GEOTECHNICAL CHARACTERISATION OF TROPICAL BLACK CLAY DEPOSIT IN ZUNGERU, NIGER STATE

BY

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MEng/SIPET/2018/9231

DEPARTMENT OF CIVIL ENGINEERING,
FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA

AUGUST, 2023

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THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL, FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA, NIGERIA, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF ENGINEERINGIN CIVIL ENGINEERING (GEOTECHNICAL ENGINEERING)

AUGUST, 2023

DECLARATION

I hereby declare that this thesis titled: **"Geotechnical Characterisation of Tropical Black Clay Deposit in Zungeru, Niger State"** is a collection of my original research work and has not been presented for any other qualification anywhere. Information from other sources (published and unpublished) has been duly cited and acknowledged.

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……………………..
Signature & Date

CERTIFICATION

The thesis titled: **"Geotechnical Characterisation of Tropical Black Clay Deposit in Zungeru, Niger State"** by: IBRAHIM, Sadiq Oricha (MEng/SIPET/2018/9231) meets the regulations governing the award of the degree of MEng. of the Federal University of Technology, Minna and it is approved for its contribution to scientific knowledge and literary presentation.

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DEDICATION

This work is dedicated to Almighty Allah, the eternal and ever sufficient. May His blessings be upon Prophet Muhammad (S.A.W), Ameen.

I also dedicated this project to my late daughter Farida Sadiq, my lovely wife Khadija, my family members and also my friends for their endless support throughout my education.

Finally, my project supervisor and my lecturers for their tireless efforts and patience in teaching me, may ALLAH bless them (Amen).

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To my fellow students (colleagues), friends and well-wishers, I say thank you for being there always.

ABSTRACT

Geotechnical characterisation of tropical black clay deposit in Zungeru, Niger State was undertaken in the study. Soil samples were collected from five different locations within the identified deposit, and tests carried out on the collected samples included Natural Moisture Content (NMC), specific gravity, oxides composition test, Loss on Ignition (LOI), mineralogical test, X-ray diffraction analysis (XRD), Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), pH, index properties (sieve analysis, liquid limit, plastic limit), bulk density, triaxial and one-dimensional consolidation test. From the results, SiO_2, Fe_2O_3, Al_2O_3, CaO and TiO_2, range from 57.80 to 66.13, 5.52 to 9.11, 14.88 to 18.24, 0.87 to 3.74 and 1.03 to 1.32% respectively, which were similar to those reported in literature for tropical black clay. Loss on Ignition (LOI) of the soils were observed to range from 4.76 to 7.44%, which are higher than those reported in literature for tropical black and expansive clays, but lower than those reported for black cotton soils in Nigeria. Mineralogy of the soil in the deposit indicated kaolinite as the major clay mineral, but with other minerals like albite and epidote also recorded. Muscovite was observed on locations where the soil was observed to be relatively less drained. SEM results of the studied soil samples generally revealed presence of air voids and relatively dense spongy fabric of flecky clay particles that are similar to those reported in the literature for tropical lateritic clay soils. EDS results show carbon, oxygen, Almininium, Silicon, Iron, magnesium, potassium, calcium, Titanium and sodium ranging from 13.79 to 30.51%, 45.54 to 55.83%, 3.84 to 8.04%, 11.94 to 20.98%, 1.83 to 5.12%, 0.37 to 0.76%, 0.23 to 0.87%, 0.30 to 1.15%, 0.61 to 0.86% and 0.21 to 0.42% respectively, which are similar to those reported in literature for tropical black clay. The relatively low Iron content in the soil is partly responsible for the dark (black) colour of soil in the deposit. pH of the soils was observed to range between 6.50 to 7.2, indicating that the soil in the deposit hovers from being slightly acidic, to neutral, and slightly basic. Index properties results of the soils generally showed them classifying under clay of low plasticity (CL), according to Unified Soil Classification System (USCS) and A-4 to A-7-6 according to American Association of State Highway and Transportation Officials (AASHTO). Shear strength parameters indicated cohesion ranging from 31.20 to 52.51kN/m^2, with angle of internal friction ranging from 3.75 to 13.34°, while bulk unit weight ranges between 18.49 and 21.93kN/m^3, which were relatively similar to those reported in literature for tropical clay soils. Variation of the settlement characteristics with depth of the clay deposit was observed, with void ratio ranging from 0.514 to 0.874. Recompression index (C_r), compression index (C_c) were generally observed to increase with depth of the deposit, while no definite trend in variation of preconsolidation stress (σ_p) and coefficient of consolidation C_v with depth of the deposit was observed. These results indicate that the soil from the deposit can generally be classified as weak and deficient for use in some Civil Engineering structures.

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ABBREVIATIONS, GLOSSARIES AND SYMBOLS

AASHTO	American Association for State Highway and Transportation Officials
BSH	British Standard heavy
BSL	British Standard Light
CBR	California Bearing Ratio
CH	Clay of High Plasticity
CL	clayey soil
EDS	Energy Dispersive Spectroscopy
Gs	specific gravity
LL	liquid Limit
LOI	Loss on Ignition
M	mass
m	metre
MDD	Maximum Dry Density
NMC	Natural moisture content
OMC	Optimum Moisture Content
PI	plasticity Index
PL	plastic Limit
UCS	Unconfined Compressive Strength
USCS	Unified Soil Classification System
SEM	Scanning Electron Microscopy
WAS	West African Standard
XRD	X-ray diffraction analysis
ρ_b	Bulk density
ρ_d	Dry density

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Study

There are many structurally unstable and problematic soils, scattered around the world, that are sources of worry to engineers working on or with them. These materials are regarded as problematic because they are characterized by unusual characteristics/behaviours, which include heaving/swelling, collapse/dispersion, erosion, excessive creep, subsidence and high compressibility/settlement. Clay is an example of problematic soils due to its low strength, high compressibility and high-volume changes, although, in some aspects of construction, they are used as embankment core in earth dams. They are also used as liners for containment of leachates.

Clay soils in general constitute a major soil group which is known to cause considerable damage to roads, dams, canal linings, foundations either through excessive swell or shrinkage (Al-Rawas *et al*., 1998; Chen, 2012). According to Warren and Houston (1995), these soils inflict over $9 billion in damages annually to engineering structures and facilities, which is more than twice the combined damages from earthquakes, floods, tornadoes and hurricanes. According to Bell and Culshaw (2001), loses due to swelling and shrinkage in clays amount to about £3billion in Britain. Black cotton soil, which is tropical black clay, is a typical expansive soil that mostly occurs widely in tropical region of the world.

Black clay or tropical black earth (clay), which is black or greyish black or in their eroded phase, greyish white in colour, is known to be potentially expansive soils (Gidigasu and Gawu, 2013). The predominant clay mineral in the soil is the smectite group. Although the soil is rich in alkali earth elements, they may sometimes contain calcium carbonate or magnesium oxide concretions. These soils are usually in an uneven pattern and of a magnitude to cause extensive damage to the structure resting on them. This results to a situation that has substantial effect structures founded on them. Such behaviour has been attributed to factors such as composition, nature of pore fluids, fabric and mineralogy of the soils (Gidigasu, 2012).

Black clay soils occur in wide climatic zones, from the humid tropics to arid areas, but they are most abundant in the tropics and sub-tropics regions. In the tropics, they occupy 60% of the total area; in the sub-tropics, they cover 30 %, while they cover only 10 % in cooler regions (Coulombe *et al*., 1996). In humid and sub-humid regions, they occupy 13% of the total land area; in sub-arid regions, 65% in arid regions, and 18% in the Mediterranean climate (Pal *et al.*, 2012).

1.2 Statement of the Research Problem

Nigerian soil map depicts only ferruginous soils, ferrallitic soils and weakly developed soils as major soil groups present in north central Nigeria. But recent unpublished, undetailed and isolated studies have shown that some deposits of black clay are scattered around the north central region of Nigeria, which have not been properly studied, characterized and documented. It is therefore, important to locate and study some of these deposits in north central region of Nigeria. Evidence of the presence (structural damages like cracks on buildings and roads) of this soil type has been observed in Zungeru area of Niger state.

1.3 Aim and Objectives

The aim of this study was to geotechnically characterise tropical black clay deposits in Zungeru, Niger state. This was achieved through the following objectives:

i. Identification of tropical black clay deposits in Zungeru.

ii. Determination of mineralogical properties of the clay deposits.

iii. Determination of geotechnical properties of the clay deposits.

1.4 Justification of Study

Previous published studies have indicated nonexistence of black clay in north central Nigeria. Hence, this study tends to locate and establish the available black clay deposits of Zungeru, in north central Nigeria and as well investigate the mineralogical and geotechnical characteristics of the soil.

1.5 Scope of Study

The scope of the study entails identification of the tropical black clay deposits in Zungeru, determination of mineralogical properties of soils from the deposits, and determination of geotechnical properties of soil samples from the deposits.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 General Information and the Geology of Nigeria

Zungeru is one of the old colonial capitals of pre-independent Nigeria. It is presently in Zungeru Local Government Area of Niger state, in north central Nigeria. According to Alhassan (2016), Nigeria, which has a surface area of 923,768 km^2 and a population of about 200 million, is one of the West African countries located within the tropical region of the world (Figure 2.1). The country lies close to the equator between latitude 4^o N and 14^o N and longitude 2^o E and 15^o E. Nigeria, politically, borders Niger Republic to the Northern side, Lake Chad to the Northeastern side, Republic of Cameroon to the Eastern side, Benin Republic to the Western side and to the Southern side is Atlantic Ocean. According to Rahaman and Malomo (1983), the country is geologically bounded on the Southern side by the Gulf of Guinea and on the Northern side by the southern edge of the Sahara Desert.

Durotoye (1983) stated that climate in Nigeria is typified by hot tropical condition, which is humid in the South and semi-arid in the North, with seasonal rainfall, resulting from influence of the wet south westerly monsoon winds from the sea and the hot dry dusty north east trade wind, known locally as hamattan, from the Sahara. The geomorphology and the quaternary history of Nigeria have evolved under the remarkable changes brought about by the intensity and periodicity of rainfall in the past. Wetter periods have been termed pluvial and drier periods – interpluvial (Durotoye, 1983).

2.2 Soils in Nigeria

Due to the climatic conditions in the tropical region (Figure 2.1), soil formation from the parent rocks (igneous, sedimentary or metamorphic), is mostly by process of chemical weathering (Huat and Ali, 2006). Although, Bowles (1996) stated that, mechanical process of weathering is also encountered within the tropics, the resulting soil is usually untransported residue of both chemical and physical process of weathering. The most important end products are clays and the resilient minerals, quartz, while other end products depend very much on the type of rock. Iron oxides, however, are also common residues in tropical region of the world. Durotoye, (1983) stated that these iron oxides impart the reddish, brownish and yellowish coloration on the weathering residues, and are generally referred to as “laterite”. Most profuse residual soils, with this coloration, in Nigeria are mainly ferruginous and ferrallitic tropical soils.

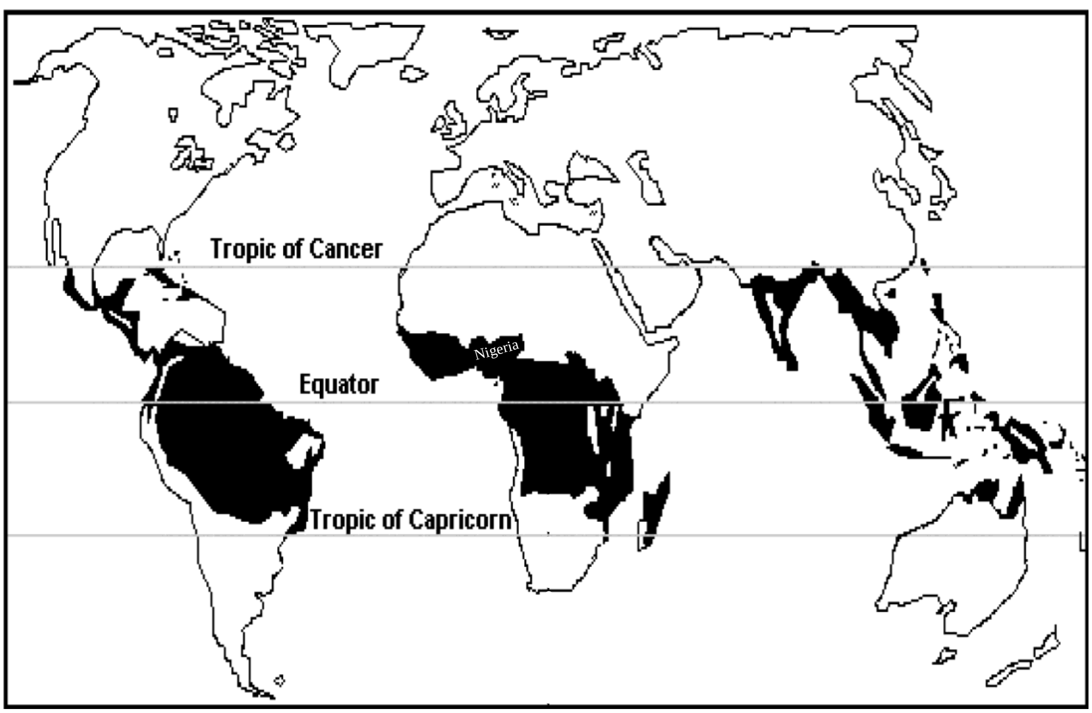

Figure 2.1: Areas with tropical climate (*source*: *Alhassan, 2016*)

Within the humid tropical climate of Nigeria and the widespread gentle slopes of the terrain, deep in-situ weathering takes place. The depth of weathering, though variable, is generally about 30 m below the surface, and may be greater in highly jointed and broken rocks (Alhassan, 2016). In the more arid part of Northern Nigeria, the depth of weathering is reported to be less than 15 m. The composition and characteristics of the weathered materials would depend very much on the parent rock from which they were formed (Durotoye, 1983).

In addition to the influence of parent rocks, residual soils in the tropics, have a vertical soil section, called the soil profile, which consists of a distinct layering, termed the soil horizons formed almost parallel to the ground surface. Huat and Ali (2006) stated that these naturally related horizons are a reflection of the weathering process. The soil profile also has a weathering aspect that gives rise to a vertical weathering profile, which is a critical aspect from the engineering perspective. The weathering profile replicates the state of weathering along the soil profile or vertical soil section from the bedrock (unaltered parent rock) to the ground surface (Huat *et al*., 2004). It consists of materials that show liberal stages of transformation or “grading” from fresh rock to entirely weathered material towards the ground surface. The weathering profile represents considerable variation from place to place due to the local variation in rock type and structure, topography and rates of erosion because of regional climatic variation, particularly rainfall (Huat and Ali, 2006). The entire weathering profile, generally, indicates a gradual change from fresh rock to a fully weathered soil (Huat *et al.,* 2004) as illustrated in Figure 2.2. Bowles (1996) stated that residual soils are usually preferred to support foundations as they tend to have better engineering properties than transported soils.

In addition to the residual soils, weakly developed and hydromorphic soils are also found in Nigeria especially along rivers banks and coastal area, though in terms of coverage, but not necessarily in the order of importance, they are fewer in extent than the residual soils. Vertisol, which is also a tropical residual soil group, having distinct engineering properties are also found in the North-eastern part of Nigeria. Figure 2.3 shows a simplified map of the distribution of major soil groups in Nigeria from study carried out by Malomo (1983).

As depicted on Figure 2.3, there are mainly four major groups of tropical soils in Nigeria: Weakly developed and hydromorphic soils, Vertisols, Ferrallitic soils and Ferruginous tropical soils. Out of these, the ferruginous and ferrallitic tropical soils are the most abundant (Malomo, 1983) and most constant under engineering structures. The vertisols and weakly developed soils occur less in Nigeria and are generally considered as weak bases for engineering structures, especially those founded on shallow foundations. Vertisols are a type of tropical black clays.

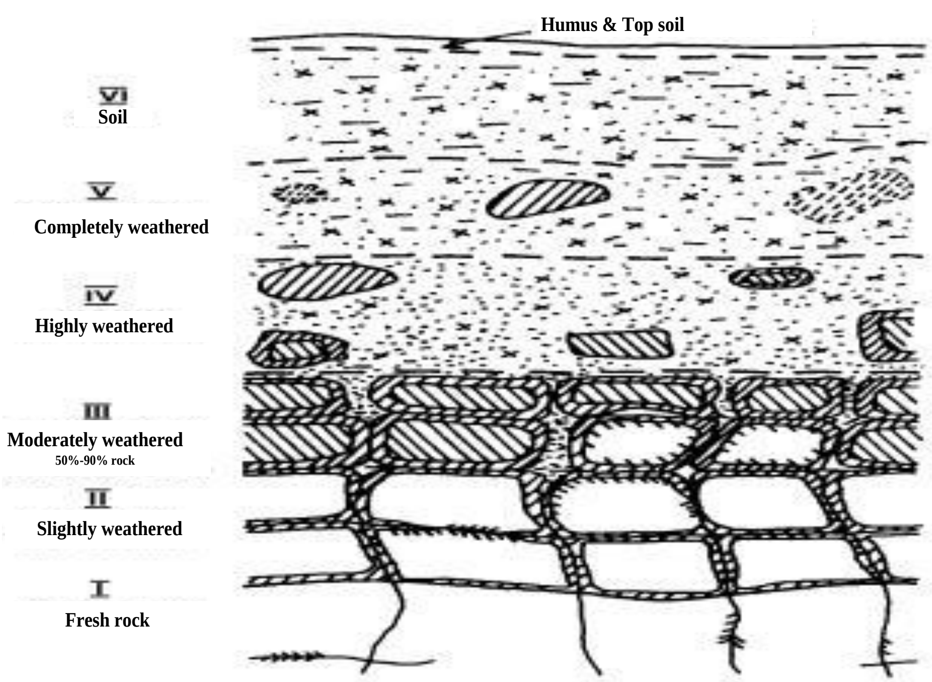

Figure 2.2: Typical tropical residual (Nigerian) soil profile (*source: Alhassan, 2016*)

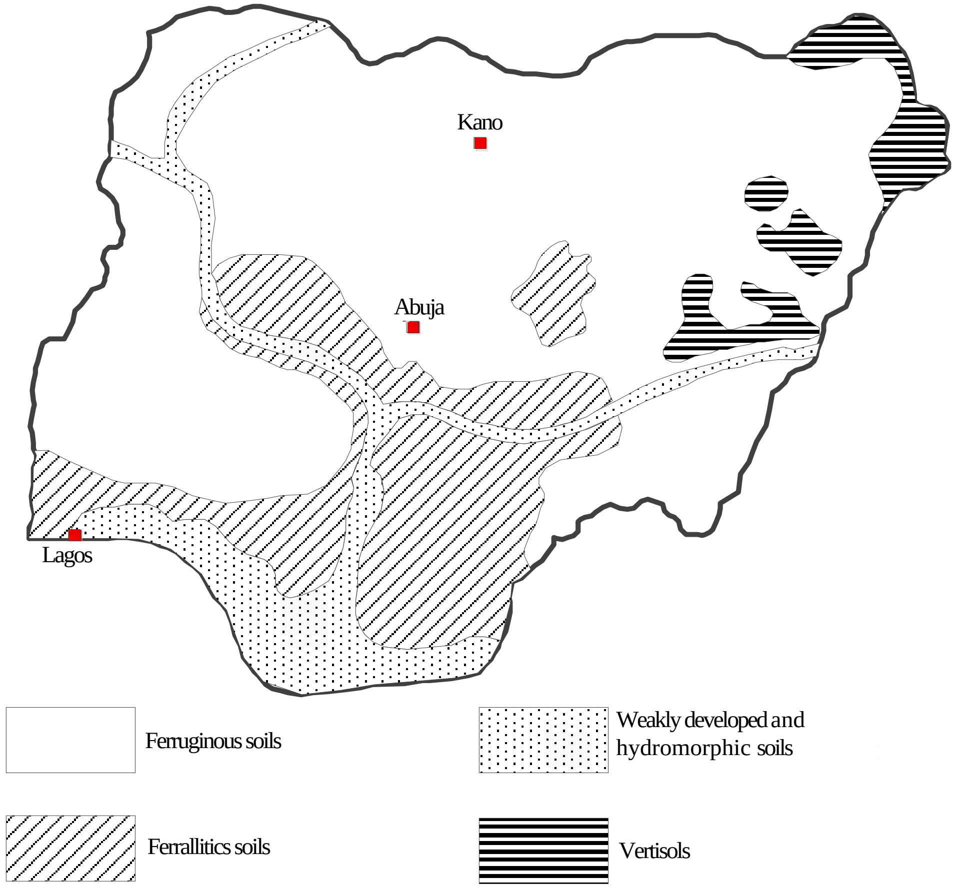

Figure 2.3: Nigerian soil groups (*source: Alhassan, 2016*)

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2.2.1 Vertisols

Vertisols, which are typical example of tropical black clays, are also called black cotton soils. According to Oyekan *et al.* (2013), they are dark colored expansive clays found in North-East

Nigeria, India, USA and other parts of the world. They are heavy black clays associated with calcium rich parent rocks in the relatively dry savannah climate (Klinkenberg and Higgins, 1968). They are characterized by black upper horizon, which is due to the presence of a black coloured humus-clay complex (Ola, 1983). Some authors (Nelson and Miller, 1992; Chen, 1998; Warren and Kirby, 2004) describes them as expansive soils that typically occurs in arid and semi-arid regions of the tropical/temperate zones marked with dry and wet seasons, with low rainfall, poor drainage and exceedingly great heat. According to Gidigasu (1976) and Gidigasu and Gawu (2013), black cotton soils are major problematic soils of some tropical countries especially in Africa and India. Problems associated with these soils have been reported in Africa, Australia, Europe, India, Israel, South America, Russia, the United States, and some regions in Canada (Ojuri and Okonta, 2013).

Morin (1971) stated that Lake Chad Basin is the only extensive lacustrine deposit of black cotton soil in Africa, although, patch deposits of this type of soil have been reported in other part of Africa. Moses and Saminu (2012), states that the black cotton soils of North Eastern Nigeria were laid during the tertiary and quaternary periods of the Chad formation and are composed of a sequence of lacustrine and fluviatile clays and sands of Pleistocene age. Ola (1983), states that these sediments (lacustrine sands, lagoonal clays, deltaic sands and clays, beach sands and gravels as well as Aeolian sands) underlie the country's North and East of Abakire and extend along the plains of Borno and Lake Chad and beyond. Adeniji (1991) reported that black cotton soils occur in continuous stretches as superficial deposits and are typical of flat terrains with poor drainage.

According to Klinkenberg and Higgins (1968), the vertisols in Nigeria occur within the Savannah ecological zone of the country, with bulk of the soils occurring in the Sudan and

Northern Guinea Savannah zones in the Northeastern part of the country. It has been reported by Ola (1983) that black cotton soils occupy an estimated area of 104,000 km^2 in Northeastern Nigeria. They have a heavy texture and the mineralogy of the soil is dominated by the presence of montmorillonite clay mineral, which is characterized by large volume change from wet to dry seasons and vice versa (Ola, 1981; Osinubi, 2006; Shamrani *et al.*, 2010). During the dry period of the year, deposits of black cotton soil in the field show a general pattern of cracks. According to Adeniji (1991), cracks measuring up to 0.7mm wide and over 1m deep have been observed on this type of soil, and in case of thick deposit, may even extend up to 3m deep or more.

The engineering properties of black cotton soils are dominated by their small particle sizes and the presence of montmorillonite clay mineral. These properties impact low permeability, high plasticity, expansiveness and shrinkage on the soils.

Soils that exhibit similar properties with vertisols have also been locally identified in different parts of the country, including in Zungeru, the old colonial capital of Nigeria, in Niger state. The composition and properties of these type of soil is dominated by clay fraction, hence their name "tropical black clays"

2.3 Clay

The term clay refers to a naturally occurring material composed primarily of fine-grained minerals which is generally plastic at appropriate water contents and will harden when dried or fired. Clay usually contains phyllosilicates (Guggenheim and Martin, 1995). It may contain materials that impart plasticity and hardness when dried or fired. Associated phases in clay may also include materials that do not impart plasticity and organic matter. Clay minerals are typically formed over long periods of time by the gradual chemical weathering of rocks, usually silicate bearing, by low concentrations of carbonic acid and other diluted solvents. These solvents, usually acidic, migrate through the weathering rock after leaching through upper weathered layers. In addition to the weathering process, some clay minerals are formed by hydrothermal activity. Thick deposits are usually formed as a result of a secondary sedimentary deposition process after they have been eroded and transported from their original location of formation. Primary clays, also known as kaolin, are located at the site of formation. Secondary clay deposits have been moved by erosion and water from their primary location.

2.3.1 Clay minerals

Clay minerals are hydrous aluminum phyllosilicates, sometimes with variable amounts of iron, magnesium, alkali metals, alkaline earths, and other cations (Grove *et al*., 2006). Clay minerals are products of weathering and low temperature hydrothermal alteration. From an academic point of view, clay minerals may be divided into the following groups (Kerr, 1952; Skempton, 1953).

2.3.1.1 Kaolinite

Kaolinite, chemical composition $Al_2Si_2O_5(OH)_4$, is a group of industrial minerals, It is a layered silicate mineral, with one tetrahedral sheet linked through oxygen atoms to one octahedral sheet of alumina octahedral. Rocks that are rich in kaolinite are known as kaolin or China clay. It is a soft, earthy, usually white mineral (dioctahedral phyllosilicate clay), produced by the chemical weathering of aluminum silicate minerals like feldspar. In many parts of the world, it is colored pink-orange-red by iron oxide, giving it a distinct rust hue. Kaolin-type clays undergo a series of phase transformations upon thermal treatment in air at atmospheric pressure. Endothermic dehydroxylation (or alternatively, dehydration) begins at

550–600°C to produce disordered metakaolin, $Al_2Si_2O_7$, but continuous hydroxyl loss (-OH) is observed up to 900°C and has been attributed to gradual oxidation of the metakaolin (Deer *et al*., 2013).

$$2Al_2Si_2O_5(OH)4 \rightarrow 2\ Al_2Si_2O_7 + 4\ H2O \quad (2.1)$$

Further heating to 925–950°C converts metakaolin to a defect aluminium-silicon spinel, $Si_3Al_4O_{12}$, which is sometimes also referred to as a gamma-alumina type structure (Deer *et al.*, 2013).

$$2\ Al_2Si_2O_7 \rightarrow Si_3Al_4O_{12} + SiO_2 \quad (2.2)$$

2.3.1.2 Montmorillonite

Montmorillonite is a very soft phyllosilicate group of minerals that typically form in microscopic crystals, forming clay. It is named after Montmorillon in France. Montmorillonite, a member of the smectite family, is a 2:1 clay, meaning that it has 2 tetrahedral sheets sandwiching a central octahedral sheet. The particles are plate-shaped with an average diameter of approximately one micrometer. Members of this group include saponite (Anthony *et al*., 1990).

Montmorillonite is the main constituent of the volcanic ash weathering product, bentonite. The water content of montmorillonite is variable and it increases greatly in volume when it absorbs water. Chemically it is hydrated sodium calcium aluminium magnesium silicate hydroxide $(Na,Ca)0.33(Al,Mg)_2(Si_4O_{10})(OH)_2 \cdot \boldsymbol{n}H_2O$. Potassium, iron, and other cations are common substitutes. The exact ratio of cations varies with source. It often occurs intermixed with chlorite, muscovite, illite, cookeite, and kaolinite (Hill, 1997).

2.3.1.3 Illite

Illite is a non-expanding, clay-sized, micaceous mineral. Illite is a phyllosilicate or layered alumino-silicate. Its structure is constituted by the repetition of tetrahedron – octahedron – tetrahedron (TOT) layers. The interlayer space is mainly occupied by poorly hydrated potassium cations responsible for the absence of swelling. Structurally illite is quite similar to muscovite with slightly more silicon, magnesium, iron, and water and slightly less tetrahedral aluminium and interlayer potassium. The chemical formula of illite is given as

$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$, but there is considerable ion substitution. It occurs as aggregates of small monoclinic grey to white crystals. Illite occurs as an alteration product of muscovite and feldspar in weathering and hydrothermal environments. It is common in sediments, soils, and argillaceous sedimentary rocks (USGS, 2019).

2.3.1.4 Chlorite

The chlorites are a group of phyllosilicate minerals. Chlorites can be described by the following four end-members based on their chemistry via substitution of the following four elements in the silicate lattice: Mg, Fe, Ni, and Mn.

i. Clinochlore: $(Mg_5Al)(AlSi_3)O_{10}(OH)_8$

ii. Chamosite: $(Fe_5Al)(AlSi_3)O_{10}(OH)_8$

iii. Nimite: $(Ni_5Al)(AlSi_3)O_{10}(OH)_8$

iv. Pennantite: $(Mn,Al)_6(Si,Al)_4O_{10}(OH)_8$

The typical general formula is:

$$(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2\cdot(Mg,Fe)_3(OH)_6 \qquad (2.3)$$

This formula emphasises the structure of the group. Chlorites have a 2:1 sandwich structure (USGS, 2019).

2.3.2 Classification of clay

Clay is commonly divided into two types:

2.3.2.1 Primary clay

Primary clay is also called residual clay, formed at the site of the parent rock. It is less common than secondary (transported or sedimentary) clay, but generally whiter and free from impurities.

Because this clay is broken down by ground water, etc. and not transported, particle size is mixed (no opportunity for sorting or grinding) and the clay is usually not very plastic, and is refractory. Most kaolin are primary clays (Hillier, 2003).

2.3.2.2 Secondary clay

Secondary clay is that clay which has been transported from multiple sources by water, or wind and has sort particle sizes. Many secondary clays contain organic (carbonaceous) and other impurities (iron, quartz, mica, etc.). On the other hand, on the basis of general composition and properties, clay is classified as (Hillier, 2003).

i. **Kaolin** is a fine white clay consisting chiefly of the mineral kaolinite.

ii. **Ball clay** contains kaolinite and certain micas, and has strong bonding properties.

iii. **Fire clay** is basically kaolinite with some iron oxides, magnesia, and alkalis. It can resist

high temperatures.

iv. **Common clay** contains more impurities than fire clay, and does not have as great resistance to heat.

v. **Bentonite** consists largely of montmorillonite. Some types that contain sodium swell when mixed with water.

vi. **Fuller's earth** is composed of montmorillonite and attapulgite (magnesium aluminium phyllosilicate with formula $(Mg,Al)_2Si_4O_{10}(OH)\cdot 4(H_2O)$) and is high in magnesia.

2.3.3 Uses of clay

2.3.3.1 Historical and modern uses

From prehistoric times, clay has been indispensable in architecture, in industry, and in agriculture. Clays exhibit plasticity when mixed with water in certain proportions. When dry, clay becomes firm and when fired in a kiln, permanent physical and chemical changes occur. Because of these properties, clay is used for making pottery items, both utilitarian and decorative. Different types of clay, when used with different minerals and firing conditions, are used to produce earthenware, stoneware, and porcelain (Murray, 2002).

Prehistoric humans discovered the useful properties of clay, and one of the earliest artifacts ever uncovered is a drinking vessel made of sun-dried clay. Depending on the content, clay can appear in various colors, from a dull gray to a deep orange-red (Murray, 2002).

Clays sintered in fire were the first form of ceramic. Bricks, cooking pots, art objects, dishware, and even musical instruments such as the ocarina can all be shaped from clay before being fired. Clay is also used in many industrial processes, such as paper making, cement production, and chemical filtering. Clay is also often used in the manufacture of pipes for smoking tobacco. Until the late 20th century bentonite clay was widely used as a mold binder in the manufacture of sand castings. Clay, being relatively impermeable to water, is also used where natural seals are needed, such as in the cores of dams, or as a barrier in landfills against toxic seepage (Churchman *et al*., 2007).

2.3.3.2 Medical and agricultural uses

A traditional use of clay as medicine goes back to prehistoric times. An example is Armenian bole, which is used to soothe an upset stomach (Dadu *et al*., 2015). Kaolin clay and attapulgite (magnesium aluminium phyllosilicate with formula $(Mg,Al)_2Si_4O_{10}(OH)\cdot 4(H_2O)$) have been used as antidiarrheal medicines (Dadu *et al*., 2015).

2.3.3.3 Clay as a building material

Clay is one of the oldest building materials on Earth, among other ancient, naturally-occurring geologic materials such as stone and organic materials like wood. Between one-half and two-thirds of the world's population, in traditional societies as well as in developed countries, still live or work in a building made with clay as an essential part of its load-bearing structure. Also, a primary ingredient in many natural building techniques, clay is used to create adobe, cob, cordwood, and rammed earth structures (Murray, 2002).

2.3.4 Characterization of clay

Moisture content, bulk density, volatile matter content, pH, alkalinity, Atterberg limits etc. are generally used to characterize any particular clay. X-ray fluorescence analysis, X-ray diffraction analysis, thermogravimetric analysis and differential thermal analysis are the additional routes for characterization of clay. Besides the firing shrinkage, water absorption etc can be found out by making of bricks from the clay and firing them.

2.3.4.1 Moisture content

Moisture content of clay is the ratio of the weight of water present in the soil, to the weight of dry clay in a given clay mass. Moisture content plays an important role in understanding the behavior of clay. It is the moisture content which changes the clay from liquid state to plastic and solid states. The property is used in a wide range of scientific and technical areas, and is expressed as a ratio, which can range from 0 (completely dry) to the value of the materials' porosity at saturation. Compaction of clay in the field is also controlled by the quantity of water present. Moisture may be present as adsorbed moisture at internal surfaces and as capillary condensed water in small pores. At low relative humidity's, moisture consists mainly of adsorbed water. At higher relative humidity's, liquid water becomes more and more important, depending on the pore size.

2.3.4.2 Bulk density

Bulk density is the ratio of the mass of unit volume of clay at a stated temperature to the mass of the same volume of gas-free distilled water at the stated temperature. The bulk density of clay is often used in relating a weight of clay to its volume. Although the density is employed in the identification of minerals, it is of limit value for identification or classification of clay because the density values of most clay fall within a narrow range. It is an important factor required for computing the most of the clay properties e.g. void ratio, particle size and degree of saturation of a clay etc.

2.3.4.3 Organic matter

Clays always contain organic material of various types and origins. In clays dating from more recent eras we can find lignin and humic acids, in colloidal form and with notable ionic exchange properties due to the functional groups -CH e –COOH present in their molecules. In clays of older eras, carbonaceous and bituminous substances are more frequent, with few functional groups capable of influencing colloidal and ionic exchange properties. Generally, the calcareous material is found in the form of lignite, in grains of variable dimensions that form agglomerates or layers, or in the form of colloidal particles clinging to the crystals of argillaceous material. In so-called “ball clays” the material in colloidal form can also be composed of humic acids which facilitate the deflocculation process. Combustion of organic substances occurs between 300 and 600°C and they decompose entirely if the quantity of oxygen is sufficient for complete reaction development. During the firing process of ceramic parts, the organic substances present in the clays can cause the development of a central area (in the ceramic object) of a different color, varying from black to yellow. This is known as the “black core”. This phenomenon is due to the thermal decomposition of the organic material and to oxidation-reduction reactions of the inorganic components.

Basically, whenever the quantity of organic substances is higher than a certain value or whenever low permeability of the ceramic object does not permit complete combustion due to lack of oxygen, carbon remains in the center of the matrix up to higher temperatures (where these can cause reduction of the iron). The size of the black core depends on various factors, such as temperature and firing cycle, forming method, porosity of the ceramic object and oven atmosphere.

2.3.4.4 pH

The hydrogen ion concentration of clay is designated as its pH value. The pH value of a solution indicates its acidic or alkaline nature. A pH value of the order of 7 suggests a neutral solution, less than 7 as acidic and more than 7 as alkaline. The pH value of a solution is expressed as the logarithm of the reciprocal of hydrogen ion concentration as shown in Equation (2.4).

$$pH = \log10 [1/H+] \quad (2.4)$$

Its level is regarded as one of the most significant properties of soil, as it effects on all other parameters of soil. Thus, it is considered while analysing any kind of soil. If the pH is less than 6 then it is said to be an acidic soil, if it ranges from 6-8.5, is normal soil and if greater than 8.5, then it is said to be alkaline soil.

2.3.4.5 Loss on ignition

Loss on Ignition (LOI) is used to determine organic Matter Content (OMC) of a soil sample. The procedure is relatively simple compared to others, used to determine percentage Organic Matter (OM). It does not involve use of any chemicals. It only involved the use of a muffle furnace. LOI calculates the percentage of OM by comparing the mass of soil sample before and after it has been ignited. Before ignition the sample contains OM, but after, all that remains is the mineral portion of the soil. The difference in mass before and after ignition represents the amount of the OM present in the soil sample.

2.3.4.6 Alkalinity

Alkalinity measures the ability of a solution to neutralize acids to the equivalence point of carbonate or bicarbonate. The alkalinity is equal to the stoichiometric sum of the bases in solution. In the natural environment carbonate alkalinity tends to make up most of the total alkalinity due to the common occurrence and dissolution of carbonate rocks and presence of carbon dioxide in the atmosphere. Other common natural components that can contribute to alkalinity include borate, hydroxide, phosphate, silicate, nitrate, dissolved ammonia, the conjugate bases of some organic acids and sulfide. Alkalinity is sometimes incorrectly used interchangeably with basicity. For example, the pH of a solution can be lowered by the addition of CO_2. This will reduce the basicity; however, the alkalinity will remain unchanged.

Clay alkalinity is mainly associated with the presence of sodium carbonates (Na_2CO_3) in it, either as a result of natural mineralization of the clay particles or brought in by irrigation and/or floodwater. The sodium carbonate, when dissolved in water, dissociates into 2Na+ (two sodium cat-ions, i.e. ions with a positive electric charge) and CO_3^{--} (a carbonate an-ion, i.e. an ion with a -double - negative electric charge). The sodium carbonate can react with the water to produce carbon-dioxide (CO_2), escaping as a gas, and sodium-hydroxide (Na^+OH^-), which is alkaline and gives high pH values (pH>10).

The causes of clay alkalinity are natural or they can be man-made. The natural development is due to the presence minerals producing sodium carbonate upon weathering. The man-made development is due to the application of irrigation water (surface or ground water) containing a relatively high proportion of sodium bicarbonates).

2.3.4.7 X-ray diffraction (XRD)

X-ray diffraction is a rapid analytical technique primarily used for phase identification of a crystalline material. X-ray diffraction analysis is widely used in the study of clays primarily to identify the phases present in a particular clay sample.

2.3.4.8 X-ray fluorescence (XRF)

X-ray fluorescence (XRF) is the emission of characteristic "secondary" (or fluorescent) x-rays from a material that has been excited by bombarding with high-energy x-rays or gamma rays. The phenomenon is widely used for elemental analysis and chemical analysis of clays.

2.3.5 Geotechnical properties of soils

Different geotechnical property of soils has different influence on the civil engineering structures. They also depend upon each other. The properties are discussed as follows:

2.3.5.1 Specific gravity

Specific gravity is the ratio of the mass of soil solids to the mass of an equal volume of water. It is an important index property of soils that is closely linked with mineralogy or chemical composition and also reflects the history of weathering. It is relatively important as far as the qualitative behavior of the soil is concerned and useful in soil mineral classification, for example iron minerals have a larger value of specific gravity than silica. It gives an idea about suitability of the soil as a construction material; higher value of specific gravity gives more strength for roads and foundations. It is also used in calculation of void ratio, porosity, degree of saturation and other soil parameters. Typical values of specific gravity are given in Table 2.1 (Bowels, 2012).

Table 2.1: Typical values of specific gravity

Type of soil	Specific gravity
Sand	2.65-2.67
Silty sand	2.67-2.70
Inorganic clay	2.70-2.80
Soil with mica or iron	2.75-3.00
Organic soil	1.00-2.60

(Source: Bowles, 2012)

Roy and Das (2014) found that increase in specific gravity can increase the shear strength parameters (cohesion and angle of shearing resistance). Roy observed that increase in specific gravity also increases the California bearing ratio i.e. strength of the subgrade materials used in road construction.

2.3.5.2 Consistency limits (Atterberg limits)

The Swedish scientist Albert Atterberg originally defined seven "limits of consistency" to classify fine-grained soils, but in current engineering practice only two of the limits, the liquid and plastic limits, are commonly used (a third limit, called the shrinkage limit, is used occasionally). The Atterberg limits are based on the moisture content of the clay. The plastic limit is the moisture content that defines where the clay changes from a semi-solid to a plastic (flexible) state. The liquid limit is the moisture content that defines where the clay changes from a plastic to a viscous fluid state. The shrinkage limit is the moisture content that defines where the clay volume will not reduce further if the moisture content is reduced.

The proper and efficient clays as raw materials for ceramic materials require considerable knowledge of their engineering properties. The engineering properties are those which describe the behavior of clay under various usages. The important properties are liquid limit, plastic limit, plasticity index, shrinkage limit etc. These properties are of great interest to ceramics makers who are called upon to select clays for ceramics making.

In a laboratory test, liquid limit is the water content at which the clay has such small shear strength that it flows to close a groove of standard width when jarred in a specified manner and plastic limit is the water content at which the clay begins to crumble when rolled into threads of specified size. Liquid limit is the boundary between liquid and plastic states. The amount of water which must be added to change the clay from its plastic limit to its liquid limit is an indication of the plasticity of the clay. The plasticity is measured by the ‘Plasticity Index’ which is equal to the liquid limit minus the plastic limit.

In general chlorite, illite and kaolinite clay minerals have relatively low shrinkage, good plastic properties and a long vitrification range. A small amount of smectite can be tolerated, but a large amount would give undesirable shrinkage and drying properties. Prakash and Jain (2002) quoted some standard liquid limit values to explain the compressibility behavior of soils. These are given on Table 2.2.

Table 2.2: Some standard liquid limits

Liquid limit values	Bahavior of clay
0 – 35	**Low Compressibility**
35 - 50	**Medium Compressibility**
>50	**High compressibility**

(Source: Prakash and Jain, 2002)

The consistency of a fine-grained soil is largely influenced by the water content of the soil. A gradual decrease in water content of a fine-grained soil slurry causes the soil to pass from the liquid state to a plastic state, from the plastic state to a semi-solid state, and finally to the solid state. The water contents at these changes of state are different for different soils. The water contents that correspond to these changes of state are called the Atterberg limits. The water contents corresponding to transition from one state to the next are known as the liquid limit, the plastic limit and the shrinkage limit (Kaniraj, 1998).

The liquid limit of a soil is the water content, expressed as percentage of the weight of the oven dried soil, at the boundary between the liquid and plastic states of consistency of the soil.

The soil has negligibly small shear strength (Kaniraj, 1998). The plastic limit of a soil is the water content, expressed as a percentage of the weight of oven dried soil, at the boundary between the plastic and semi-solid states of consistency of the soil. The plastic limit for different soils has a narrow range of numerical values. Sand has no plastic stage, but very fine sand exhibits slight plasticity. The plastic limit is an important soil property. Earth roads are easily usable at this water content. Excavation work and agricultural cultivation can be carried out with the least effort with soils at the plastic limit. Soil is said to be in the plastic range when it possesses water content in between liquid limit and plastic limit. The range of the plastic state is given by the difference between liquid limit and plastic limit and is defined as the plasticity index. The plasticity index is used in soil classification and in various correlations with other soil properties as a basic soil characteristic (Raj, 2012). Based on the plasticity index, the soils were classified by Atterberg, shows the correlations between the plasticity index, soil type, degree of plasticity and degree of cohesiveness (Table 2.3) (Prakash and Jain, 2002).

It has been observed that the plasticity index of a soil increases linearly with the percentage of the clay-sized fraction. Laskar and Pal (2012) found that plasticity depends on grain size of soil. With the increase of sand content plasticity index of soil decreases, which might be due to decrease of inter molecular attraction force. Due to decrease of attraction force, liquid limit of the soil decreases and accordingly plasticity index decreases. But as the clay content increases inter molecular attraction force increases and liquid limit increases.

Table 2.3: Types of soils based on plasticity index

Plasticity index (%)	Soil type	Degree of plasticity	Degree of cohesiveness
0	Sand	Non-plastic	Non-cohesive
<7	Silt	Low plastic	Partly cohesive
7-17	Silt clay	Medium plastic	Cohesive
>17	Clay	High plastic	cohesive

(Source: Prakash and Jain (2002)

2.3.5.3 Particle size analysis

The percentage of different sizes of soil particles coarser than 75µm is determined by sieve analysis whereas less than 75 µ are determined by hydrometer analysis. Based on the particle size analysis, particle size distribution curves are plotted. The particle size distribution curve (gradation curve) represents the distribution of particles of different sizes in the soil mass (Mallo and Umbugadu, 2012). It gives an idea regarding the gradation of the soil i.e. it is possible to identify whether a soil is well graded or poorly graded. In mechanical soil stabilization, the main principle is to mix a few selected soils in such a proportion that a desired grain size distribution is obtained for the design mix. Hence for proportioning the selected soils, the grain size distribution of each soil is required to be known (Prakash and Jain, 2002).

Apparao and Rao (1995) explained that the grain size analysis is widely used in classification of soils. The data obtained from grain size distribution curves is used in the design of filters for earth dams and to determine suitability of soil for road construction, air fields, etc. Raj (2012), stated that the particle size of sands and silts has some practical value in design of filters and in the assessment of permeability, capillarity, and frost susceptibility. Very relevant and useful information may be obtained from grain size curve such as (i) the total percentage of larger or finer particles than a given size and (ii) the uniformity or the range in grain-size distribution. Bowles (2012) found that particle-size is one of the suitability criteria of soils for roads, airfield, levee, dam and other embankment construction. Information obtained from particle-size analysis can be used to predict soil-water movement, although permeability tests are more generally used. The susceptibility to frost action in soil, an extremely important consideration in colder climates, can be predicted from the particle-size analysis. Very fine soil particles are easily carried in suspension by percolating soil water, and under drainage systems are rapidly filled with sediments unless they are properly surrounded by a filter made of appropriately graded granular materials. The proper gradation of this filter material can be predicted from the particle-size analysis. Particle-size of the filter materials must be larger than the soil being protected so that the filter pores could permit passage of water but collect the smaller soil particles from suspension.

According to Dafalla (2013), the shape of soil grains, whether rounded, sub-rounded, or angular will affect shearing strength of the soil mass. Angular grains provide more interlock and increased shear resistance. The gradation and size of the sand affect the shear resistance. Well-graded materials provide more grain to grain area contact than poorly graded materials. Porosity and spaces available for clay within the sand is an important while considering the mixtures of clays and sands.

2.3.5.4 Shear Strength

The shear resistance of soil is the result of friction and the interlocking of particles and possibly cementation or bonding at the particle contacts. The shear strength parameters of soils are defined as cohesion and the friction angle. The shear strength of soil depends on the effective stress, drainage conditions, density of the particles, rate of strain, and direction of the strain. Thus, the shearing strength is affected by the consistency of the materials, mineralogy, grain size distribution, shape of the particles, initial void ratio and features such as layers, joints, fissures and cementation (Poulos, 1989). The shear strength parameters of a granular soil are directly correlated to the maximum particle size, the coefficient of uniformity, the density, the applied normal stress, and the gravel and fines content of the sample. It can be said that the shear strength parameters are a result of the frictional forces of the particles, as they slide and interlock during shearing (Yagiz, 2001). Soil containing particles with high angularity tend to resist displacement and hence possess higher shearing strength compared to those with less angular particles (Ranjan and Rao, 1991). Different researchers explained that the capability of a soil to support a loading from a structure, or to support its overburden, or to sustain a slope in equilibrium is governed by its shear strength. The shear strength of a soil is of prime importance for foundation design, earth and rock fill dam design, highway and airfield design, stability of slopes and cuts, and lateral earth pressure problems. It is highly complex because of various factors involved in it such as the heterogeneous nature of the soil, the water table location, the drainage facility, the type and nature of construction, the stress history, time, chemical action, or environmental conditions.

As per Prakash and Jain (2002), confining pressures play significant role in changing the behavior of soils in deep foundations. Similarly, in high rise earth dams, the confining pressures are of very high magnitude. Triaxial test is the only test to simulate these confining pressures. For short term stability of foundations, dams and slopes, shear strength parameters for unconsolidated undrained or consolidated undrained conditions are used, while for long term stability shear parameters corresponding to consolidated drained conditions give more reliable results.

Akayuli *et al*. (2013) found that the friction angle is high for a sandy soil than its cohesion and vice versa for clayey soil. There is general increase in cohesion with clay content. As more clay is introduced into the sandy materials, the clay particles fill the void spaces in between the sand particles and begin to induce the sand with interlocking behavior. Hence, clayey sand soils are expected to exhibit low cohesion whereas the cohesion increases with high clay content.

2.3.5.5 Consolidation

When a soil layer is subjected to compressive stress due to construction activities, it undergoes compression. The compression is caused by rearrangement of particles, seepage of water, crushing of particles, and elastic distortions. Settlement of a structure is analyzed for three reasons: appearance of structure, utility of the structure, and damage to the structure. The aesthetic view of a structure can be spoiled due to the presence of cracks or tilt of the structure caused by settlement. Settlement caused to a structure can damage some of the utilities like cranes, drains, pumps, electrical lines etc. Further settlement can cause a structure to fail structurally and collapse. According to Prakash and Jain (2002), the main aim of a consolidation test is to obtain soil data which are used in predicting the rate and amount of settlement of structure founded on clay primarily due to volume change of the clay. The information obtained for foundations resting on clay are:

i. Total settlement of foundation under any given load,
ii. Time required for total settlement due to primary consolidation,
iii. Settlement for any given time and load,

iv. Time required for any percentage of total settlement or consolidation, and

v. Pressure due to which soil already has been consolidated/compressed.

Lowering of water table or dewatering is probably the best-known cause of massive settlement. When submerged, soil particles are subjected to buoyancy. Upon dewatering, the buoyancy is removed and the apparent increase in pressure results in consolidation, even though there is no increase in external load. Vibrations can also have a densification effect on soils and lead to subsequent settlement. The effects can be severe when the vibration frequency matches the soil's natural frequency. Soils often fail and settle disastrously as a result of earthquakes. Devastating landslides are often one of the results of such occurrences. Of the three phases of soil, only the solid phase controls the resistance to compression and shear. Water, present in a moist soil is highly incompressible but as a liquid, is not capable of resisting shear loads. Air, present in unsaturated soils, will not support compression or shear loads.

2.3.5.6 Permeability

The amount, distribution, and movement of water in soil have an important role on the properties and behavior of soil. The engineer should know the principles of fluid flow, as groundwater conditions are frequently encountered on construction projects. Water pressure is always measured relative to atmospheric pressure, and water table is the level at which the pressure is atmospheric. Soil mass is divided into two zones with respect to the water table:

i. below the water table (a saturated zone with 100% degree of saturation) and

ii. just above the water table (called the capillary zone with degree of saturation $\leq$ 100%).

Data from field permeability tests are needed in the design of various civil engineering works, such as cut-off wall design of earth dams, to ascertain the pumping capacity for dewatering excavations and to obtain aquifer constants (Raj, 2012). The permeability of soils has a decisive effect on the stability of foundations, seepage loss through embankments of reservoirs, drainage of subgrades, excavation of open cuts in water bearing sand, and rate of flow of water into wells. Prakash and Jain (2002), explained that water flowing through soil exerts considerable seepage forces, which have direct effect on the safety of hydraulic structures. The rate of settlement of compressible clay layer under load depends on its permeability. The quantity of stored water escaping through and beneath an earthen dam depends on the permeability of the embankment and the foundation respectively. The rate of drainage of water through wells and excavated foundation pits depends on the coefficient of permeability of the soils. Shear strength of soils also depends indirectly on its permeability, because dissipation of pore pressure is controlled by its permeability. According to U. S. Bureau of Reclamation, soils are classified as (i) Impervious: k (coefficient of permeability) less than 10-6 cm/sec, (ii) Semi pervious: k between 10-6 to 10-4 cm/sec (iii) Pervious: k greater than 10-4 cm/sec.

2.4 Review of Past Studies on Tropical Soils (Clays) in Nigeria

Many studies have been carried out on tropical soils (clays) in Nigeria. Bello (2012) geotechnically evaluated reddish-brown tropical clays in Nigeria and reported kaolinite as the major clay mineral in the soils with Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) ranging between 1.68 and 1.98 Mg/m^3 and 12.3 and 21.2% respectively. 7.7 to 9.2% Fe_2O_3, 4.1 to 7.2% CaO, 0.10 to 0.35% MnO_3, 0.6 to 1.6% K_2O, 0.12 to 0.3 Cr_2O_3, 3.3 to 5.1% Al_2O_3, and 2.2 to 5.7% SiO_2 were also reported, with 5.2 to 5.9% natural moisture content, 2.62 to 2.66 specific gravity, 43 to 48% Liquid limit, 28 to 32% plastic limit, 14 to 16% plasticity index, 6.25 to 8.60% linear shrinkage, 59.2 to 66.4% passing sieve 0.075mm, 17.46 to 17.85 kN/m^3 maximum dry unit weight and 15.1 to 17.8% OMC. Alhassan *et al*. (2012), Alhassan *et al.* (2014) and Alhaji *et al*. (2020a) have earlier reported kaolinite as the major clay mineral in separately studied reddish- tropical clay soils in northcentral Nigeria.

Meshida *et al.* (2013) studied tropical black clay, collected from Dikwa-Gamboru road, Borno State, Nigeria, and reported 39.61% SiO_2, 30.87% Al_2O_3, 0.43% Fe_2O_3, 0.3%9 CaO, 0.36% MgO and 0.52% K_2O. Liquid limit, plastic limit, plasticity index, shrinkage limit, free swell and OMC values of 66.0, 24.5, 41.5, 9.4, 70 and 20.5% respectively. MDD, unsoaked California Bearing Ratio (CBR), soaked CBR and Unconfined Compressive Strength (UCS) values of 1.484 Mg/m^3, 24%, 15% and 32.7kN/m^2 respectively.

Osinubi *et al.* (2016) studied tropical black clay collected along Numan-Ngurore in Adamawa state of Nigeria and reported 31.1% SiO_2, 16.19% Al_2O_3, 4.74% Fe_2O_3. Natural moisture content of 8.9%, percent passing sieve 0.075mm of 69.1%, liquid limit of 50.4%, plastic limit of 17.1% plasticity index of 33.3% and linear shrinkage of 15.7% were also reported, specific gravity value of 2.30 and swelling pressure of 42.6 kN/m^2. MDD of 1.59, 1.68 and 1.83Mg/m^3, with corresponding OMC of 18.5, 16.8 and 14.0%, at British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH) respectively were reported, together with 3, 6 and 8% CBR at the respective compaction energy. In a similar study Eberemu *et al*. (2021) reported 63.208% SiO_2, 20.601% Al_2O_3, 8.522% Fe_2O_3 and 2.63% K_2O for a tropical black clay collected along Gombe-Biu Road in Gombe state, Nigeria, with percentage passing 0.075mm sieve, natural moisture content, free swell, liquid limit, plastic limit, plasticity index, linear shrinkage, 78.7, 15.1, 70.0, 53.0, 26.7, 26.3, and

17.5% respectively, and 2.42, 11.5, 1.65Mg/m^3 as specific gravity, OMC and MDD respectively. In another study using tropical black clay from the region, Uloko *et al*. (2021) reported percentage passing BS No. 200 Sieve as 83%, 68% liquid Limit, 46% plastic Limit, 22% plasticity index, 10% linear shrinkage, 3.98% LOI, 1.45 Mg/m^3 MDD, 22.9% OMC, 163 kN/m^2 unconfined compressive strength, 80% free swell and specific gravity of 2.68.

Oluyemi-Ayibiowu *et al*. (2016) investigated some tropical soils in Nigeria and reported liquid limit, plastic limit, plasticity index and linear shrinkage values ranging from 36.5 to 58.4%, 19.7 to 32.5%, 16.8 to 25.9% and 5.8 to 9.8% respectively. With the soils classifying between A-2-6 to A-7-6, MDD, OMC and CBR ranging between 1.56 to 2.14 Mg/m^3, 9.0 to 15.5% and 7.7 to 32.5% respectively.

Moses *et al.* (2018) reported SiO_2, Al_2O_3 and Fe_2O_3 of 51.41, 20.29 and 13.20% respectively for a tropical black clay, collected from Numan Local Government Area of Adamawa State, in North East part of Nigeria. Also, natural moisture content, liquid limit, plastic limit, plasticity index, linear shrinkage, free swell values and Loss on Ignition (LOI) of the soil was reported as 14.5, 70.63, 32, 31, 21, 90 and 4.87% respectively. With specific gravity given as 2.34, 1.45 and 1.67Mg/m^3 were reported as MDD at BSL and WAS compaction efforts respectively, with corresponding 17 and 15% OMC.

Dogo *et al*. (2018) studied tropical black clay from Gwagwalada area of Abuja, Nigeria, and reported natural moisture content, liquid limit, plastic limit, plasticity index and LOI of the soil was reported as 35.06, 63.00, 28.37, 34.63 and 17.78% respectively, and specific gravity of 2.66. 1.6258 and 1.7928Mg/m^3 were given as MDD at BSL and WAS compaction efforts respectively, with corresponding OMC as 24.5 and 20.94% respectively. Haruna *et al*. (2017)

also reported percentage passing sieve 0.075mm, natural moisture content, liquid limit, plastic limit, plasticity index, Linear shrinkage, free swell values of 99.00, 25.32, 66.80, 35.20, 31.60, 18.90, 73.00% respectively, and specific gravity of 2.54 for a tropical black clay.

Nwokediuko *et al.* (2019) studied characteristics of tropical red soils of southern Nigeria, and reported percentage passing sieve 0.075mm, liquid limit, plastic limit and plasticity index to range from 44.12 to 60.92, 34.44 to 46.32, 21.57 to 27.19 and 11.20 to 21.43 respectively, while MDD and OMC ranged from 1.55 to 1.72 Mg/m^3 and 14.6 to 20.9% respectively. Shear strength parameters were also reported to range from 5 to 22 kN/m^2 and 29 to 38° respectively, for cohesion and angle of internal friction. Madueke *et al*. (2021a) and Madueke *et al.* (2021b) studied tropical rainforest soils derived from the coastal plain sands of southeastern Nigeria, and reported bulk density ranging between 1.28 to 1.69 Mg/m^3.

Okeke *et al.* (2020) investigated consolidation characteristics of soils from parts of Anambra basin, southeastern, Nigeria, and reported moisture content, liquid limit, plasticity index and dry density ranging from 33 to 51%, 33 to 56%, 30 to 31% and 1.11 to 1.58Mg/m^3 respectively, while compression index of the within the range of 0.73 to 0.68. In another study, Okeke *et al.* (2016) geotechnically and geochemically characterized tropical lateritic soil deposits in Owerri, southeastern Nigeria and reported 34.6 to 37.6 SiO_2, 25.10 to 27.4% Al_2O_3, 22.0 to 25.0% Fe_2O_3, 0.24 to 0.27% CaO and 0.17 to 0.20% MgO, with liquid limit, Plastic limit, Plasticity index, MDD, OMC, unsoaked and soaked CBR ranging from 26 to 32.00%, 19.40 to 20.80%, 6.6 to 11.30%, 1.95 to 2.02Mg/m^3, 8.0 to 10.0%, 43 to 63% and 11 to 33% respectively.

Annafi *et al*. (2020a) and Annafi *et al*. (2020b) reported percentage passing sieve 0.075mm, natural moisture content, liquid limit, plastic limit, plasticity index and LOI values of 67.9, 11.9, 60.3, 32.6, 27.7 and 43.67% respectively, while 1.47Mg/m^3, 25.6 and 3% were reported as MDD, OMC and unsoaked CBR respectively, with 2.29 as specific gravity. Ikara *et al*. (2021), reported liquid limit and plasticity index of 49 and 23 respectively, soaked CBR values ranging from 6.6 to 9.8 %, OMC and MDD values of 17.5, 22, 21 % and 1.61, 1.63, 1.69%, respectively, at BSL, BSH and WAS compaction energy respectively, for a non-lateritic soil having 6.74 % Aluminium oxide (Al_2O_3), 61.31 % Silicon oxide (SiO_2), 14.02 % Iron oxide (Fe_2O_3), 4.672 % Potassium oxide (K_2O) and [SiO_2/ (Al_2O_3+Fe_2O_3)] of 2.96.

Yohanna *et al*. (2021) studied some selected tropical soils and reported percentage of the soil passing sieve 0.075mm ranging from 58.8 to 74.2%, natural moisture content ranging from 16.24 to 19.5%, specific gravity ranging from 2.44 to 2.59, liquid limit ranging from 43.4 to 56%, plastic limit ranging from 21.3 to 25%, plasticity index from 22.1 to 31%, MDD, at BSL, WAS and BSH ranging from 1.68 to 1.72, 1.64 to 1.76 and 1.56 to 1.83 Mg/m^3 respectively, with corresponding OMC ranging from 16 to 19.3 , 15 to 20 and 14 to 23.5%.

Oyelami *et al*. (2022) carried out a preliminary geotechnical assessment of residual tropical soils around Osogbo metropolis as materials for road subgrade, and reported kaolinite as the most abundant clay mineral in the soils, with liquid and plastic limits ranging between 32.0 and 47.2% and 19.7 and 25.9% respectively. MDD and OMC, at British Standard Heavy, ranges from 1.210 to 1.520 Mg/m^3 and 13.0 to 24%, respectively, while the CBR values ranges from 3.01 to 44.59%. Shear strength parameters of the soils showed cohesion ranging from 30 to 185 kN/m^2, with angle of internal friction between 5 and 11°.

Ifetayo and Pretorius (2018) reported 14% natural moisture content, 2.60 specific gravity, 60% percent passing sieve 0.075mm, 48% liquid limit, 20% plastic limit, 28% plasticity index and 14% linear shrinkage for a tropical black cotton soil from Adamawa state, Nigeria. In a similar study Yohanna *et al*. (2022) evaluated of geotechnical properties of black clay taken along Gombe - Adamawa Road, and reported percentage passing sieve 0.075mm, natural moisture content, liquid limit, plastic limit, plasticity index, as 77.69, 3.90, 45.18, 25.82 and 19.43% respectively, while specific gravity, MDD and OMC were given as 2.41, 1.55 Mg/m^3, and 19.0% respectively. Also, Akinwamide and Abe (2017) reported 14, 60, 48, 20, 28 and 14% as natural moisture content, liquid limit, plastic limit, plasticity index and linear shrinkage values respectively for a tropical black clay, having specific gravity as 2.60.

Jungudo *et al*. (2020) investigating the engineering properties of tropical black clay and reported 2.35 Specific gravity, 51% Liquid limit, 28.57% Plastic limit, 21.43% Plasticity index, 1.71Mg/m^3 MDD, 18.9% OMC, with combined SiO_2+Al_2O_3+Fe_2O_3 ranging from 50 to 70%, with 85% passing sieve 0.075mm. Similar results were also presented by Omisande (2020) for tropical black clay from Idogo town, Yewa South local Government area of Ogun State.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Materials

3.1.1 Geology of the study area

The soil samples used in this study were collected within the premises of Niger state Polytechnic, Zungeru, in Niger state. The geology of Zungeru is characterized by Schist Belt. According to Obaje (2009), the Birnin Gwari Schist formation and the underlying quartzo-feldspathic rocks of the Zungeru Granulite Formation, together, form a single structural unit, termed the Zungeru-Birnin Gwari Schist Belt. It is a simple N–S syncline, 150 km long, with the northern part displaced dextrally by a NE–SW transcurrent fault. The Zungeru Granulite Formation outcrops on both flanks of the schist belt. It is largely made up of fine-medium grained quartzo-feldspathic rocks which are interbedded with amphibolites and some quartzites.

The study area is part of Zungeru (Sheet 163) in northcentral Nigeria. It lies between latitudes 9°46’ N and 9°52’N and Longitudes 6°07’ and 6°13’E (Figure 2). The area is accessible through major roads like the Minna-Zungeru, Zungeru-Wushishi and the Zungeru-Kontagora in the North, West and Southeast respectively. It is also accessible by innumerable minor roads and footpaths. By rail, it is accessible by Zungeru-Minna-Kano rail line to the North and Zungeru-Lagos rail line to the South. According to Agbor (2014) Basement rocks of Zungeru area consist of gneisses, schists, migmatites and intercalations of amphibolites and quartzites. Zungeru generally lies at the northeast edge of Bida Basin (Figure 3.1).

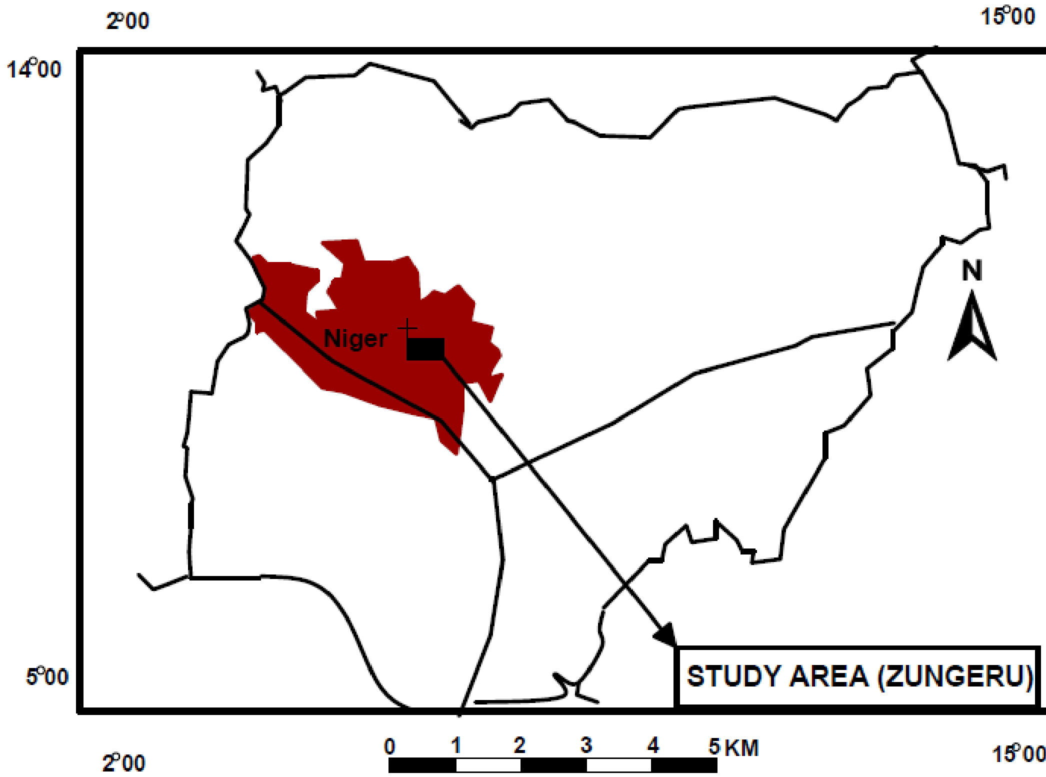


Figure 3.1: Map of Nigeria showing the study area (*source: Agbor, 2014*)

The clay soil samples that were used for this project were obtained from Zungeru Local Government Area of Niger State. Both disturbed and undisturbed samples were collected from five different locations (Trial Pits – TP) within the study area. At each of the five TPs soil samples were collected at two different depths (0.5 and 1.0m), making a total of ten different soil samples all together. Soil samples A, B were collected from TP 1, C, D were collected from TP 2, E, F were collected from TP 3, G, H were collected from TP 4 and I, J were collected from TP 5. Undisturbed samples were collected using galvanized steel samplers, while the disturbed samples were collected and conveyed in sacks, to the geotechnics laboratory of Civil Engineering Department, Federal University of Technology Minna.

3.2 Methods

The following laboratory tests were performed on the collected soil samples in accordance with BS1377 (1990). These tests include Mineralogical, physico-chemical (pH and Loss on ignition-LOI) and Geotechnical properties tests.

3.2.1 Mineralogical test

Mineralogical tests using XRD and XRF analysis was carried out to identify the composition the clay samples.

3.2.1.4 X-ray diffraction analysis (XRD)

This test was carried out to determine the clay minerals present in the samples. The X-Ray Diffraction (XRD) test was carried out in Ithemba laboratory, Somerset West 712 in Republic of South Africa. Phase characterization of the minerals and estimate of the average crystallite size of the various synthesised materials were carried out on a Bruker AXS D8 X-ray Diffractometer system, coupled with Cu-Kα radiation of 40 kV and a current of 40 mA. The λ for Kα was 0.1541 nm, while the scanning rate was 1.5°/min, which was operated at a stepping width of 0.05° over the 2θ range.

The powdered sieved samples were placed and clipped onto the rectangular aluminium sample holder. The diffractograms were recorded in the 2θ range of 20 - 90º, while the phase identification was done. The system used a time constant of 0.5s, scanning step of 0.2º, scanning angle range of of between 20 and 90º and scanning speed of 60sec/step.

The Scherer equation shown below was used to determine the crystal size from half height peak width.

$$d = \frac{k\lambda}{\beta \cos\theta} \tag{3.1}$$

where,

d is crystallite size in nanometer,

k= 0.94,

λ is the wavelength of the X-ray which is 0.1541 nm,

θ is the half-diffraction angle, and

β is the full width at half-maximum in radian.

3.2.1.5 Energy Dispersive Spectroscopy (EDS)

The EDS test was carried out in Electron Microscope unit of the Department of Physics, Faculty of Natural Sciences, University of Western Cape, Capetown, Republic of South Africa. 0.05 mg of the synthesized soil materials were sprinkled on a sample holder, covered with carbon adhesive tape and were sputter coated with Au-Pd, using Quorum T15OT for 5 minutes, prior to the test and analysis. The sputter coated samples were characterized using Zeiss Auriga High Resolution Scanning Electron Microscopy (HRSEM). The secondary electron mode was activated for imaging, and the homogeneous region on the samples were identified. The microscope was operated with Electron High Tension (EHT) of 20 kV for EDS and then the elemental composition of the sample was determined with EDS.

3.2.1.6 Scanning Electron Microscopy (SEM)

The SEM, which was carried out to visualize morphology and microstructure of the synthesised products (soil samples) was analysed using Zeiss Auriga HRSEM. 0.05 mg of the synthesised materials were sprinkled on a sample holder covered with carbon adhesive tape and were sputter coated with Au-Pd using Quorum T15OT for 5 minutes prior to test and analysis. The sputter coated samples were characterized using Zeiss Auriga HRSEM, and the microscope was operated with Electron High Tension (EHT) of 5 kV for imaging. This was carried out to determine the major composition of minerals and elements, contained in the soil samples.

3.2.2 pH of soil

pH of the soil samples was determined following Jackson *et al*. (1948) procedure. The oven dried soil sample, weighing 12.5 g was suspended in 25ml of distilled water and stirred continuously. The pH was measured using calibrated pH meter.

3.2.3 Loss on ignition (LOI)

Soil samples were Oven dried for a minimum of two hours, at 150°C ± 5°C, maintain at 100°C and the mass taken. Masses of the beaker plus the warm soil samples, to the nearest ±1 mg were recorded. The samples were heated and maintain at 360°C ±5°C, for two hours, and then cooled to 105°C and maintained at this temperature until weighing. The beaker and warm ash in a draft-free environment were weighed to the nearest ±1 mg. LOI (organic matter) was calculate and reported as percent to the nearest tenth of a percent.

3.2.5 Geotechnical properties test

3.2.4.1 Soil identification tests

Soil identification tests was carried out, which includes; Natural moisture content test, grain size distribution test, Atterberg limit test and specific gravity test. These tests were carried out using the disturbed samples.

Natural moisture content

The procedure adopted is as outlined in BS1377 (1990). This involved weighing three empty moisture cans to the nearest 0.01g (M_1). After taking masses of the empty moisture can, about 30g of fresh soil sample was placed in each of the cans and weighed again to the nearest 0.01g

(M_2). The cans containing the wet sample were place in an oven at 100 to 105°C to dry for 24 hours. The moisture cans, containing the dried soils were weighed (M_3). The natural moisture content was then be determined using Equation (3.1):

$$NMC = \frac{M_2 - M_3}{M_3 - M_1} \quad (3.1)$$

Where,

M_1 = Mass of empty container

M_2 = Mass of container with wet soil

M_3 = Mass of container with dry soil

Specific gravity test

The procedure adopted in the study is as outlined in BS 1377(1990). The density bottles with stoppers were washed dried and weighed empty with the stopper as M_1. About 50g of soil sample which pass through sieve size 2mm was poured into the density bottles. The density bottles and content together with the stoppers were weighed as M_2. Distilled water was tthen added and covered and allowed to fully soak. After this, the stoppers were inserted, and the bottles together with the content were shaken, and the stoppers were then removed and water added to reach 250ml capacities. The bottles with the content and stoppers were then weighed as M_3. The density bottles were then emptied and thoroughly cleaned and oven dried at 105°C. The clean and oven dried density bottles were then filled with distilled water to 250ml capacities and stoppers inserted and then weighed as M_4. The specific gravity of the sample was calculated using Equation (3.2).

$$GS = \frac{M_2 - M_1}{(M_4 - M_1) - (M_3 - M_2)} \quad (3.2)$$

Where;

M_1 = Weight of bottle

M_2 = Weight of bottle +dry soil

M_3 = Weight of bottle + soil + water

M_4 = Weight of bottle + water.

Sieve analysis

The procedure adopted is also as outlined in BS 1377 (1990) which involved soaking 300g of soil for 24hours and then washing, oven drying and making it ready for the grain size test. The retained samples during washing on sieve size 2.0 and 0.075mm were carefully removed and placed in a pan, which were in turn be placed in oven at 105 to 110^{o}C for 24 hours. Set of sieves were then measured empty and arranged sequentially with the largest on top and the lowest size below as follows; 5.0, 3.35, 2.0, 1.18, 0.85, 0.60, 0.425, 0.300, 0.150, and 0.075mm, and base pan. The oven dried samples were then poured into the uppermost sieve and the stack placed on mechanical sieve shaker and allowed to shake for 10 minutes. The weight of each sieve was taken and recorded. The weights of empty sieves were subtracted to give the weight of the retained soil on each sieve. The percentage of total sample, passing each of the sieves were calculated.

Atterberg limits test

The tests conducted includes Liquid Limit (LL) and Plastic Limit (PL). These tests were carried out in accordance with BS 1377 (1990).

Liquid limit test

Cone penetrometer method of liquid limit determination was used. Reasonable quantity of air-dried sample was pulverized and sieved through 425μm sieve. About 200g of the sieved sample was placed on a flat glass and mixed thoroughly with clean water using spatula until the soil mass become a thick paste. The paste was then pushed into the cup with spatula, making sure air was not trapped, until filled. The top of the soil was trimmed with the top of the cut and placed beneath the cone. The cone was then be lowered so that it just touched the surface of the soil. When the cone was in correct position, a slight movement of the cup gives a small mark on the surface of the soil and the reading of the dial gauge was recorded.

The cone was then released for a period of 1-5 seconds. After penetration, the dial gauge was lowered to the new position of the cone shaft and readings recorded. The difference between the readings at the beginning and at the end of the test was recorded as the cone penetration. Average of two penetrations was recorded. The cone was lifted out and cleaned. A moisture content sample of about 10g was taken from the area penetrated by the cone for moisture content determination. The soil was then removed from the cup, remixed and the procedure outlined above was repeated using the same sample with more water added until penetration of about 20mm was recorded. The relationship between the moisture contents and cone penetration was plotted. From the plotted graph, moisture content at 20mm penetration was taken as liquid limit of the soil.

Plastic limit test

About 20g of the pulverized soil sample sieved through 425µm sieve, was used for the test. The soil was thoroughly mixed with clean water. A small sample of soil ball was then rolled between the hand and glass plate. The rolling was continued until a thread that grumbles at about 3mm diameter was obtained. The crumbled soil was then gathered and placed in moisture can for moisture content determination. Plasticity Index (PI) was determined from the result of liquid and plastic limits.

3.2.2.5 Strength properties test

Determination of unit weight

The unit weight of the collected samples was determined in accordance with BS 1377 (1990), using coring method. This test was conducted using undisturbed samples. Unit weight (γ) of a soil sample is the weight of the sample in (kN) divided by the volume of the soil specimen in (m^3), as given in Equation (3.3).

$$\gamma = \frac{W}{V} \tag{3.3}$$

Where,

W = total weight of sample in kN

V = total volume of sample in m^3

Determination of shear strength parameter though triaxial test

For this test, soil samples collected at 1.0m depth in the five trial pits were used. The apparatus that was used for this test are triaxial machine, split mould, suction mould, palette knife, lubricating oil of light grade, latex membrane electronic weighing balance and a mechanical pump.

A split mould of internal diameter and height of 38 and 84mm respectively was used. The soil specimens were extruded from the split mould and trimmed using a palette knife to a height of 76mm. Rubber membrane was placed inside the suction mould and drawn to the inside surface by means of small amount of vacuum through the suction tube "using mouth power".

The cylindrical shape specimens were placed on the platen and another platen (cap) was placed on top of the specimen. The rubber membrane was worn over the specimens completely, covering the specimen and the platens at the bottom and top of it, completely surrounded by a membrane.

This was then placed in a cylindrical sample cell on the triaxial cell base, and confined by the cell pressure σ_3 using the cell fluid (water). The source of the cell fluid was water tank/mechanical pump. The required lateral pressure was applied using mechanical pump and additional axial stress was applied to the top of the soil cylinder by through a movable piston. The vertical pressure was increased till failure occurred, while lateral pressure (σ_3) was kept constant. The maximum vertical load at failure and corresponding deformation was recorded.

Using three different prepared cylindrical specimens from the undisturbed samples of the soil, the test was conducted at three different lateral pressure σ_3 of 100, 200 and 300 kN/m^2. The vertical (deviator) pressure (σ_2) and principal major stress (σ_1) was obtained using Equations (3.4) and (3.5) respectively.

The values of principal major stress (σ_1) at corresponding principal minor stress (σ_3) was plotted on x-axis as stress σ (kN/m^2) and semi-circles passing through these points drawn. A common tangential line to the semi-circles was drawn, which represents Mohr's failure envelope. The intercept of this tangential line on y-axis represents the cohesion c and the inclination with x-axis represents the angle of friction ϕ.

Shear stress was calculated using Equation (3.6).

$$\sigma_2 = \frac{7.14 \times proving\ ring\ dial\ guage\ reading}{Area\ of\ specimen} \tag{3.4}$$

$$\sigma_1 = \sigma_2 + \sigma_3 \tag{3.5}$$

$$\tau = c + \sigma + tan\phi \tag{3.6}$$

Where,

σ_3 = cell pressure, σ_2 = vertical applied load, σ = normal stress,

τ = shearing stress

ϕ = Angle of friction

Determination of settlement parameters

For this test in this study, one dimensional consolidation test procedure as highlighted in BS 1377 (1990) was adopted.

CHAPTER FOUR

4.0 RESULTS AND DISCUSION

4.1 Oxides Composition of the Soils

Table 4.1 present oxides composition of the soil collected from the deposit. From the result, SiO_2, Fe_2O_3, Al_2O_3, CaO, TiO_2, and Loss on Ignition (LOI), range from 57.80 to 66.13, 5.52 to 9.11, 14.88 to 18.24, 0.87 to 3.74, 1.03 to 1.32% and 4.76 to 7.44% respectively. These oxides composition is similar to those reported by Eberemu *et al*. (2021) for a tropical black clay collected along Gombe - Biu Road in Gombe state, Nigeria**,** and those reported by Moses *et al.* (2018) for a tropical black clay from Numan Local Government Area of Adamawa State. Osinubi *et al.* (2016) also reported similar oxide composition for tropical black clay from Numan-Ngurore in Adamawa state of Nigeria. The silicon-sesquoxide [SiO_2/ (Al_2O_3+Fe_2O_3)] ratio conforms with the report by Ikara *et al*. (2021).

Table 4.1: Oxide composition of the soils

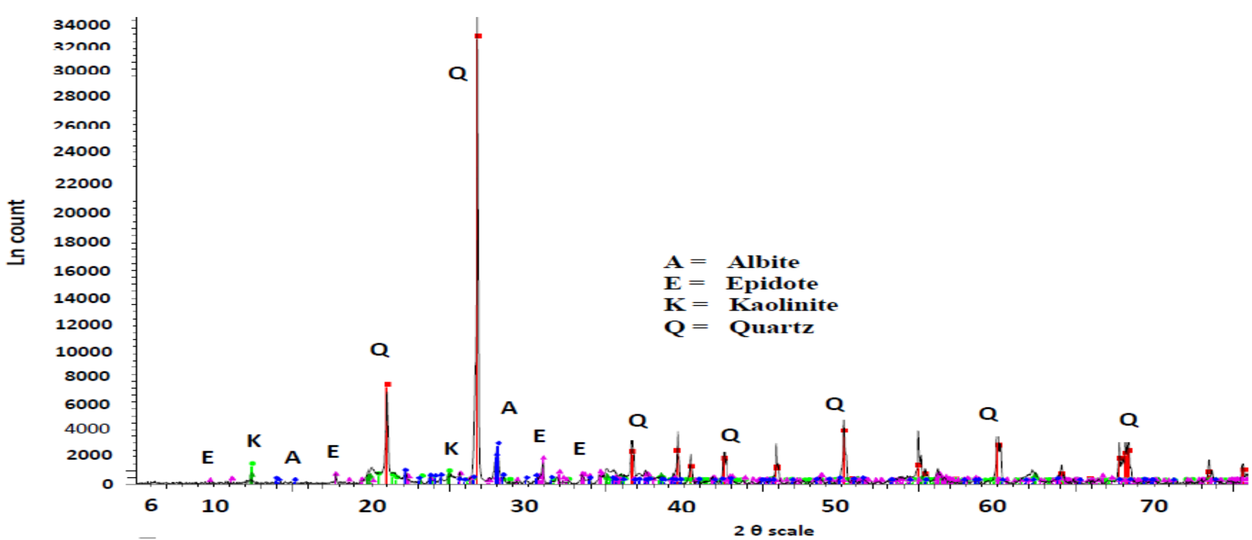
	Oxide (%)													
Sample	Fe_2O_3	MnO	Cr_2O_3	V_2O_5	TiO_2	CaO	K_2O	P_2O_5	SiO_2	Al_2O_3	MgO	Na_2O	LOI	Sum
A2	7.57	0.17	0.01	0.03	1.22	2.82	0.43	0.00	62.66	16.80	0.59	0.62	6.59	99.50
B2	9.11	0.49	0.01	0.04	1.03	3.05	0.40	0.00	57.80	17.09	0.90	0.75	6.93	97.63
C2	7.88	0.15	0.01	0.03	1.08	3.27	0.38	0.03	60.81	16.61	0.65	1.58	6.16	98.65
D2	7.89	0.24	0.01	0.03	1.05	2.84	0.63	0.02	63.23	16.20	0.66	0.77	6.41	99.99
E2	6.84	0.27	0.01	0.03	1.17	3.01	0.70	0.03	62.80	15.86	0.84	1.47	5.78	98.82
F2	6.43	0.17	0.00	0.02	1.11	3.74	0.63	0.02	65.10	14.88	1.10	1.93	4.93	100.07
G2	5.52	0.03	0.02	0.02	1.17	0.87	1.62	0.02	62.84	17.64	0.51	0.53	7.06	97.84
H2	6.34	0.10	0.01	0.03	1.32	1.24	1.22	0.03	66.13	15.34	0.56	1.17	6.17	99.66
I2	6.32	0.08	0.01	0.03	1.30	1.58	1.35	0.02	64.55	16.48	1.14	1.32	4.76	98.94
J2	5.49	0.05	0.01	0.03	1.18	1.05	1.59	0.02	63.38	18.24	0.52	0.73	7.44	99.72

4.2 Loss on Ignition (LOI)

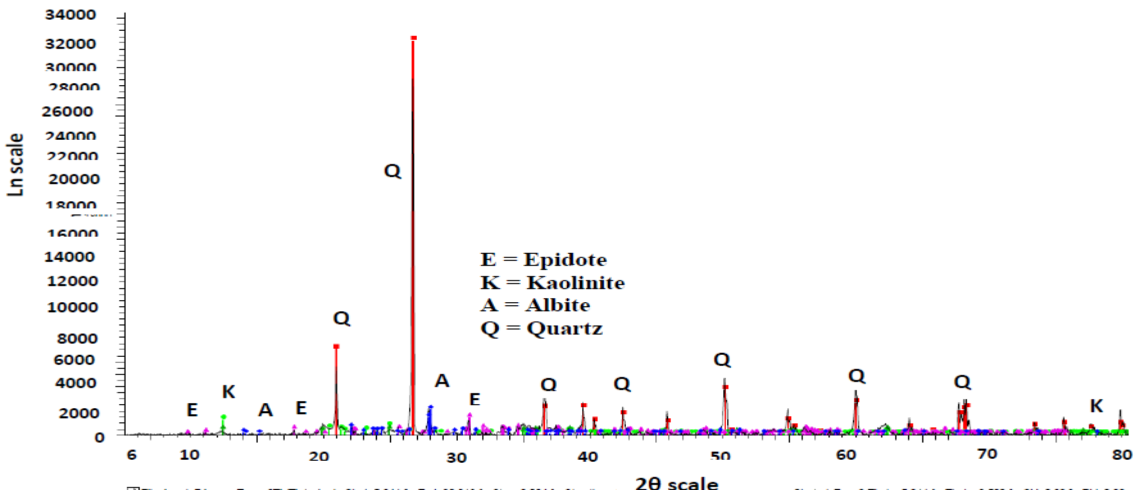
Loss on Ignition (LOI) values of the studied soils are also presented on Table 4.1. From the results, it is observed that the LOI of the soils from the deposit range from 4.76 to 7.44%. these values are higher than those reported by Moses *et al.* (2018) and Uloko *et al.* (2018) for tropical black clay and expansive clay respectively, but lower than those reported by Dogo *et al.* (2018), Annafi *et al*. (2020a) and Annafi *et al*. (2020b), for black cotton soils.

4.3 Mineralogy of the Soils

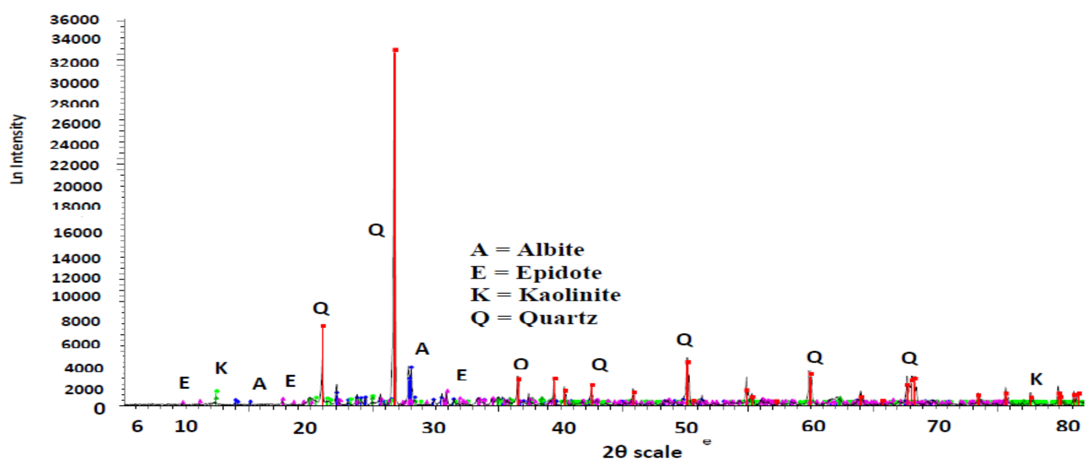
Figures 4.1 to 4.10 presents XRD results for the soils. From the figures, kaolinite is observed to be the major clay mineral in the soil deposit, which is similar to those reported by Oyelami *et al*. (2022). Other minerals like albite and epidote were also recorded. In addition to kaolinite, albite and epidote, muscovite was observed on location (TP 4 and 5) within the deposit, where the soil was observed to be relatively less drained. The presence of kaolinite as the major clay mineral in the soil deposit confirms the low plasticity nature of the soil, since this clay mineral have less affinity to water.



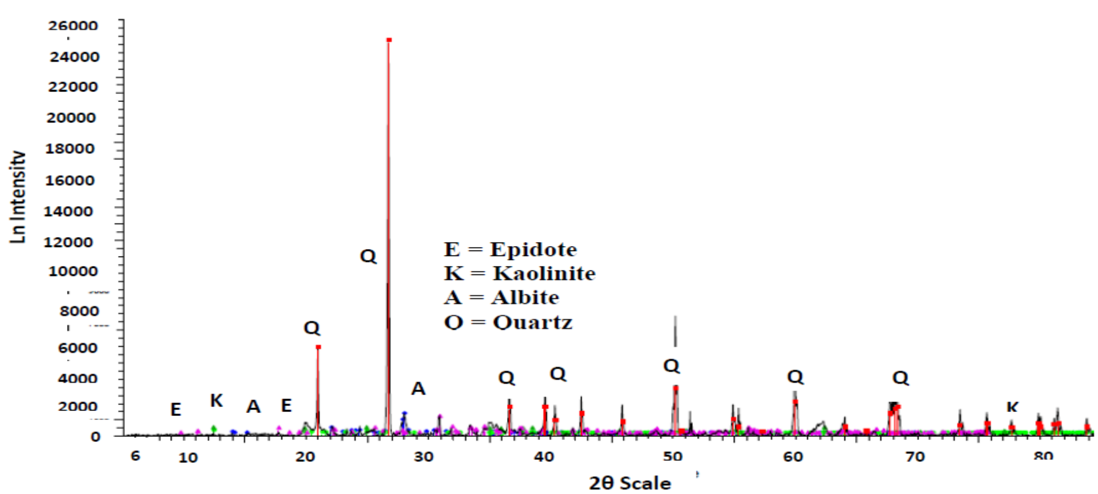
Figures 4.1: XRD of soil sample A from TP 1



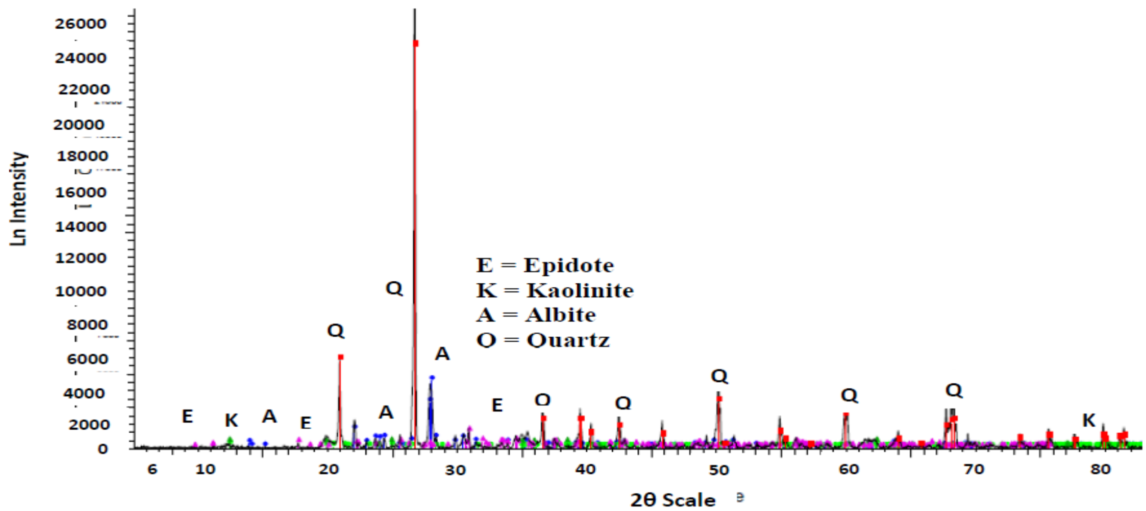
Figures 4.2: XRD of soil sample B from TP 1



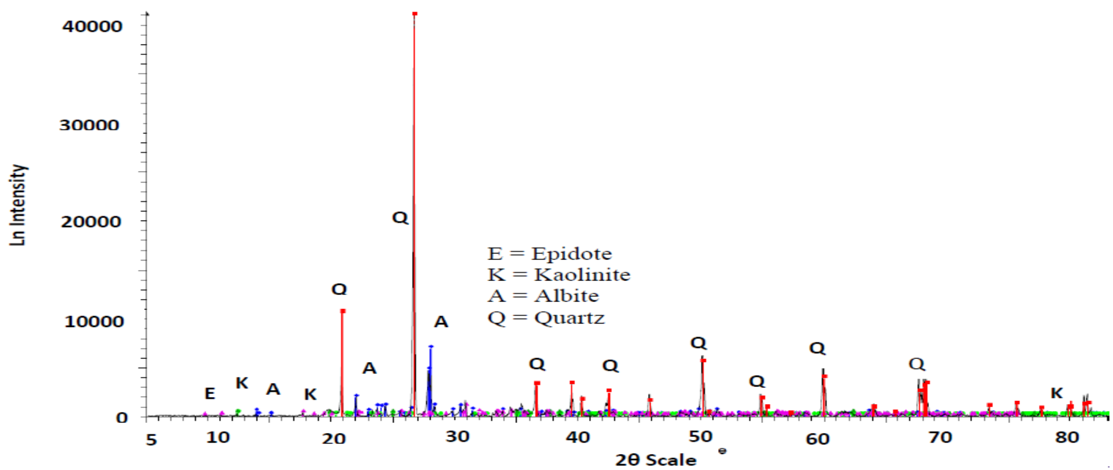
Figures 4.3: XRD of soil sample C from TP 2



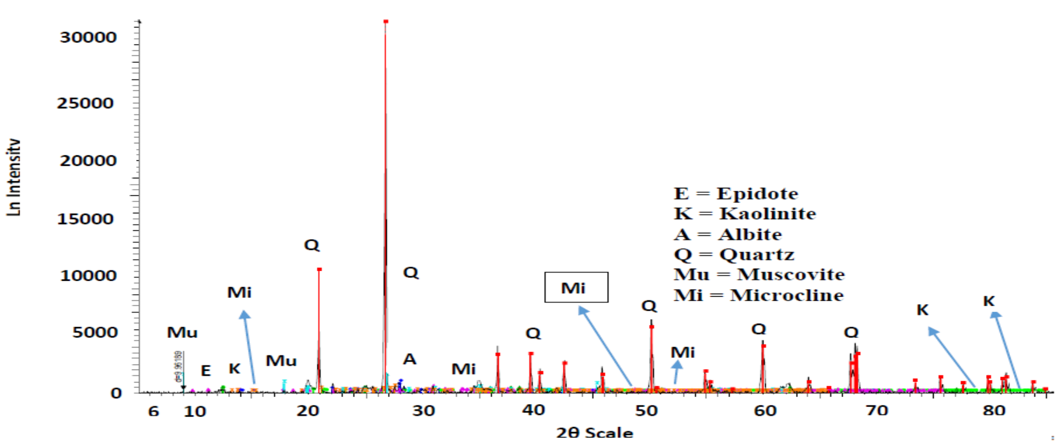
Figures 4.4: XRD of soil sample D from TP 2



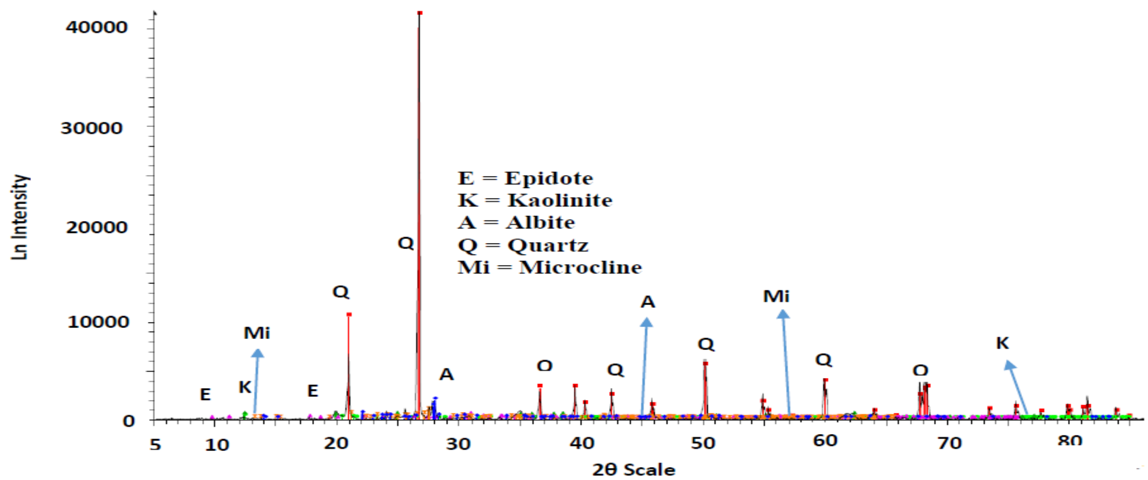
Figures 4.5: XRD of soil sample E from TP 3



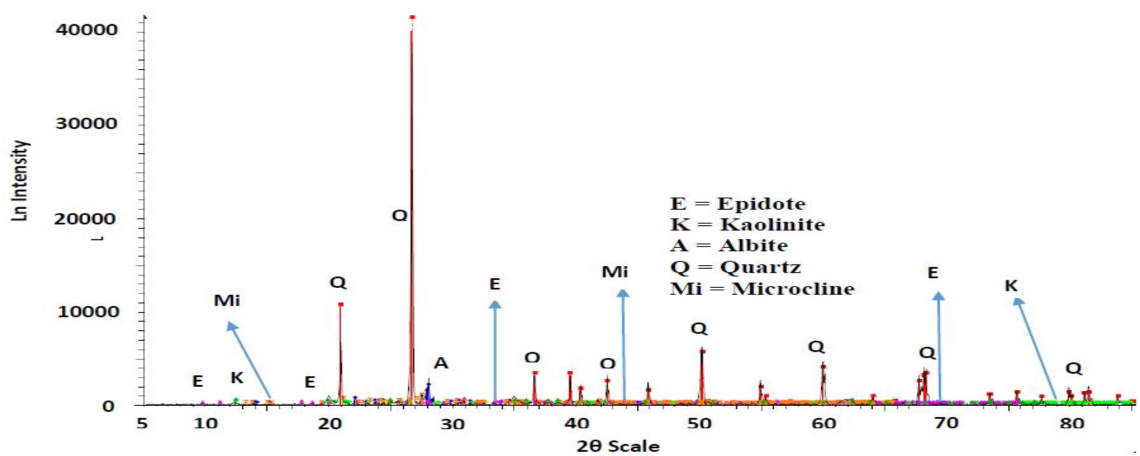
Figures 4.6: XRD of soil sample F from TP 3



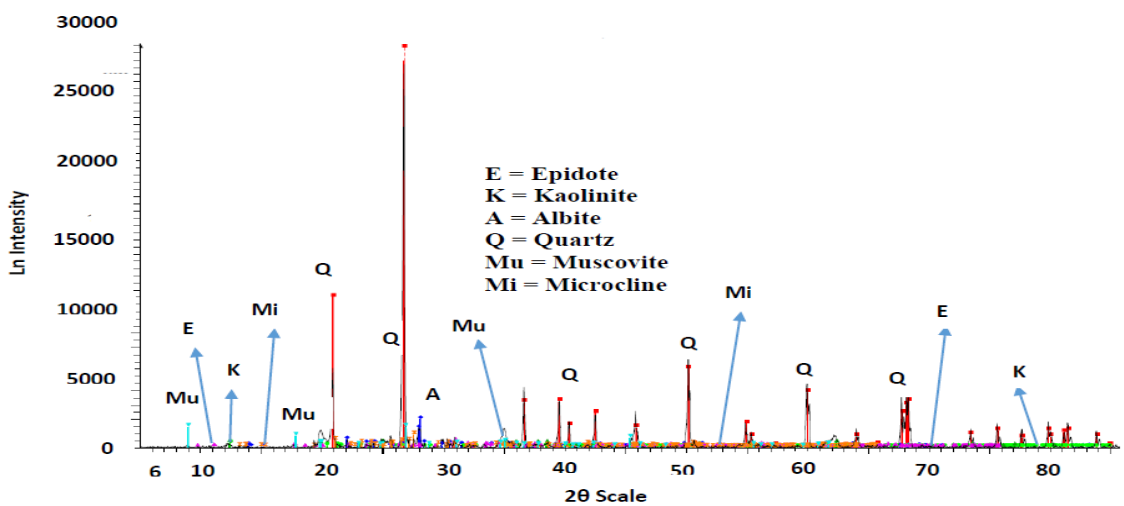
Figures 4.7: XRD of soil sample G from TP 4



Figures 4.8: XRD of soil sample H from TP 4



Figures 4.9: XRD of soil sample I from TP 5

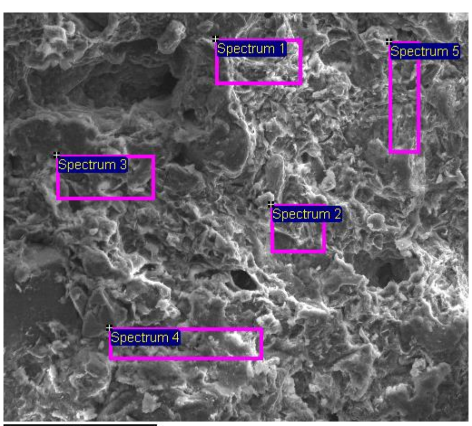


Figures 4.10: XRD of soil sample J from TP 5

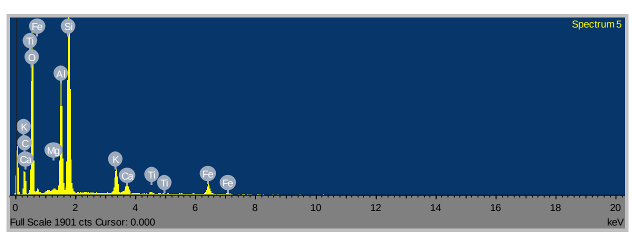
4.4 SEM and EDS Results of the Soils

Plates i to x and Table 4.2 present Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) results of the studied soil samples. SEM images of the soil samples from the studied deposit (Figures 4.11 to 4.20), generally revealed presence of air voids and relatively dense spongy fabric of flecky clay particles that are similar to those reported by Zhang *et al*. (2013), Jaiswal and Lai (2016), Abdullah *et al*. (2018) and Alhaji *et al*. (2020b).

The EDS results (Figures 4.11 to 4.20 and Table 4.2) show carbon ranging from 13.79 to 30.51%, oxygen ranging from 45.54 to 55.83%, Almininium ranging from 3.84 to 8.04%, Silicon ranging from 11.94 to 20.98%, Iron ranging from 1.83 to 5.12%, 0.37 to 0.76% magnesium, 0.23 to 0.87% potassium (with no trace in TP 1), 0.30 to 1.15% calcium (with no trace in TP 4 and 5), 0.61 to 0.86% Titanium and 0.21 to 0.42% Sodium (with no trace in TP 1, 2 and 5). This result is similar to those reported by Alhaji *et al*. (2020) for tropical black clay along Gwagwalada-Abuja road in Federal Capital Territory, Nigeria. The relatively low Iron content in the soil deposit is partly responsible for the dark (black) colour of soil in the deposit.

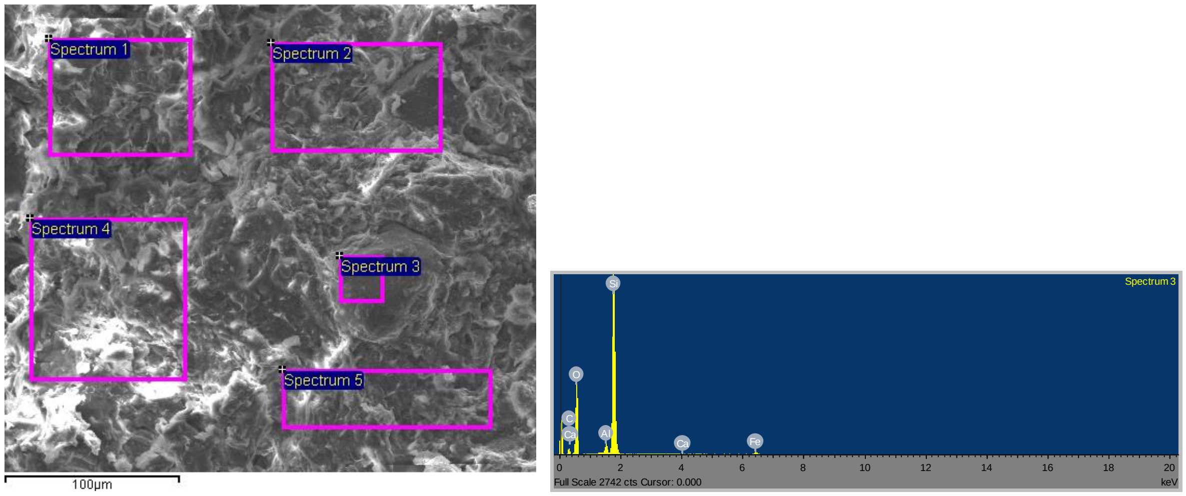


A



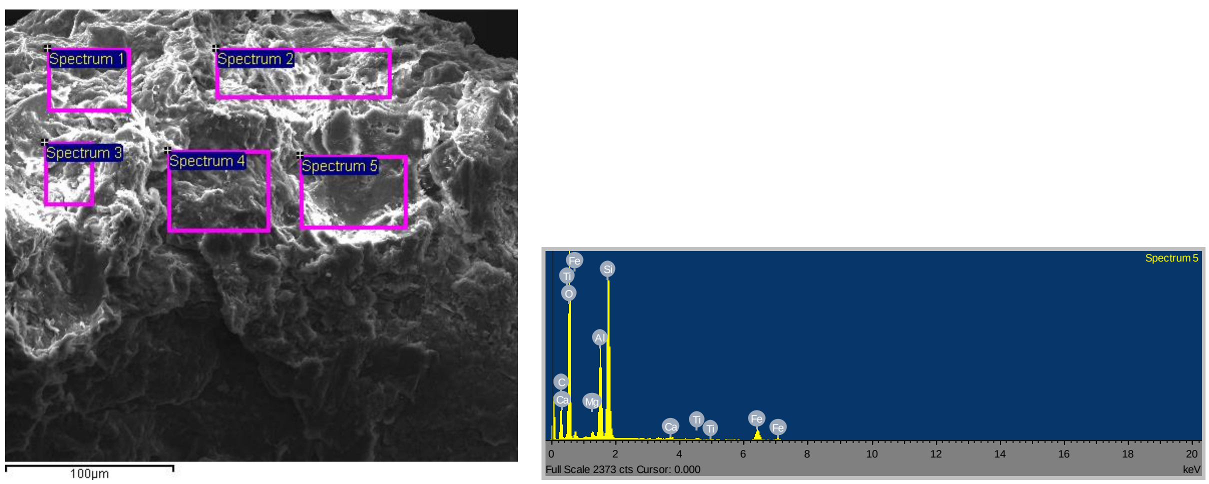
B

Plate i: SEM (A) and EDS (B) of soil sample A from TP 1



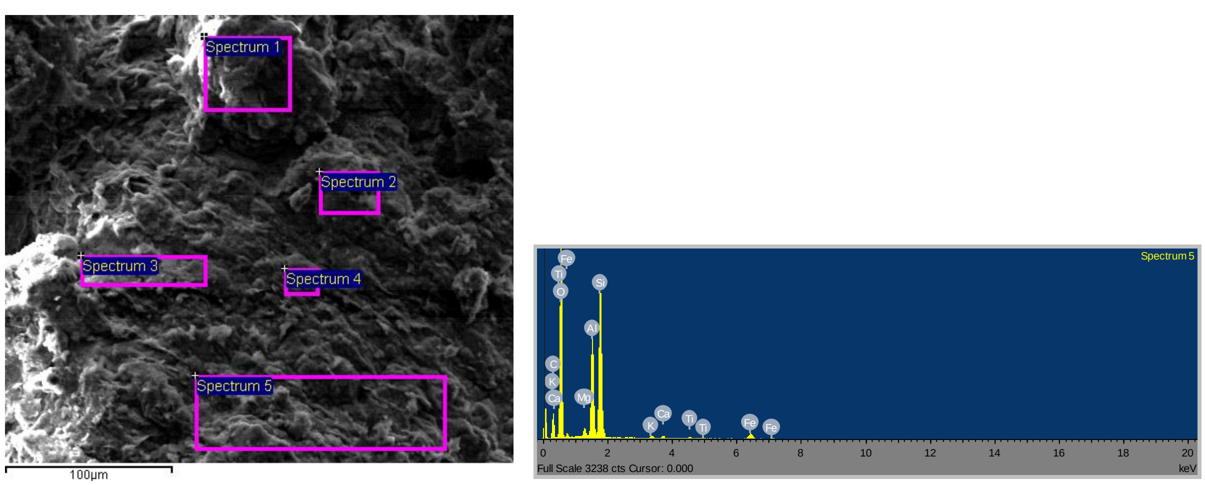
A B

Plate ii: SEM (A) and EDS (B) of soil sample B from TP 1



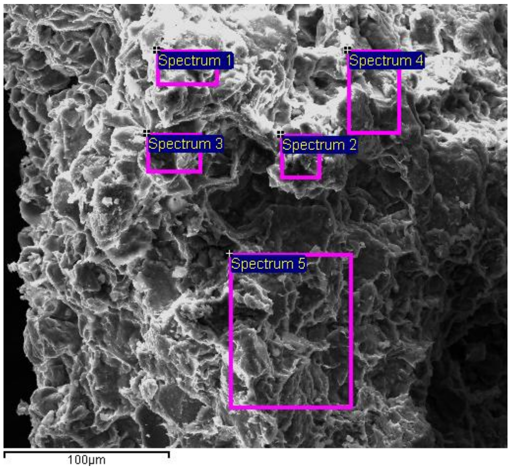
A B

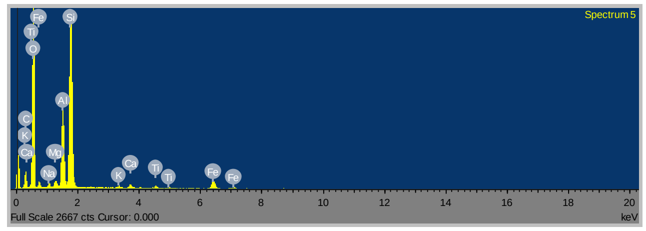
Plate iii: SEM (A) and EDS (B) of soil sample C from TP 2



A B

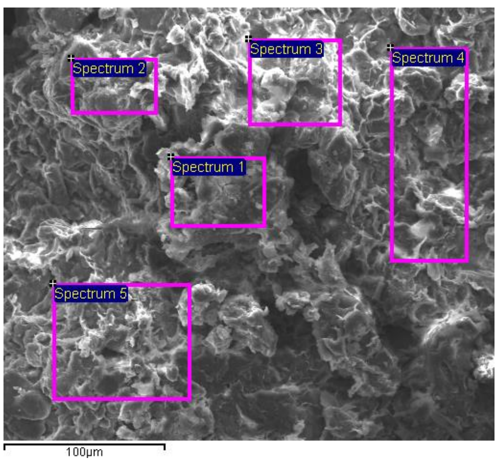
Plate iv: SEM (A) and EDS (B) of soil sample D from TP 2

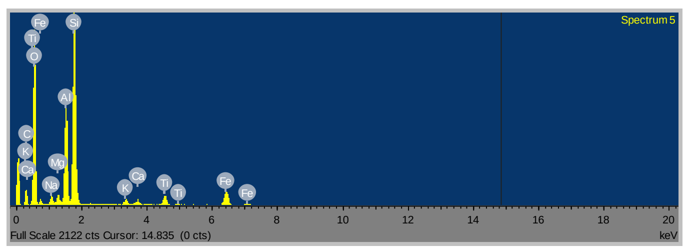




A B

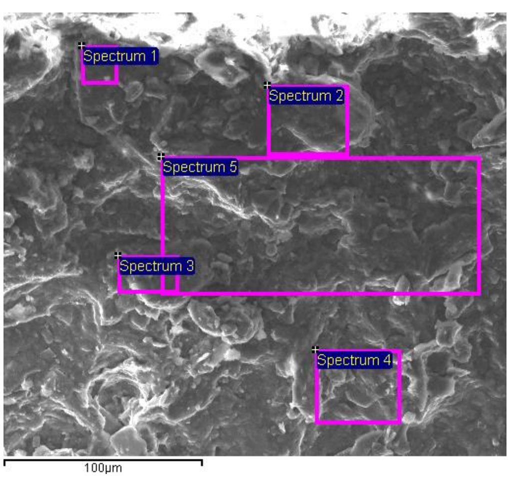
Plate v: SEM (A) and EDS (B) of soil sample E from TP 3

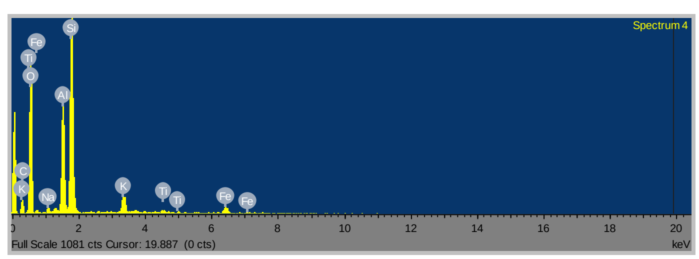




A B

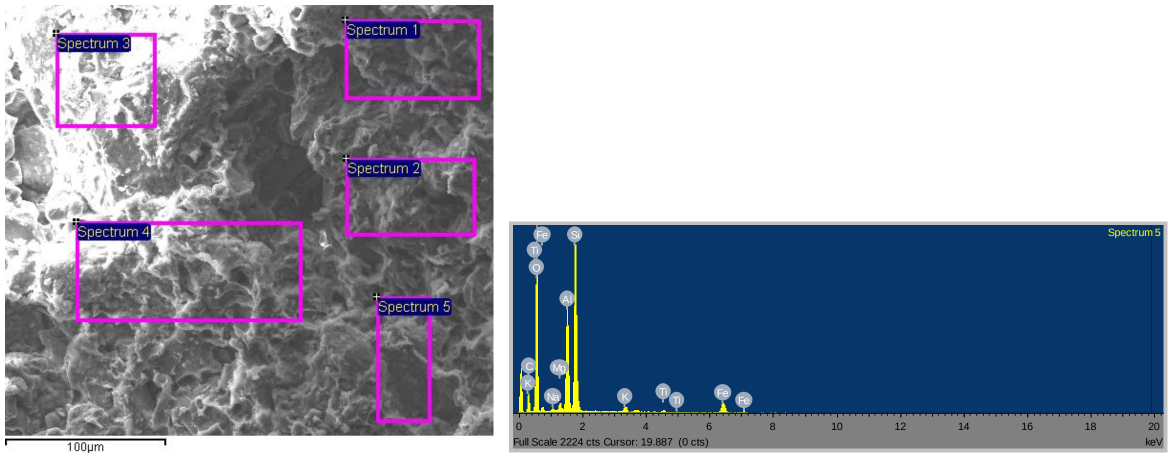
Plate vi: SEM (A) and EDS (B) of soil sample F from TP 3





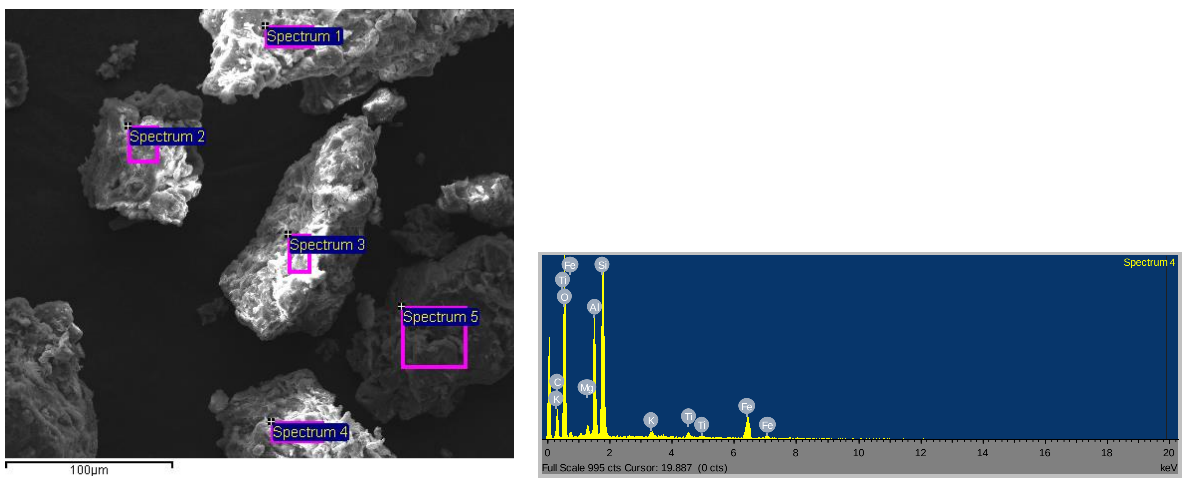
A B

Plate vii: SEM (A) and EDS (B) of soil sample G from TP 4



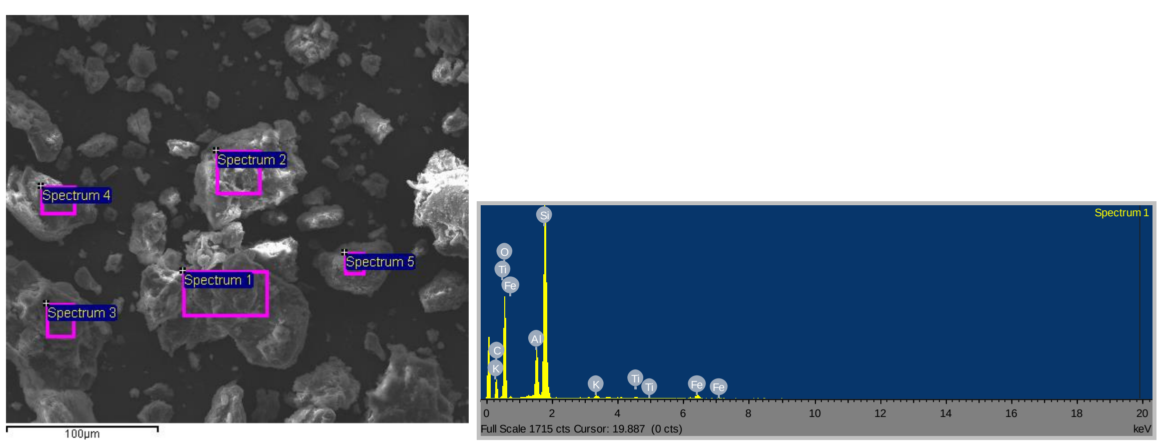
A B

Plate viii: SEM (A) and EDS (B) of soil sample H from TP 4



A B

Plate ix: SEM (A) and EDS (B) of soil sample I from TP 5



A B

Plate x: SEM (A) and EDS (B) of soil sample J from TP 5

Table 4.2: EDS results of the soils

Sample	Mean Weight % of Element										
	C	O	Na	Mg	Al	Si	K	Ca	Ti	Fe	Total
A3	22.39	53.43	-	0.43	7.43	11.94	0.68	0.65	0.21	2.85	100
B3	13.79	53.05	-	-	8.04	19.55	-	1.15	-	4.41	100
C3	21.25	54.99	-	0.54	6.95	12.09	-	0.37	0.28	3.52	100
D3	19.98	55.83	-	0.61	7.7	12.76	0.23	0.30	0.39	2.19	100
E3	20.30	53.51	0.94	0.49	5.62	15.59	0.28	0.71	0.23	2.34	100
F3	15.24	53.81	0.75	0.69	6.47	17.15	0.48	0.48	0.86	4.07	100
G3	19.37	51.08	0.21	-	5.66	20.98	0.87	-	0.36	1.47	100
H3	22.04	49.61	0.42	0.37	5.96	16.7	0.55	-	0.48	3.86	100
I3	30.51	45.54	-	0.56	5.35	12.06	0.48	-	0.38	5.12	100
J3	25.52	50.8	-	0.54	3.82	17.53	0.33	-	0.16	1.83	100

4.4 pH of the soils

Variation of pH values of soils from the studied deposit is presented on Table 4.3. From the table, it is observed that pH values deposit ranges between 6.50 to 7.2. This indicates that the pH values of soil deposit hovers from being slightly acidic, to neutral, and slightly basic. These results are similar to those reported by Alhaji *et al.* (2020b).

4.5 Geotechnical Properties

4.5.1 Index properties of the soils

Table 4.3 presents summary of result of index (physical) properties of soils from the studied deposit. From the result particle size analysis and Atterberg limits (liquid limit, ranges from 37.05 to 48.00%), clay from the deposit can generally be regarded as those with medium compressibility (Prakash and Jain, 2002), and classifies under clay of low plasticity (CL), according to Unified Soil Classification System (USCS) and A-4 to A-7-6 according to American Association of State Highway and Transportation Officials (AASHTO). The observed low plasticity, is attributed to the kaolinite clay mineral predominating in the soils. These results made soil from the deposit to be generally regarded as weak and deficient for use in some Civil Engineering structures. This result is similar to those reported by Bello (2012), Nwokediuko *et al*. (2019), Okeke *et al.* (2016), Yohann *et al.* (2021) and Yohann *et al.* (2022) for tropical soils, but slightly different from those reported by Meshida *et al.* (2013), Osinubi *et al.* (2016), Eberemu *et al*. (2021), Uloko *et al*. (2021), Moses *et al.* (2018), Dogo *et al*. (2018) and Alhaji *et al*. (2020b) for tropical black (cotton) soil that is common in north-eastern part of Nigeria.

The relatively low plasticity nature of the soil from the deposit is not unconnected with the major clay mineral (kaolinite) observed. Alhassan *et al.* (2012) and Alhassan *et al.* (2014) reported that since kaolinite has low affinity to water, it is responsible for the low plasticity values recorded in the studied soil. From the plasticity result, according to Ola (1981), soil from the deposit can be regarded to have low to medium swelling potential, which is generally lower than those reported by Haruna *et al*. (2017) and Moses *et al.* (2018) for black cotton soils.

Table 4.3: Geotechnical properties of the soils

Property		**Sample**									
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
Natural Moisture Content (%)		16.15	15.86	16.37	16.29	12.61	14.19	18.46	17.48	18.42	18.92
Fraction Passing BS No 200 Sieve (%)		86.80	71.17	84.83	71.73	91.87	90.63	96.00	63.93	96.00	94.42
Liquid Limit (%)		45.2	48.00	43.21	49.12	39.32	42.07	37.15	42.01	37.05	41.00
Plastic Limit (%)		26.97	32.39	31.29	33.73	21.88	20.36	24.6	24.26	31.37	23.08
Plasticity Index (%)		18.23	15.61	11.92	15.19	17.44	21.71	12.55	17.75	5.68	17.92
USCS		CL	CL	CL	CL	CL	CL	CL	CL	CL	CL
AASHTO Classification		A-7-6	A-7-5	A-7-5	A-7-5	A-6	A-7-6	A-6	A-7-6	A-4	A-7-6
MDD (Mg/m^3)	BSL	1.80	1.83	1.73	1.90	1.79	1.95	1.66	1.67	1.80	1.86
	BSH	1.98	1.90	2.05	2.05	2.13	2.19	1.88	1.92	1.90	1.96
OMC (%)	BSL	18.70	14.30	22.00	17.5	18.50	14.30	23.70	20.10	20.00	15.80
	BSH	8.30	11.60	15.80	16.40	14.60	8.90	15.00	18.00	12.30	14.20
Unsoaked CBR (%)	BSL	3.89	4.49	5.13	5.15	4.67	6.18	5.01	5.31	4.12	4.07
	BSH	10.67	12.32	16.16	16.22	14.71	19.47	17.12	18.89	15.56	16.22
Soaked CBR (%)	BSL	2.11	3.37	2.91	2.92	2.18	3.26	2.38	2.78	1.97	2.01
	BSH	6.89	8.90	9.48	9.20	6.87	10.27	10.71	11.34	9.77	10.97
pH		7.1	6.9	7.2	6.8	7.0	6.7	6.8	6.5	6.9	6.5

Although, the soil samples were collected during dry season, the relatively high natural moisture content recorded is attributed to the fine nature of the soils (fraction passing BS No 200 sieve ranges from 63.93 to 96.00%). The fine nature, coupled with the plasticity nature of the soil are responsible for the observed compaction characteristics, which is similar to those reported by Bello (2012), Nwokediuko *et al*. (2019), Okeke *et al.* (2016), Yohann *et al.* (2021) and Yohann *et al.* (2022) for tropical soils. The CBR results of the studied soil deposit are also similar to those reported by Meshida *et al.* (2013), Oluyemi-Ayibiowa *at al.* (2016) and Oyelami *et al.* (2022) for tropical clays soils of Nigeria. Relatively lower CBR values were reported by Osinubi *et al.* (2016), Annafi *et al.* (2020a) and Annafi *et al.* (2020b) for tropical black cotton soils.

4.5.2 Strength characteristics

4.5.2.1 Shear strength parameters

Table 4.3 presents results of shear strength parameters of soil samples taken from the studied deposit. From the results, it is observed that cohesion of soil from the deposit range from 31.20 to 52.51 kN/m^2, while angle of internal friction ranges from 3.75 to 13.34°. Bulk unit weight of the soil ranges between 18.49 and 21.93 kN/m^3. Nwokediuko *et al.* (2019) reported 5 to 22 kN/m^2 cohesion, but with relatively higher values for angle of internal friction. The observed shear strength parameters are relatively similar to those reported by Oyelami *et al*. (2022).

4.5.3 Settlement characteristics

The one-dimensional consolidation test results are presented on Table 4.4. Index properties test results (Table 4.2) indicated the soils to be clay of low plasticity (CL). From the Table 4.4, variation of the settlement characteristics with depth of the clay deposit is observed. The result indicates void ratio of the deposit ranging from 0.514 to 0.874. With exception of TP4, where void ratio decreases with depth, it was generally observed to increase with depth of the deposit. This variation in void ratio is typical for tropical residue soil deposit, which usually have upper layer of relatively less clayey nature, followed by layers of more clayey nature, and since clay soil has more void ratio than granular soil, this accounts for the observed variation. The observed trend at TP 4, is attributed to the location of the sample point (built up area), where the upper strata most have undergone compaction/consolidation from traffic (both human and vehicular).

Recompression index C_r was generally observed to increase with depth of the deposit. This observed trend is attributed to variation of state of parking (density) of the soil with increase in depth. Lithologically, it is expected that density of a soil deposit increases with depth, implying that if the deposit is disturbed, dipper layers will require more effort for recompaction than upper layers.

Table 4.3: Shear strength parameters of the clay deposit

Sample	Bulk unit weight (kN/m^3)	Cohesion (kN/m^2)	Angle of internal friction (degree)
A	19.89	31.12	8.23
B	21.93	41.44	9.18
C	19.87	31.20	6.95
D	20.87	37.27	6.15
F	20.16	29.16	12.99
F	20.54	44.79	3.75
G	20.04	41.57	12.45
H	20.16	48.66	13.34
I	18.49	50.51	7.69
J	21.49	52.51	5.69

Compression index C_c was generally observed to increase with depth of the deposit. This trend is attributed to the variation in nature of the soil with increase in depth. Since layers at upper depths are relatively less clayey in nature, it is expected that these layers will undergo less consolidation settlement than soil at lower depth that are relatively more clayey in nature.

No definite trend in variation of preconsolidation stress σ_p and coefficient of consolidation C_v with depth of the deposit was observed. While at some locations, increase in these characteristics, with depth was observed, at some other locations, decrease was noticed, implying the heterogeneity of soil, even within a particular deposit.

Table 4.4: Settlement characteristics of the clay deposit

Trial Pit	Initial void ratio	Recompression C_r	Compression index C_c	Preconsolidation pressure σ_p	Coefficient of consolidation cv
TP1/0.5	0.710	0.0415	0.150	120	$3.77 x 10^{-5}$
TP1/1.0	0.741	0.0233	0.218	100	$3.68 x 10^{-5}$
TP2/0.5	0.534	0.000	0.110	170	$1.36 x 10^{-5}$
TP2/1.0	0.706	0.043	0.154	60	$3.39 x 10^{-6}$
TP3/0.5	0.514	0.000	0.100	130	$2.62 x 10^{-5}$
TP3/1.0	0.812	0.007	0.168	200	$1.75 x 10^{-5}$
TP3/1.5	0.874	0.050	0.150	125	$4.81 x 10^{-6}$
TP3/2.0	0.777	0.015	0.218	120	$5.30 x 10^{-6}$
TP4/0.5	0.818	0.033	0.133	80	$3.76 x 10^{-5}$
TP4/1.0	0.747	0.020	0.138	120	$2.93 x 10^{-5}$
TP5/0.5	0.655	0.000	0.236	320	$1.92 x 10^{-5}$
TP5/1.0	0.692	0.0066	0.070	170	$1.603 x 10^{-5}$

The trend in variation of the preconsolidation stress with depth, observed in this study, relatively conformed with study carried out by Alhaji and Alhassan (2013) on overconsolidation ratio of some selected soil deposits in Nigeria, and another study carried out by Abdulkarim *et al*. (2018) on preconsolidation stress of residual soils in north-central Nigeria. Adebisi and Adeyemi (2012), in a study on assessment of compressibility characteristics of residual laterized soils in southwestern Nigeria, also reported variability of compressibility characteristics with depth. Carreón-Freyre *et al*. (2015), in reporting analysis of the variation of the compressibility index of volcanic clays and its application to estimate subsidence in lacustrine areas, presented curves of void ratio (e) vs logarithm of vertical effective stress, which evidently indicated similar variation of preconsolidation pressure with depth. Józsa (2013) and Sohail *et al*. (2012) also reported similar trend in variation of compressibility characteristics with depth.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

From the study, the following conclusion is drawn:

Tropical black clay deposit was identified in Zungeru and geotechnically characterised. Oxide composition of the soils indicated SiO_2, Fe_2O_3, Al_2O_3, CaO, TiO_2 ranging from 57.80 to 66.13, 5.52 to 9.11, 14.88 to 18.24, 0.87 to 3.74 and 1.03 to 1.32% respectively, with and Loss on Ignition (LOI) ranging between 4.76 and 7.44%. The relatively low Iron content in the soil deposit is partly responsible for the dark (black) colour of soil in the deposit.

Mineralogy of the soils indicated kaolinite as the major clay mineral in the deposit, but with other minerals like albite and epidote also recorded. Muscovite was observed on locations where the soil was observed to be relatively less drained. SEM results generally revealed dense spongy fabric of flecky clay particles, while EDS results show carbon, oxygen, Almininium, Silicon, Iron, magnesium, potassium, calcium, Titanium and sodium ranging from 13.79 to 30.51%, 45.54 to 55.83%, 3.84 to 8.04%, 11.94 to 20.98%, 1.83 to 5.12%, 0.37 to 0.76%, 0.23 to 0.87%, 0.30 to 1.15%, 0.61 to 0.86% and 0.21 to 0.42% respectively. pH of the soils was observed to ranges between 6.50 to 7.2, indicating slightly acidic, to neutral, and slightly basic.

Index properties results of the soils generally showed the soils classifying under clay of low plasticity (CL), according to Unified Soil Classification System (USCS) and A-4 to A-7-6 according to American Association of State Highway and Transportation Officials

(AASHTO), indicating that the soil being generally classified as weak and deficient for use in some Civil Engineering structures.

Shear strength parameters indicated cohesion ranging from 31.20 to 52.51kN/m^2, with angle of internal friction ranging from 3.75 to 13.34°, while bulk unit weight ranges between 18.49 and 21.93kN/m^3, which were relatively similar to those reported in literature for tropical clay soils. Variation of the settlement characteristics with depth of the clay deposit was observed, with void ratio ranging from 0.514 to 0.874. Recompression index (C_r), compression index (C_c) were generally observed to increase with depth of the deposit, while no definite trend in variation of preconsolidation stress (σ_p) and coefficient of consolidation C_v with depth of the deposit was observed.

Soils in the deposit have relatively high bulk unit weight, but generally low bearing strength, which makes them similar to Black Cotton Soil (BCS) of northeastern Nigeria, in this regard, but dissimilar in the clay mineral content.

5.2 Recommendations

From the study, the following recommendation is made:

1. Soil from the deposit is generally classified as weak and deficient and should therefore be handled as such when use in Civil Engineering structures.

5.3 Contribution to Knowledge

The study, geotechnically characterised tropical black clay deposit in Zungeru, Niger State and established 57.80 to 66.13, 5.52 to 9.11, 14.88 to 18.24, 0.87 to 3.74 and 1.03 to 1.32% as ranges of SiO_2, Fe_2O_3, Al_2O_3, CaO and TiO_2 respectively, with kaolinite as the major clay mineral. It also established that carbon, oxygen, Alminimium, Silicon, Iron, magnesium, potassium, calcium, Titanium and sodium content in the soil ranges from 13.79 to 30.51%, 45.54 to 55.83%, 3.84 to 8.04%, 11.94 to 20.98%, 1.83 to 5.12%, 0.37 to 0.76%, 0.23 to 0.87%, 0.30 to 1.15%, 0.61 to 0.86% and 0.21 to 0.42% respectively, indicating that the relatively low Iron content in the soil is partly responsible for the dark (black) colour of soil in the deposit. The study also established that soil from this deposit generally classified under clay of low plasticity (CL), according USCS and A-4 to A-7-6, according AASHTO, with shear strength parameters (cohesion and angle of internal friction) ranging from 31.20 to 52.51 kN/m^2 and 3.75 to 13.34° respectively, and bulk unit weight ranging between 18.49 and 21.93 kN/m^3. The study also established variability in settlement characteristics with depth of soil in the deposit indicating that, soil from the deposit can generally be classified as weak and deficient for use in some Civil Engineering structures.

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