and 7º53'N and longitudes 6º39' and 6º48'E. The city experiences two seasons: the rainy season spans from April to October, while the dry season ranges from November to March, and it falls within the Guinea Savannah vegetation belt. The annual rainfall averages about 1150 mm, with an average temperature of about 27.7°C. Lokoja covers a total land area of approximately 63.82 sq. km (Adetunji & Isah, 2015). During the dry season, from November to February, temperatures can rise to between 33ºC and 36ºC. The vegetation is characterized as Guinea Savannah, with denser gallery forests along some rivers. The area is underlain by the basement complex, which primarily consists of quartzo-feldspathic granite, gneisses, and schists (Hockey *et al.*, 1986).

The study area lies between latitude 7º46’00’’N to 7º50’00’’N and longitude 6º32’00’’E to 6º36’00’’E and a total area of 50km^2. The area is situated on a topographical map of Lokoja sheet 247 North West of the Federal Survey of Nigeria. The area on a subset base map of scale 1: 50,000 (Fig. 1), is located near Zariagi village in Lokoja local government area of Kogi State, north-central Nigeria. It is bounded to the north by Agbaja plateau and to the south by Obajana. All are underlain by the crystalline rocks of Precambrian Basement Complex of Nigeria.

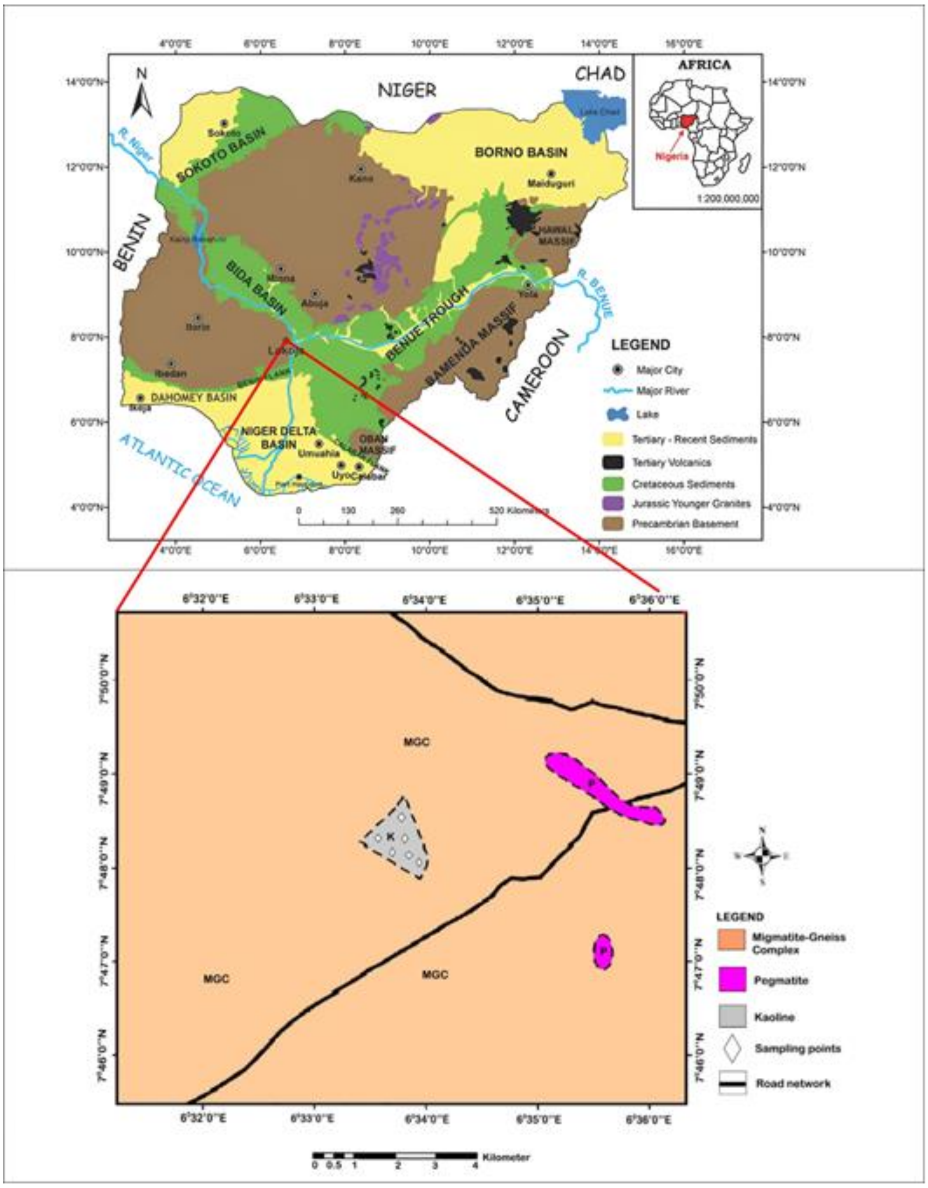

Figure 1: (a). Generalized geological map of Nigeria (adapted from Lar *et al*., 2018) and (b.) Geological map of the Zariagi area showing the kaolin clay deposit

MATERIALS AND METHODS

The studied samples are from the claystone deposit near Zariagi village. Six clay samples were collected from six hand-dug pits at the following coordinates: N7° 48' 10.11" E6° 33' 54.13" N7° 48' 10.82" E6° 33' 53.34", N7° 48' 11.65" E6° 33' 53.48", N7° 48' 11.33" E6° 33' 54.46", N7° 48' 12.27" E6° 33' 54.85", N7° 48' 12.71" E6° 33' 55.65" with a varied depth between 4.0 to 6.0 m deep and contained 1.0 to 1.5 m thick claystone horizons. The sampling was performed randomly within the study area. The depth varied based on topography and overburden and hence, the clay deposit was not at a uniform depth. The samples collected from these trial pits were analyzed in the Department of Earth Sciences’ laboratory, Prince Abubakar Audu University, Kogi state, Nigeria, for relevant geotechnical analysis.

The below geotechnical tests were conducted in order to provide a comprehensive insight into the soil's physical properties:

Specific Gravity Test

The following process were adopted for determining the specific gravity of the sample:

i. The density bottle and its stopper were dried at 110°C, cooled in a desiccator, and weighed (W1).
ii. A quantity of the sample (between 50g to 80g) is transferred to the density bottle, and the combined weight is recorded (W2).
iii. The density bottle, including the soil sample, is filled up to half-mark with air-free distilled water and left to soak

for about three hours. It is then gently stirred with a glass rod to remove any air bubbles.

iv. The bottle is filled to the brim with water, stoppered, wiped clean, and weighed (W3).
v. The density bottle is emptied, cleaned, filled with distilled water, stoppered, wiped dry, and weighed (W4).

Particle Size Distribution Test

Engineering method

Few quantities of each sample was sieved through the conventional stack of sieve in a mechanical sieve shaker for a period of 20 minutes. The sample retained on each sieve was weighed and recorded accordingly. The percentage of soil finer than each sieve was computed and plotted against sieve opening on a semi logarithmic graph. These processes were repeated for the remaining samples. It must be noted that, the soil natural moisture content was determined before the test. The soil that passed through the 0.063 mm sieve was further analyses using hygrometer analysis.

Hydrometer method

Each of the dry sample sieved through a 75micron meter was mixed with 2.0g calgon to form solution and poured into a 1000 ml graduated cylinder. After thorough mixing for about 30 seconds, the solution was made up to 1000 mi mark with distilled water. A control cylinder was put alongside the graduated cylinder.

Then, a 152H hydrometer device was inserted with care and readings were taken at an interval of 0, 3, 5, 8, 11, 13, 25, 38, and 480 minutes. This was done for all the samples until similar readings were obtained. A thermometer was used to measure the temperature of the solution at each reading and a composite correction value was taken from the hydrometer inserted into the cylinder containing control solution. Thereafter, computations were made to obtain the diameter of the soil particles and their Percent finer (partial and total). The result was the combined with those from mechanical sieve analysis to plot the graph.

Atterberg Test

Liquid Limit Test: Method: GTM-7, 2015

Each sample was air-dried and sieved through 60 µm standard sieve. Then, each soil was divided into four portions. Each of the four was mixed gently with distilled water and spatula until a paste condition was reached. The paste was spread into the cassagrande cup using the spatula to assume a thickness of about 12 mm inside the cup. A groove was made at the centre of the cup. Thereafter, the cup is repeatedly dropped from a height of about 10 mm in an anticlockwise direction on a rubber base at the rate of 120 blows per minutes. The created groove gradually closes up due to the impact of dropping. The number of blows at the reasonable closeup of the groove was recorded. Certain quantity of the paste (sample) from the cassagrande cup was collected, inserted in a weighing can, weighed, and placed in the laboratory oven for moisture content determination. These steps were repeated using the remaining sample. The volume of water was increased with 5 ml in subsequent tests.

Plastic Limit Test: Method: GTM-7, 2015

The test was performed using parts of the thoroughly mixed samples for the liquid limit test. Each sample was kneeled and rolled into ellipsoidal shape. Rolling was achieved using bare hand-fingers on a smooth surface with just sufficient pressure. The rolling reduced the diameter of the sample uniformly throughout the its length. The rolling continued until the thread crumles and the soil could no longer be rolled. At this stage, the broken soil fragments were weighed with a drying can whose weight has been determined. The sample was then heated for about 24 hours using a laboratory oven and its moisture content determined in order to establish its plastic limit.

Linear Shrinkage Test

To determine linear shrinkage of a soil, a paste of soil which passed through 425-micron meter was prepared from the sample. This was filled into a linear shrinkage mold of 140 mm length. The inside of the device had been earlier greased before filling with soil paste. It was oven-dried for 24 hours and the resulting length was after drying was measured. The linear shrinkage was the calculated from the expression:

Loss on Ignition Test

Method: ISO 11536:2015(E)

Using crucible tong, six crucibles were placed and covered with their lids in the muffle furnace at 1000°C for 60 minutes, ensuring that there is no loose material on the floor of the muffle furnace that could possibly adhere to the crucible. The crucible was removed from the furnace and placed in the desiccator with their lids immediately. The crucibles were allowed to cool for 30 min. Then, each of the cooled crucible and lid was weighed to the nearest 0.01 g. Certain quantity of each soil sample was transfer to the crucible, weighed with their respective lid, heated in a muffle furnace at 1000°C for 60 minutes, allowed to cool, and re-weighed with lid.

Calculation of loss on ignition

The loss on ignition (LOI), expressed as a percentage by mass, is calculated to a dry basis as indicated below:

The total mass loss after ignition (TMLw), including moisture, is calculated from Formula:

m1 is the mass of the ignited crucible and lid, in grams;

m2 is the mass of the crucible and lid plus the air-equilibrated test portion, in grams;

m3 is the mass of the crucible and lid plus test portion after ignition, in grams.

Permeability Test

Falling Head Method

Each soil samples were air-dried, then, used to fill the permeameter mould to the required level. Wire guage was placed on the top and bottom of the soil sample in the mould to serve as filters. The mould was clamped and bolted. The burette was filled to a convenient height and hydraulic head across the sample was measured. The flow of water was allowed to be constant. Thereafter, the burette was filled to highest mark (h1), and testing was commenced by allowing flow of water though the outlet. After a while, the water flow was stopped, and the volume of water height (h2) and time taken were recorded simultaneously. This process was repeated for additional three times using the same h1 and h2 for each test.

Where:

a = cross sectional area of burette (cm2)

A = cross sectional area of soil sample (cm2)

h1 = hydraulic head across sample at the beginning of test

h2 = hydraulic head across sample at the end of test

L = sample length (cm)

t = elapsed time (sec)

|n = natural logarithm

Note: a = 0.88 cm2; L = 16 cm; Internal diameter of mold = 15 cm; Cross sectional area (A) of soil sample (A = Πr2) = 176.73 cm2.

Compaction Test

3000g of each soil sample was weighed and mixed with varied percentages (4, 8, 12, and 12) of water by spatula. The moistened sample was then divided into three relatively equal parts for each layer during compaction. Each of the mold's layers was filled with one part of the moistened sample and compacted by the specified number of blows. Note that, the dropping height of the rammer is 0.3m. The blows were distributed uniformly over the surface of each layer. The amount of soil was sufficient to fill each mold, leaving not more than 6mm height, which was struck off when the collar was removed. Then, the mold was trimmed and weighed. The moisture content of the soil was obtained from representative sample of the compacted soil. The bulk and dry densities of the soil were then determined.

(Kg/m3)

M = mass of compacted soil

V = volume of compacted soil

Where M.C = moisture content of the soil

Then, the dry unit weight was plotted against the corresponding moisture content and a curve emerged. The position of the maximum point on the curve was regarded as the maximum dry density (MDD) at optimum moisture content (OMC).

RESULTS AND DISCUSSION

The physical parameters determined for Zariagi clay are summarized in the following tables and figure.

Particle Size Distribution

Analyzing the grain size distribution in a clay deposit is a crucial step in assessing its potential applications. The tables below give the values of their various particle size distribution.

Table 1: Graphic Mean and Interpretation (Wentworth, 1922)

Graphic Mean Values		Interpretations
Sample 1	2.0	Medium sand
Sample 2	2.0	Medium sand
Sample 3	2.2	Fine sand
Sample 4	2.2	Fine sand
Sample 5	1.8	Medium sand
Sample 6	2.2	Fine sand

Since the grain size ranges from fine to medium, it suggests that the clay exhibits higher strength, moderate permeability, and better compaction.

Table 2: Sorting Values and Interpretation (Folk & Ward, 1957)

Sorting Values		Interpretations
Sample 1	1.90	Poorly sorted
Sample 2	1.63	Poorly sorted
Sample 3	1.72	Poorly sorted
Sample 4	1.90	Poorly sorted
Sample 5	1.61	Poorly sorted
Sample 6	2.04	Very Poorly sorted

Poorly sorted clay could often indicate a dynamic depositional environment such as coastal areas with fluctuating energy levels.

The particle size analysis curve (Fig. 2) shows the closeness of the curves, indicating a uniform grain size distribution among the samples.

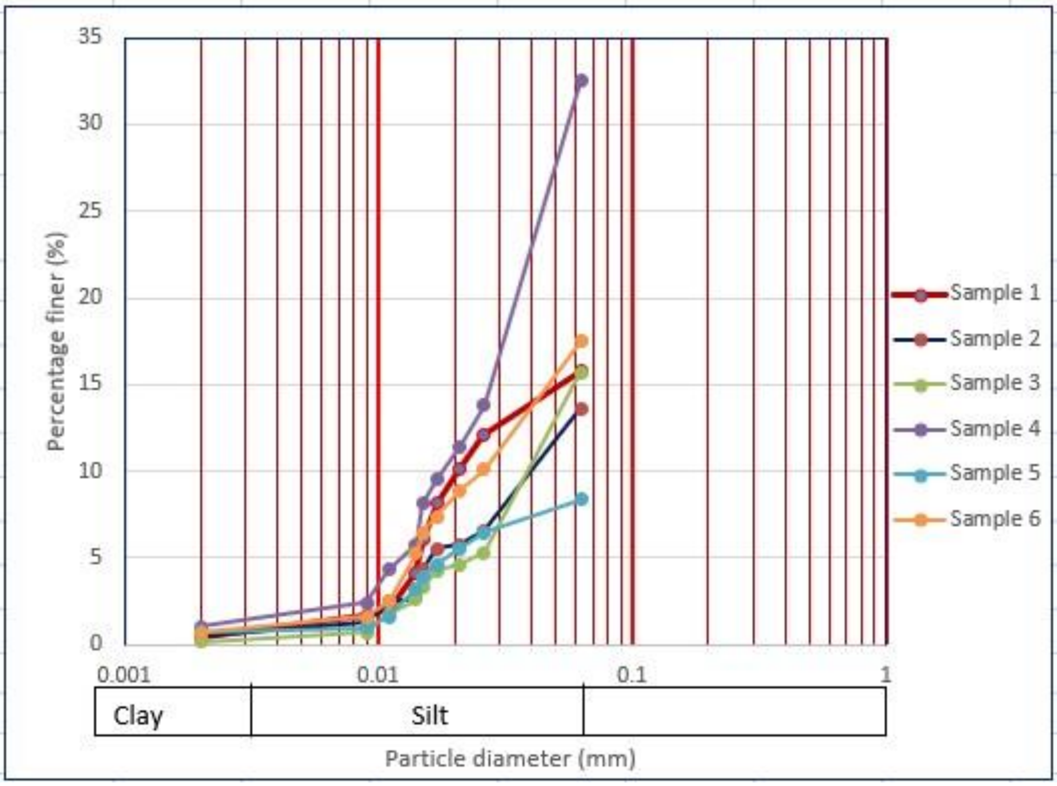

Figure 2: Particle size analysis curve

The grain size analysis shows that the samples are dominated by small-sized particles (<0.1 mm). From the graphs shown in Figure 2, it could be inferred that the proportion of silty-clay-sized particles constitutes a larger percentage of the samples. According to the findings of Hubadillah (2016), a distribution dominated by clay-sized particles suggests that the clay has a higher tendency for agglomeration, as smaller particles are more prone to clumping together. Similar studies have indicated that soils intended for use as barrier materials in landfills should contain at least 30% fines (Benson et al., 1994) and a clay content of more than 10% (Declan & Paul, 2003).

Consolidation Test

Table 3: Consolidation test result of clay in the study area

Sample	Average Coefficient of consolidation (C_v)[m²/yr]	Settlement (mm)
1	0.00407	0.7391
2	0.03635	0.7608
3	0.07258	0.7652
4	0.07309	0.7456
5	0.07281	0.7565
6	0.03680	0.7263

The result of the consolidation test shows that sample 1 has the lowest C_v and settlement values, suggesting slower consolidation and less settlement. Sample 4 has the highest C_v, indicating faster consolidation, and its settlement value is relatively lower compared to other samples, suggesting that despite faster consolidation, the actual settlement is not as high while Samples 2, 3, 5, and 6 fall between these extremes. This implies good material for building construction.

Specific Gravity Test

Table 4: Specific gravity of clay in the study area

Sample	W1 (g)	W2 (g)	W3 (g)	W4 (g)	Specific Gravity (Gs)
1	58.69	95.01	200.25	178.8	2.44
2	58.69	95.22	200.98	178.8	2.55
3	58.69	100	203.95	178.8	2.56
4	58.69	96.44	201.41	178.8	2.49
5	58.69	98.43	203.24	178.8	2.60
6	58.69	99.71	203.64	178.8	2.54

The values obtained in the above specific gravity of all the clay samples falls within the typical range for a soil specific gravity, which means it is applicable for various engineering purposes.

Atterberg Limits Test and Plasticity Index

Atterberg limits gives properties that can indicate the amount and type of clay in a sample. They are also essential for understanding the industrial behaviour of clays (Spagnoli & Sridharan, 2013). The results of the Atterberg limits test and plasticity index are summarized in Table 5.

Table 5: Summary of Atterberg Limits Test and Plasticity Index of clay in the study area

Sample	Liquid limit (LL)	Plastic limit (PL)	Plasticity Index (PI) =(LL – PL)
1	36.50	33.80	2.70
2	36.00	33.38	2.62
3	36.80	34.66	2.14
4	37.00	34.29	2.71
5	35.80	33.27	2.53
6	36.40	34.26	2.14

The plastic limit and plasticity Index values indicate that the values are within the clayey range, suggesting a moderate degree of plasticity, while the liquid limit value shows a low percentage of silt particles. The result of the liquid limits of the clay samples collected from the study area shows that the liquid limit of the samples ranges from 36.00% to 37.00%, which indicates low plasticity and could suggest an inorganic clay (Emesiobi, 2000). The plastic limit varied between 33.27% - 34.7% and its plasticity index is of the order of 2.14% to 2.71%. The Atterberg limits parameters meet the requirement for use as barrier soils.

Linear Shrinkage Test

Table 6: Summary of linear shrinkage of clay in the study area

Linear Shrinkage	Original Length, Lo (mm)	Final Length, Lf (mm)	Linear Shrinkage = (1 – (Lf/Lo))*100 (%)
S1	140.00	136.00	2.86
S2	140.00	134.00	4.29
S3	140.00	135.00	3.57
S4	140.00	135.00	3.57
S5	140.00	134.00	4.29
S6	140.00	136.00	2.86

The linear shrinkage percentages for the samples range from 2.86% to 4.29%, indicating a moderate degree of linear shrinkage and low volumetric shrinkage due to the low amounts of sand and the absence of a mixed layer swelling clays in the clay samples. The values obtained indicating moderate shrinkage and low volumetric changes due to the low sand content and the absence of mixed-layer swelling clays. This indicates good firing efficiency since the values fell within the recommended linear shrinkage range (2.0–10.1%) for alumina-silicates, kaolin, and fire clays (ASTM, 1982), the results suggest better grain interlock, which enhances the strength of the refractory material.

The Loss on Ignition Test

Table 7: The loss on ignition (LOI) of clay in the study area

Sample	TML_w	A	LOI (%)
1	5.62	1.74	3.95
2	5.38	1.50	3.94
3	5.00	1.31	3.74
4	5.67	1.74	3.99
5	5.14	1.28	3.90
6	5.93	1.50	4.49

The loss on ignition of the above samples falls within the range of 3.74% to 4.49%, which suggests the absence of swelling clays and low organic matter contents in these clay samples. Extremely high LOI values might suggest the presence of a significant amount of organic matter or other volatile compounds.

Compaction Test

The results of the compaction test are summarized in Table 8. The optimum moisture content (OMC) ranged from 14.90% to 18.50% while the corresponding maximum dry density (MDD) varied from 1270 kg/m^3 to 1320kg/m^3.

Table 8: Summary of the compaction test result of clay in the study area

Sample	Maximum Dry Density (Kg/m^3) (MDD)	Optimum Moisture Content (%) (OMC)
1	1239	18.50
2	1270	15.00
3	1285	14.90
4	1315	15.30
5	1320	15.90
6	1319	16.05

Except for sample 1 that relatively high, all the remaining results have OMC values that are within a moderate range. This implies that less moisture is required to reach the maximum dry density and it means that the soil requires moderate water to achieve maximum compaction. This is generally desirable, especially in construction applications, as it implies better compaction efficiency and improved load-bearing capacity.

Permeability Test

Table 9: Permeability values of clay in the study area

Sample	h1 (cm)	h2 (cm)	t (sec.)	vol. out (cm^3)	K (cm/sec.)
1	50	20	227.25	30	0.000140
2	50	20	229.25	30	0.000138
3	50	20	227.5	30	0.000139
4	50	20	235.5	30	0.000135
5	50	20	238.25	30	0.000133
6	50	20	227.25	30	0.000140

The permeability values you provided in the test results are in the range of 0.000133cm/sec. to 0.000140 cm/sec. These values fall within a relatively moderate range, which implies a moderate permeability.

CONCLUSION

The study has provided an improved and better understanding of the geotechnical properties and characteristics of the underlying clay soil across the studied area. It assessed the geotechnical characteristics of residual clay derived from crystalline basement rocks in the Zariagi area of Lokoja, northcentral Nigeria.

The results classified the samples as clayey materials with low plasticity and low hydraulic conductivity, indicated by liquid limits ranging from 36% to 37% and plastic limits from 33.38% to 34.66%. The plasticity index, ranging from 2.14% to 2.71%, showed that the clay exhibits low to medium swelling potential when wet and can withstand volumetric shrinkage when dry. The Atterberg limits also met the requirements for use as barrier soils. Specific gravity values were typical for soil-specific gravity. Compaction tests revealed an optimum moisture content (OMC) of 14.90% to 18.50% and a maximum dry density (MDD) of 1270 kg/m³ to 1320 kg/m³, suggesting the clay is suitable for building construction. Linear shrinkage percentages ranged from 2.86% to 4.29%, indicating moderate shrinkage and low volumetric changes due to the low sand content and the absence of mixed-layer swelling clays. Loss on ignition values from 3.74% to 4.49% suggested low organic matter content and absence of swelling clays. Permeability values ranging from 0.000133 cm/sec to 0.000140 cm/sec suggest moderate permeability.

The findings show that the clay exhibits properties suitable for construction and civil engineering applications. Grain size analysis and Atterberg limit tests classified the samples as clayey materials with low plasticity and hydraulic conductivity. The specific gravity, compaction, and linear shrinkage tests indicated moderate values, further confirming the clay's suitability for building construction. Additionally, low loss on ignition values suggest minimal swelling clays and low organic content. The permeability results also support the clay's appropriateness for use as barrier soil and in construction.

The residual clay in the Zariagi area meets the requirements for landfill, barrier soil and is suitable for building construction, offering potential solutions for civil and geotechnical engineering challenges.

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