

THE EFFECT OF PARTICLE SIZE AND PARTICLE SIZE DISTRIBUTION ON THE MODULUS OF RUPTURE OF SOME NIGERIAN CLAYS

BY

**OSONWA NOBERT OKEY (B.ENG.)
REG. NO: 20114775958**

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CERTIFICATION

This is to certify that this research work "THE EFFECTS OF PARTICLE SIZE AND PARTICLE SIZE DISTRIBUTION ON THE MODULUS OF RUPTURE OF SOME NIGERIAN CLAYS", was carried out by Osonwa Nobert O. (Reg. No 20114775958) in partial fulfilment of the requirements for the award of Masters Degree (M.Eng) in Materials and Metallurgical engineering at the Federal University of Technology Owerri.

Dr. C.S Nwobodo
(Supervisor)

Signature & Date

Dr. C.S Nwobodo
(Ag. H.O.D)

Signature & Date

Engr. Prof. E.E Anyanwu
(Dean S.E.E.T)

Signature & Date

Engr. Prof. (Mrs) K.B Oyoh
(Dean Post Graduate School)

Signature & Date

External Examiner

Signature & Date

DEDICATION

This work is dedicated to my wife.

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ABSTRACT

The effects of particle size and particle size distributions of three clay samples, on their modulus of rupture were studied.

The three clay samples were collected from natural clay deposits at Nsu; Ohiya-Umuahia; and Awo-Omamma all in south eastern Nigeria. The particle size analysis of the clay samples was done by laser diffraction in wet suspension mode and the results disclosed that Awo-Omamma clay has greater proportion of the larger sized particles, ($21\mu\text{m} - 25\mu\text{m}$) and ($25\mu\text{m} - 51\mu\text{m}$), than Ohiya clay and Nsu clay. Also the three clay samples have volume mean diameters (VMD) of $6.56\mu\text{m}$, $8.93\mu\text{m}$ and $11.29\mu\text{m}$ for Nsu clay, Ohiya clay and Awo-Omamma clay respectively. The moduli of rupture of the clay samples were also determined for the green state as well as when fired to 900°C and 1100°C . Other thermo-physical parameters of the clay samples such as porosity; shrinkage and bulk density were also determined. The modulus of rupture of Awo-Omamma clay was 0.183N/mm for the green state, 0.426N/mm when fired at 900°C and 0.544N/mm when fired at 1100°C . These values were quite low when compared to 0.369N/mm and 0.569N/mm dry modulus of rupture values for Nsu and Ohiya clays respectively. Nsu and Ohiya clays also have superior mechanical behaviour when fired as indicated by the modulus of rupture values of 1.04N/mm ; at 900°C and 1.51N/mm at 1100°C for Nsu clay, and 1.35N/mm at 900°C and 1.53N/mm at 1100°C for Ohiya clay. Comparison of the modulus of rupture of the three clay samples with their particle size distributions revealed that a high proportion of the larger sized particles, ($21\mu\text{m} - 51\mu\text{m}$) will lower the modulus of rupture of the clay. The proportions of this particle size range contained by the three clay samples are 16.14% for Awo-Omamma, 6.65% for Ohiya and 4.05% for Nsu clay.

KEY WORDS: Nigerian clay, Modulus of rupture, particle size distribution, volume mean diameter, thermo-physical properties, ceramics.

CHAPTER ONE

INTRODUCTION

1.1. BACKGROUND INFORMATION

The Merriam-Webster dictionary defines clay as an earthy material that is moist but hard when fired, that is composed mainly of fine particles of hydrous aluminium silicates and other minerals, and that is used for bricks, tiles and pottery.(Merriam-Webster Dictionary 2012).

According to Schroeder, the term clay is often operationally defined. The term clay denotes both,

- (a). a particle size range, and
- (b). a set of material physical properties. In the engineering field, the upper limit of size range is often reported at $<4\mu\text{m}$.

(P. Schroeder 2012).

The term clay mineral is most commonly used to denote a family of hydrous alumino-silicates. Most clay minerals are found in nature with particle sizes in the range of $<4\mu\text{m}$. Clay is the chief raw material for the ceramics industry. The natural properties of a particular clay deposit, including chemical composition, mineralogy, particle size distribution, etc, are influenced by the composition of the parent rock and the

wethering mechanism. Some of these properties can not be altered except possibly through blending with some other clay minerals or grinding, which is energy intensive. These techniques can increase the production costs of a ceramic plant considerably.

Thus the type, nature , mineralogy and technological parameters of a particular clay deposit will determine what areas of ceramic applications it is most suited for.

This research aims to sturdy the effects of particle size and particle size distribution on the modulus of rupture of some Nigerian clays. The clay samples were collected from Nsu, in Ehime Mbano Local Government Area of Imo State; Ohia in Umuahia South Local Government area of Abia state; and Umuejike-Awo Omamma in Oru east Local Government Area of Imo state.

1.2 **PROBLEM STATEMENT**

Recent surveys by the Raw Material Research and development Council, (RMRDC) have shown that clays of various kinds and grades abound through out Nigeria's sedimentary basins and on the basements.

Clay is the chief ingredient for traditional pottery which is still widely practiced across Nigeria. More importantly it is the chief raw material for the manufacture of several high value ceramic products such as refractory bricks for furnaces and kilns; burnt bricks for building construction; wall and floor tiles; table ware; porcelain; electrical insulation devices; etc.

The Ajaokuta steel plant requires about 43503 tonnes per year of fire clay refractory.(Aderibigbe 1989). Added to the needs of other pyro-metallurgical industries, this could mean an enormous consumption of refractory materials per anum.

The refractory needs of all such industries in Nigeria were well over 300,000 tonnes as at the year 2000. (Ndaliman 2007). However despite her extensive deposits of clay minerals, Nigeria continues to depend on importation to meet these needs. (Borode etal 2000).

Also modest growths recorded in the building construction industry in the last decade has led to unprecedented demand for structural ceramics like wall and floor tiles, bath tubs, etc. The tile market in Nigeria is worth 50 billion naira per annum. Ninety five percent of floor tiles that sell in Nigeria are imported. In fact 50 containers of floor tiles were imported per day as at 2009. (Jennifer Abraham 20012).

Clay products such as ceramic wares; burnt bricks; roofing and floor tiles are cheaper and more durable materials than cement, especially under tropical conditions. (Nnuka 2001). Increased utilisation of clay products will enable Nigeria to reduce the present over dependence on cement. Ironically the bulk of clay requirements in Nigeria are met through importation, mainly from United Kingdom, USA, Japan and China. (Nnuka 2001).

Similarly all electrical insulation materials used in the electricity industry in Nigeria, including ceramic and porcelain disc insulators for high tension electric cables are presently imported. The continued dependence on importation despite the huge ceramic resource potential in Nigeria could be attributed directly to lack of adequate technical mapping and

characterisation of several of these deposits. Hence there is urgent need for more comprehensive technical research works on Nigerian clay deposits with a view to providing all necessary technical data for their industrial exploitation.

1.3 RESEARCH OBJECTIVES.

Due to the commercial viability of these clay deposits, Mark (2007), Keke (2009) and Ikele (2010) have carried out recent research works on Nsu and Ohiya clay deposits.

Mark (2007) and Keke (2009), in the course of their work have carried out a chemical analysis of Nsu and Ohiya clays, respectively, while Ikele (2010) have studied the rheological behaviour of these clays.

However, in addition to mineralogical and chemical compositions, other properties necessary for the characterisation of clay minerals for industrial usage include; the drying and firing behaviour, (including shrinkage and colour), apparent porosity; bulk density; water absorption capacity; plasticity; modulus of rupture. (Nnuka 2001).

The particle sizes of the clay mineral plays a significant role in determining these parameters. Thus the objectives of this research work include:-

- The determination of the particle sizes and particle size distributions of the three clay samples.
- The determination of the mechanical behaviour of the three clay samples as indicated by the modulus of rupture.
- The determination of other thermo-physical properties of the three clay samples, including shrinkage and porosity behaviours.
- The determination of the chemical and mineralogical composition of the three clay samples.
- The determination of the effect of the particle size and particle size distribution on the modulus of rupture of the three clay samples.

1.4 JUSTIFICATION OF STUDY

According to Nnuka (2001), the bulk of clay requirements in Nigeria are met through importation. This is obviously because industries that utilise clay raw materials will prefer to

buy materials with known technical specifications and behaviour, with the attendant loss of huge amounts of foreign exchange to overseas countries.

Despite the huge clay resource potentials that abound in Nigeria, the technical specifications and behaviour of several of these deposits have not been fully understood. There is need for a systematic and exhaustive investigation on Nigerian clay deposits, to be able to fully ascertain the type and amount of impurities, colour, nature and mineralogical content, plasticity, green and fired characteristics.

Ceramic products are obtained as a result of a specific procedure of processing of clayey raw materials, feldspars and sand. During wet preparation and forming stages, it is important that ceramic slurries and pastes show a good rheology, plasticity and binding capacity for non clay raw materials. All these properties influence the shrinkage and thus the mechanical resistance of the products. (Maria Gorea 2002).

Thus, all of these are essential scientific data on which plans and predictions for large scale, long term commercial exploitation need be based.

This research work will enhance the understanding of the technical (mechanical) behaviour of the Nsu, Ohiya-Umuahia, and Awo-Omamma clay deposits as it relates to their natural particle sizes and size distributions.

1.5 RESEARCH SCOPE AND LIMITATIONS.

This research work shall cover all the necessary material preparation methods for the suitable determination of the real particle size distributions of the clay samples, using laser diffraction technique in wet suspension mode, as well as preparation of specimens for determination of shrinkage, (both drying and firing), apparent porosity, plasticity, and also the preparation of samples for the modulus of rupture test by 3-point loading using the Electric Transversal Strength Machine (ETSM).

Modulus of rupture will be determined both in the green state and fired state. However, because of the local unavailability of laser diffraction technique of particle size analysis, which have been proven to be superior to traditional methods of sieving and sedimentation techniques, the clay samples were sent to **TCR ENGINEERING SERVICE PVT**

LIMITED MUMBAI INDIA, for particle size analysis using the laser diffraction technique.

Also due to the limitations of the laboratory kiln at the Project Development Institute (PRODA) Enugu, the maximum firing temperature for the specimens were 1100°C. Certain clays undergo full vitrification at temperatures up to 1200 °C.

Also the Electric Transversal Strength Machine used to perform the MOR test on the specimens could not automatically generate strength vs deflation curves for the samples.

Also because of the brittle nature of the moulded specimens, much care was required in handling the specimens, especially while they were in the green state.

CHAPTER TWO

LITERATURE REVIEW.

2.1 ORIGIN, STRUCTURE AND CLASSIFICATION OF CLAYS.

Clay minerals are formed over long periods of time by the gradual weathering of mainly silicate bearing rocks by low concentrations of carbonic acid and other diluted solvents.(Bailey 1980).

The type of clay mineral in a particular deposit and its characteristics, including the particle size, will depend on the type of parent materials and the degree of weathering.

The properties of clays are determined by the fact that they are layered minerals. They are a sub group of the layer silicates. Generally clay minerals are hydrated aluminium silicates based on $(Si_2O_5)_n$ sheets.(Barry Carter 2007).

The main features of the structure of clay minerals which we need to be familiar and conversant with include, the arrangement of atoms in well defined sheets and

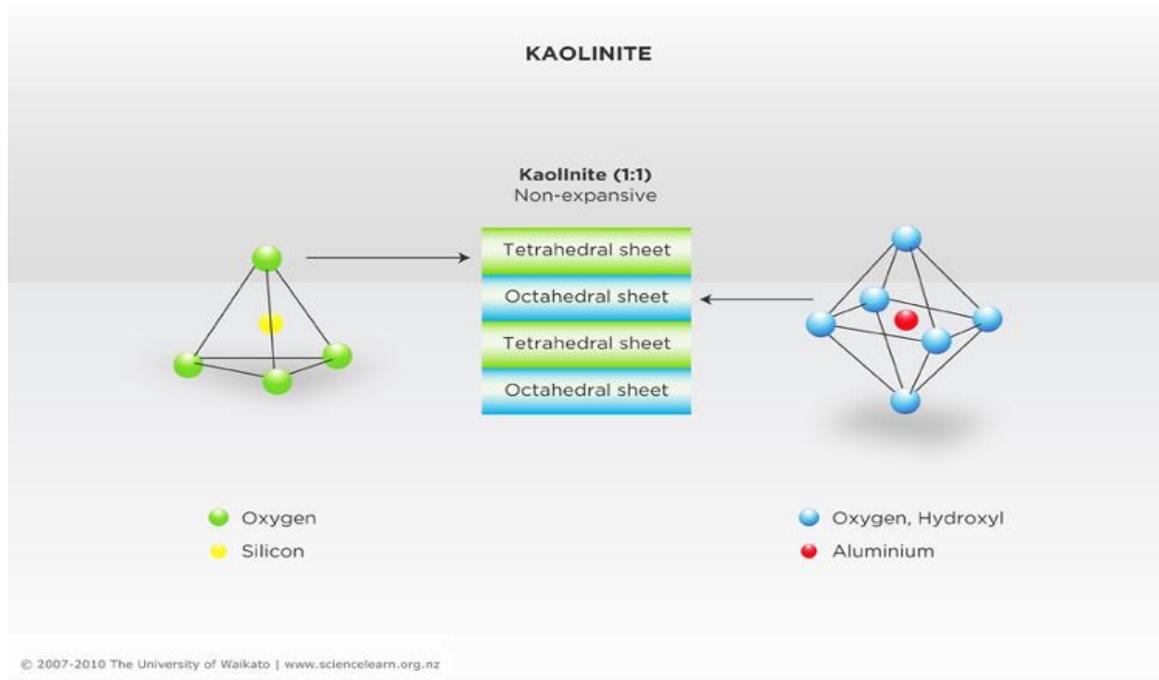


Figure 2.1a: The basic unit of kaolinite is composed of a 2D layer of silicate groups tightly bonded to a 2D layer of aluminate groups.

Culled from www.sciencelearn.org.nz

Cumberland Drill Hole and Powder



- Silica, Aluminum atom
- Magnesium atom
- Oxygen atom
- Hydroxyl group

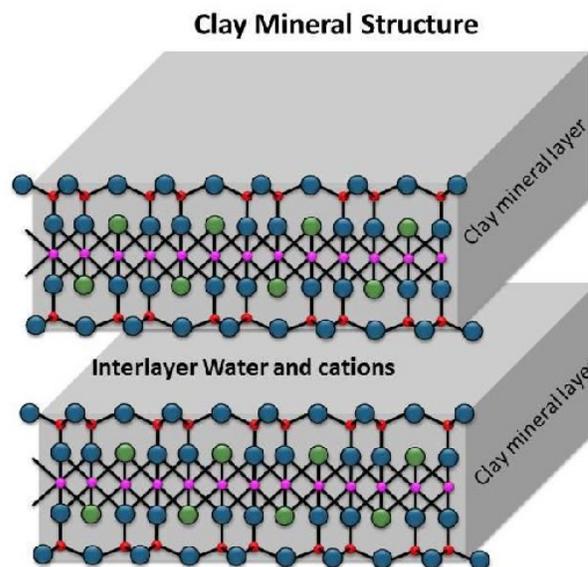


Figure 2.1b: Clay Mineral Structure

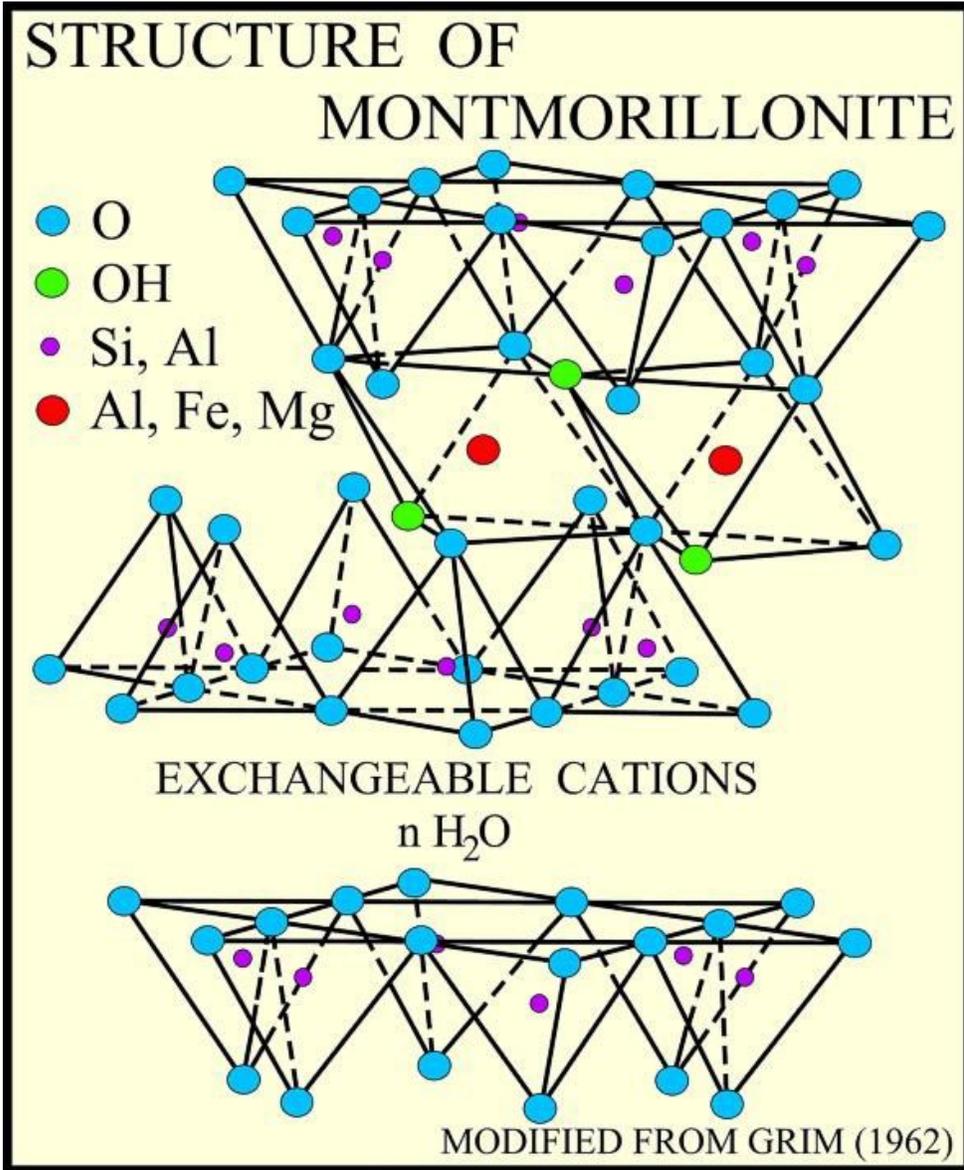


Figure 2.1c: Structure of Montmorillonite. Culler from www.sciencelearn.org.nz

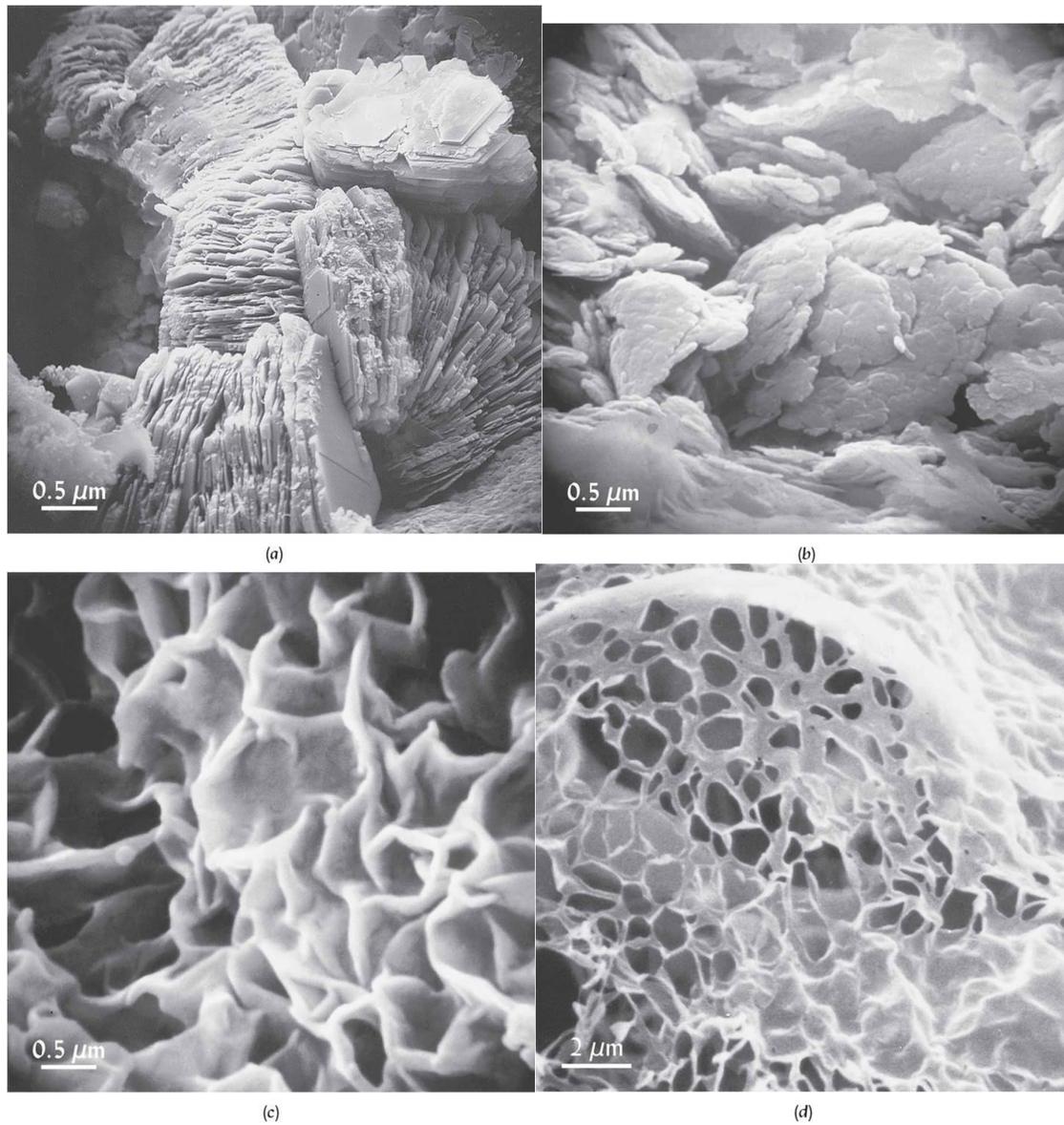


Figure 2.1d: Crystals of three silicate clay minerals and a photomicrograph of humic acid found in soils. (a) Kaolinite from Illinois (note hexagonal crystal at upper right). (b) A fine-grained mica from Wisconsin. (c) Montmorillonite (a smectite group mineral) from Wyoming. (d) Fulvic acid (a humic acid) from Georgia.

Culled from www.faculty.yc.edu

layers, with the anions, mainly O, OH, and occasionally F, grouped tetrahedrally and octahedrally about the cations, mainly Si, and Al, in tetrahedral positions and Al, Mg, and Fe, in octahedral positions, together in some minerals with interlayer cations such as K, Na, Ca, Mg. (Brindley 1951).

However, some modifications have since been introduced to this nomenclature. The present definition of clay minerals, as given by Brindley and Pedro in 1972 states that, "clay minerals belong to the family of phyllosilicates and contain continuous two-dimensional tetrahedral sheets of composition T_2O_5 , (T= Si, Al, Be, . . .) with tetrahedra linked by sharing three corners of each, and with the fourth corner pointing in any direction. The tetrahedral sheets are linked in the unit structure to octahedral sheets or to groups of co-ordinated cations, or individual cations".(Bailey 1980).

Clays are generally classified into four main groups; kaolinite, montmorillonite-smectite, illite, and chlorite. There are about 30 different types of clays within these four main categories, however most natural clays are

mixtures of these different types, along with other weathered minerals. (Bailey 1980). Table 1. below shows a classification scheme for clay minerals from the Mineralogical Society of America.

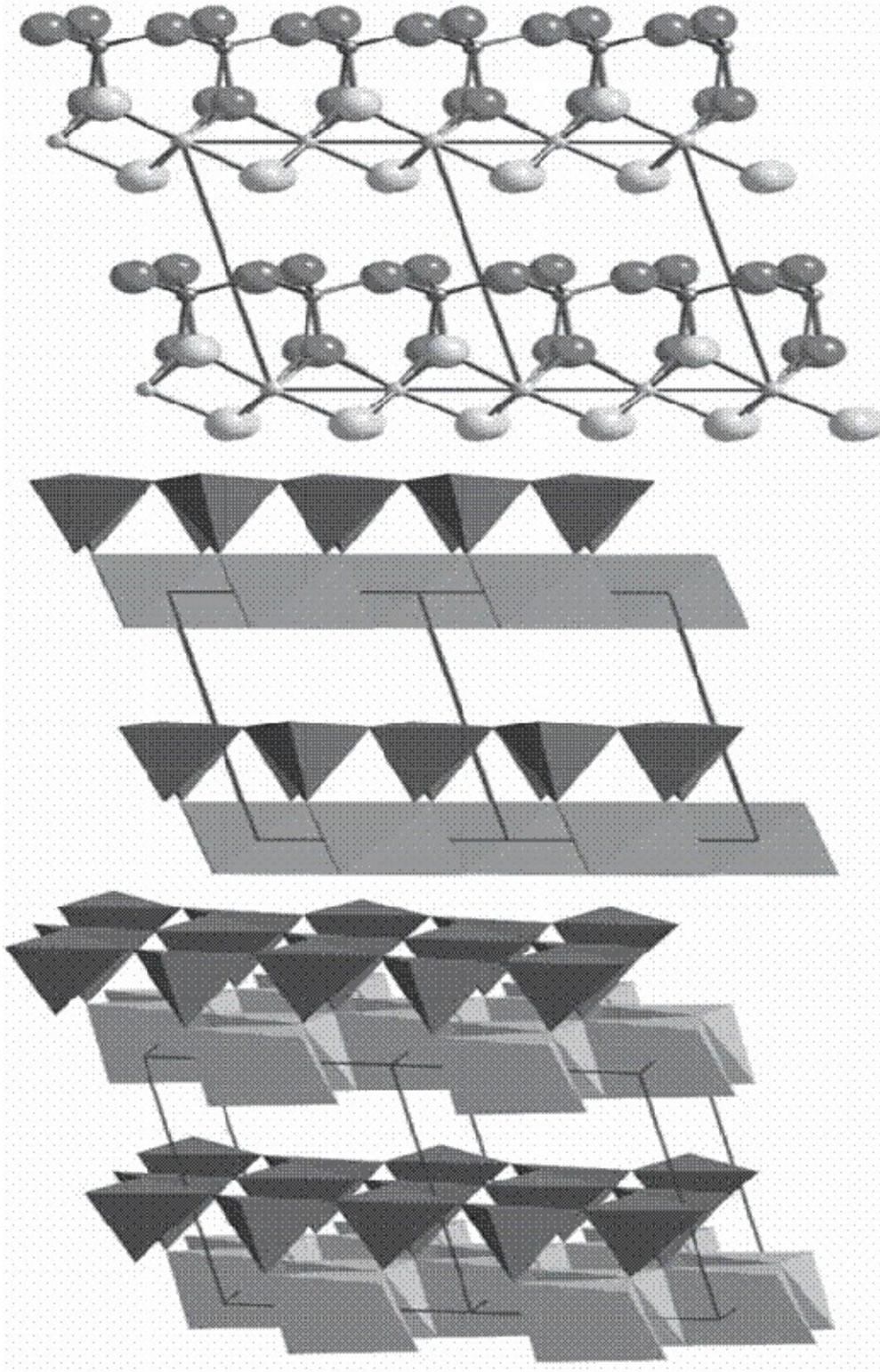


Figure 1: In the crystal structure of kaolinite, the SiO_4 tetrahedra form one side of the sheet while the octahedra contain OH^- on the outer layer attached to the Al^{3+} ions. The sheets are held together only by van der Waals bonds.

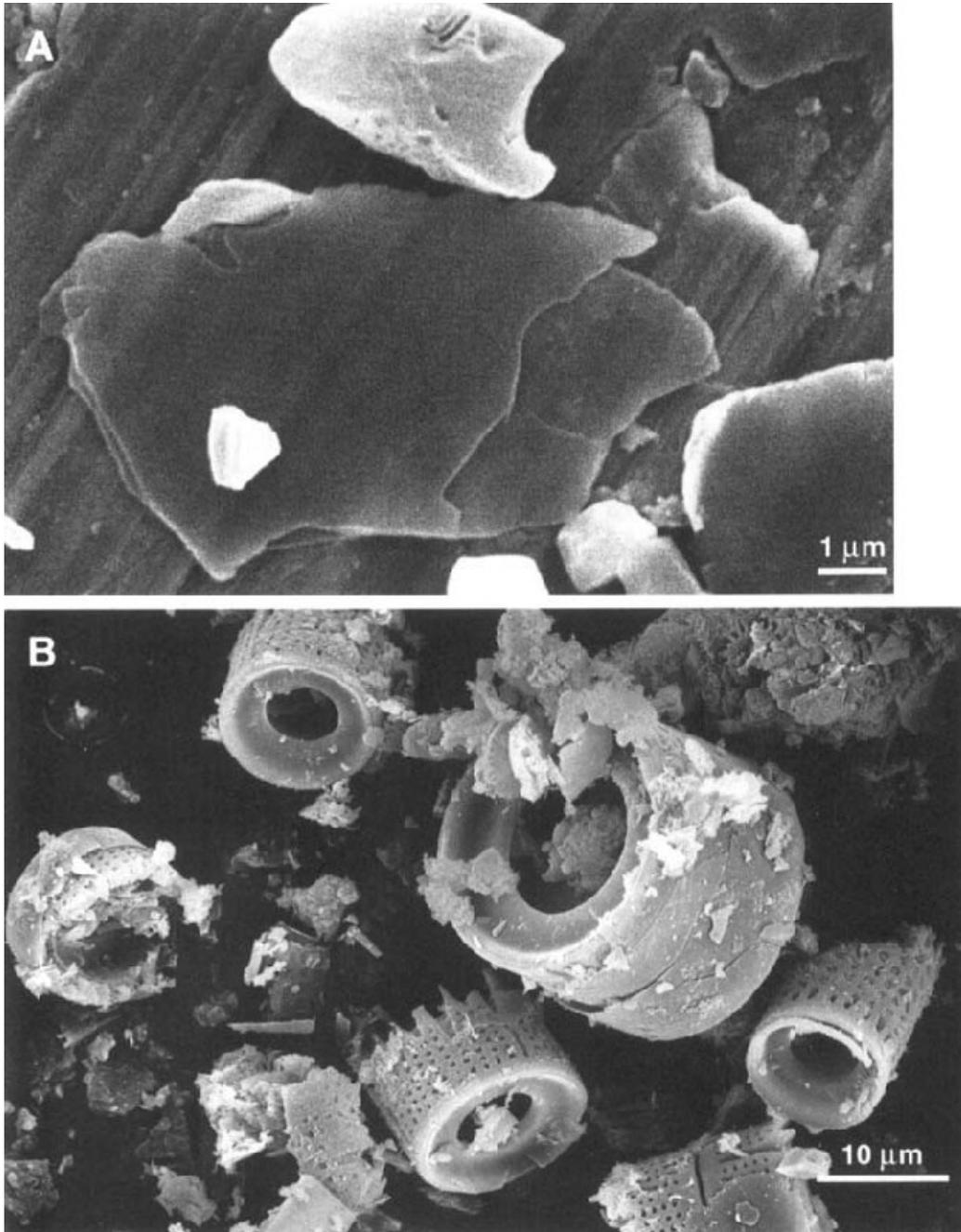


Fig. 2. (A) SEM-photograph of the clay fraction 1-2 μm of sample 25822; precipitates with the pipette method. The platy particle in the centre has a maximum diameter of about 10 μm. (Konert and Vandenberghe 1997)

Table 2.1: Classification scheme for clay minerals, from the Mineralogical Society of America.

Layer Type	Group (\underline{X} =Charge per formula unit)	Sub group	Species*
1.1	Kaolinite-Serpentine $\underline{x} \sim 0$	Kaolinite serpentine	Kaolinite, dictite, halloysite, chrysotile, lizardite
	Pyrophyllite- talc $\underline{x} \sim 0$	Pyrophyllite Talc	Pyrophyllite Talc
	Smectite $\underline{x} \sim 0.2 - 0.6$	Diocahedral smectite, trioctahedral smectite	Montmorillonite Bcidellite Saponite, Hectorite, Sauconite
	Vermiculite $\underline{x} \sim 0.6-0.9$	Diocahedral vermiculite, trioctahedral vermiculite	Diocahedral vermiculite, trioctahedral vermiculite
	Mica # $\underline{x} \sim 0$	Diocahedral Mica Triocahedral Mica	Muscovite Paragonite Phlogopite Biotite Lepidolite
	Brittle Mica $\underline{x} \sim 2$	Diocahedral Brittle mica Triocahedral Brittle mica	Margarite Clintonite Anandite
	Chlorite	Diocahedral Chlorite	Donbassite
	\underline{X} variable	Di, trioc- tahedral	Cookeite Sudoite
		Chlorite Triocahedral Chlorite	Clinochlore Chamosite Nimite

* Only a few examples are given.

The status of illite or (hydromica), sericite, e.t.c are left open at present, because many materials so designated may be interstratified.

2.2 PARTICLE SIZE AND PARTICLE SIZE DISTRIBUTION OF CLAYS.

2.2.1 WHAT IS PARTICLE SIZE?

Particle size is a notion introduced for comparing the dimensions of solid particles, (flecks), liquid particles,(droplets), or gaseous particles, (bubbles). The notion of particle size applies to colloidal particles; particles in ecology; particles in granular material; or particles that form a granular material. (Wikipedia 2013).

The dictionary of earth sciences define particle size, (grain size), as the diameter or volume of the grains in a sediment or sedimentary rock. It goes further to say that particle size can be determined by sieving; by measuring the settling velocity; or by direct measurement of individual clasts. (Ailsa Allaby 1999).

2.2.2 CLASSIFICATION OF PARTICLE SIZE.

There are various methods to classify particle size of materials. However two commonly used methods are the

Udden-Wentworth scale (Wentworth scale), and the British Standard classification.

In the Udden-Wentworth scale, the sedimentary grades are -: >256mm, boulder; 64-256mm, cobble; 2-64mm, pebble; 62.5-2000 μ m, sand; 4-62.5 μ m, silt; less than 4 μ m, clay.

In the British standard classification; >200mm, boulder; 60-200mm, cobble; 2-60mm, gravel; 600-2000 μ m, coarse sand; 200-600 μ m, medium sand; 60-200 μ m, fine sand; 2-60 μ m, silt; less than 2 μ m, clay. (Ailsa Allaby 1999).

The particle size of a spherical object can be unambiguously and quantitatively defined by its diameter. However a typical object is likely to be irregular in shape and non spherical, thus the above quantitative definition cannot be applicable. Nevertheless there are several ways of extending the quantitative definition as to obtain a definition that also applies to non-spherical particles.

For example a definition can be based on replacing a given particle with an imaginary sphere that has one of the properties identical with the particle. Thus–:

- Volume based particle size equals the diameter of the sphere that has the same volume as a given particle.
- Weight based particle size equals the diameter of the sphere that has the same weight as a given particle.
- Area based particle size equals the diameter of the sphere that has the same surface area as a given particle.

Real systems, for example a sample of clay are practically always poly-disperse, meaning that the particles in an ensemble have different sizes. This leads us to the notion of particle size distribution which reflects this poly-dispersity.

2.3 WHAT IS PARTICLE SIZE DISTRIBUTION?

The particle size distribution of a powder, or a granular material, or particles dispersed in fluid, is a list of values or a mathematical function that defines the relative

amount, typically by mass, of particles present according to size. (Jillavenkatesa 2001).

Particle size distribution may also be referred to as grain size distribution. The particle size distribution of a material can be important in understanding its physical and chemical properties. It affects the strength and load bearing properties of rocks and soils.

2.4 METHODS OF PARTICLE SIZE DETERMINATION.

There are several methods of measuring the particle sizes of colloidal substances like clay minerals. They can be broadly classified into direct methods and indirect methods.

Direct methods include mechanical sieving, optical techniques, microscopy, and laser light scattering techniques. Indirect methods include sedimentation techniques.

Indirect methods of particle size measurement relate the settling of particles through some medium to the diameter of the particle. The relationship between the

velocity of fall and the diameter of a spherical particle is given by,

$d = K\sqrt{v}$, ----- (equation 2.1). where d = diameter of particle,

v = velocity of fall,

K = constant. (Johnson 1942).

Although particles of clay are not perfect spheres, when they are allowed to fall in dilute suspension without interference, the tumbling motion imparted to the particle by its irregular shape and the viscosity of the medium make it in effect a sphere. For this reason perhaps, the data obtained by using the above formula are in good agreement with direct measurements made with optical equipment and electron microscopes. (Johnson and Lawrence 1942).

Indirect methods of particle size measurement can further be classified into three broad categories—: sedimentation; elutriation and centrifugation.

Sedimentation is the tendency for particles in suspension to settle out of the fluid in which they are

entrained and come to rest against a barrier. This tendency is due to their motion through the fluid in response to the forces acting on them.

Elutriation is a process for separating lighter particles from heavier ones using a vertically directed stream of gas or liquid. This causes the smaller or lighter particles to rise to the top (overflow), due to their lower terminal velocities as compared to the velocity of the rising fluid.

Centrifugation is a process that involves the use of the centrifugal force for the sedimentation of mixtures with a centrifuge. The theoretical basis for this technique is the effect of gravity on particles in suspension. Two particles of different masses will settle in a tube at different rates in response to gravity.

The determination of particle size distribution in natural, homogeneous particle populations is subject to artefacts arising not only from the limitation of the technique used, but also from aggregation and disaggregation process which can occur during sampling,

sample work up and during separation and / or measurement.
(Martin Hasselov et al 2001).

The choice of which method of particle sizing to be used depends on a number of factors. They include–:

- Nature of the material to be sized, e. g estimated particle size and particle size ranges; solubility; ease of handling; toxicity; flow ability; intended use.
- Costs including initial equipment costs and running costs.
- Specification requirements.
- Time constraints.

In the particle size range down to 25 microns, direct methods involving optical equipment and microscopy techniques are sometimes more adequate than methods involving sedimentation. (Dallavalle 1948).

Between the 25 micron and $\frac{1}{2}$ micron range, sedimentation or elutriation are used to a greater advantage than direct methods involving optical equipment. Below $\frac{1}{2}$ micron, the sedimentation methods must be augmented by some means of centrifugation.

(Norton and Spiel 1938). For sub micron particles, it is necessary to use either transmission electron microscopy or scanning electron microscopy. (A.M Healy 2010).

2.4.1 **MICROSCOPY METHOD.**

The advent of the electron microscope,(both scanning and transmission types), with much greater resolutions have led to great advancements in the direct methods of particle size measurement. The microscopy method of particle size measurement comes with the following advantages–:

- Ability to examine each particle individually.
- Ability to distinguish aggregates from single particles.
- When coupled to image analysis computers, each field can be examined and distribution obtained automatically.

However, the following limitations are also associated with microscopy–:

- Depth of focus is about 10 μ m at x100 and only 0.5 μ m at x1000.

- With small particles, diffraction effects increase, causing blurring at the edges – thus determination of particles $<3\mu\text{m}$ is less and less certain.

Manual optical microscopy techniques have the following advantages–:

- Relatively inexpensive.
- It can examine each particle individually and can detect aggregates; 2 D shape; colour; melting point; etc.
- It can keep a permanent photographic record.
- It requires only small sample sizes.

It is however associated with the following short comings:

- It is time consuming, which can result in high operator fatigue. Hence only few particles are examined.
- Very low through put.
- No information on 3-D shape.
- Certain amount of subjectivity associated with sizing operator bias.

In general microscopy offers the ability to examine particles individually, providing a visual means to see sub-micron specimens. Particle shape can also be determined. The major limitations of microscopy are that equipment are relatively expensive and involve time consuming sample preparations. It also has low through put and hence not suitable for routine use.

Other developments include the use of automatic and image analysis microscopes which are faster and involve less operator fatigue than manual equipment. However, they can be very expensive.

2.4.2 SIEVING ANALYSIS.

Sieving analysis is performed using a nest or stack of sieves where each lower sieve has a smaller aperture size than that of the sieve above it.

A sieve is a device with meshes or perforations, through which finer particles of a mixture of various sizes may be passed to separate them from coarse ones, through which the liquid may be drained from liquid

containing material, or through which soft materials may be forced for reduction to fine particles. (Merriam – Webster Unabridged Dictionary 2013).

Sieves can be referred to either by their aperture size or by their mesh size, (or sieve number). The mesh size is the number of wires per linear inch. Sieves are generally used for size ranges between 5 μ m to 3mm approximately.

Sieving may be performed wet or dry; by machine or by hand; for a fixed time or until powder passes through the sieve at a constant low rate.

The advantages of the sieve technique include their relative inexpensiveness, ease of use and wide size range of applicability. Its shortcomings include, known problems of reproducibility, wear / damage of the sieve in use or during cleaning; difficulties with irregular / agglomerated particles or rod like particles, labour intensiveness.

2.4.3 SEDIMENTATION.

Sedimentation methods of particle size analysis are based on Stoke's law. The Stoke's law gives a more precise relation between particle size and terminal velocity of fall of the particle through a fluid. The terminal velocity of fall of a particle in a fluid increases with size.

The Stoke's law is expressed as,

$$v = (\rho_s - \rho_f)gd_{\text{sph}}^2/18\eta \text{ ----- (equation 2.2) or}$$

$$d_{\text{sph}} = \sqrt{18\eta x/(\rho_s - \rho_f)gt} \text{ ----- (equation 2.3)}$$

Where v = terminal velocity of fall,

d_{sph} = diameter of spherical particle,

ρ_s = density of sphere,

ρ_f = density of fluid,

g = acceleration due to gravity,

η = viscosity of fluid,

x = distance fallen by sphere in time t .

The particle size distribution of a fine powder can be determined by examining a sedimenting suspension of the powder. There are two basic methods–:

- The incremental method in which the changes with time in the concentration or density of the suspension at known depths are determined. This can be further classified as fixed time or fixed depth technique.
- The cumulative method in which the rate at which the powder is settling out of suspension is determined; i.e. the accumulated particles are measured at a fixed level after all the particles between it and the fluid's surface have settled.

2.4.4 **THE ANDREASEN PIPETTE.**

This is a specialised instrument used to determine particle size and particle size distribution of colloidal substances using the Stoke's law. Size distribution is determined by allowing a homogeneous suspension to settle in a cylinder and taking samples from the settling suspension at a fixed horizontal level at intervals of time.

Each sample will contain a representative sample of the suspension with the exception of particles greater than a critical size, all of which will have settled below the

level of the sampling point. The concentration of solid in a sample taken at time t , is determined by centrifugation of the sample followed by drying and weighing, or simply by drying and weighing.

This concentration expressed as a percentage of of the initial concentration gives the percentage (w/w) of the particles whose falling velocities are equal to or less than x/t . Substituting this value for x/t in the Stoke's law gives the corresponding stokes diameter. (Healy 2010).

The advantages of using the Andreasen pipette include-:

- Equipment required can be relatively inexpensive.
- It can measure a wide range of sizes with considerable accuracy and reproducibility.

The disadvantages include-:

- Sedimentation analysis must be carried out at concentrations which are sufficiently low for interactive effects between particles to be negligible so that their terminal falling velocities can be taken as equal to those of isolated particles.

- Large particles create turbulence and are slowed down, often recorded undersize.
- Careful temperature control is necessary to suppress convection currents.
- The lower limit of particle size is set by the increasing importance of Brownian motion for progressively smaller particles.
- Particle re-aggregation during extended measurements.
- Particles have to be completely insoluble in the suspending liquid.



Figure 3: The Andreasen Pipette

2.4.5 OTHER PARTICLE SIZE MEASURING TECHNIQUES.

ELECTRICAL SENSING ZONE METHOD.

The instrument used in this technique measures particle volume and then relates it to the diameter of a sphere of equivalent volume as the particle. The number and size of particles suspended in an electrolyte is determined by causing them to pass through an orifice on either side of which is immersed an electrode.

The changes in electric impedance (resistance) as particles pass through the orifice generate voltage pulses whose amplitude are proportional to the volumes of the particles.

OPTICAL SENSING ZONE METHOD.

Here the equipment relates the obscuration of light source to particle size area. It has the advantage of not requiring an electrolytic medium.

LASER DIFFRACTION

This technique is used for particles in the range of 0.02 - 2000 μm . The particles are made to pass through a laser beam and the light scattered by them is collected over a range of angles in the forward direction.

The angles of diffraction are inversely related to the particle size. The particles pass through an expanded and collimated laser beam in front of a lens in whose focal plane is positioned a photo sensitive detector consisting of a series of concentric rings.

The distribution of the scattered intensity is analysed by computer to yield the particle size distribution. (Healy 2010).

The advantages of the laser diffraction method include-:

- Non-intrusiveness as it uses a low power beam.
- Fast :it takes typically less than 3 minutes to take a measurement and analysis.
- High precision and wide range.

- Absolute measurement; no calibration is required as the instrument is based on fundamental physical properties.
- Simple to use and high versatility.

However it is a very expensive equipment and requires that a difference must exist in refractive index between particles and the suspending medium.

PHOTON CORRELATION SPECTROSCOPY.

This is often used for particle size ranges of 1nm to 5 μ m.

The principle is based on the fact that large particles move more slowly than small particles, so that the rate of fluctuation of light scattered from them is also slower. The rate of change of these light fluctuations is used to determine the size distribution of the particles scattering light.

Comparison is made of a snap-shot of each speckle pattern with another taken micro seconds later. The time dependent change in position of the speckles relates to the change of position of the particles and hence particle size.

The dynamic light signal is sampled and correlated with itself at different time intervals using a digital correlator and associated computer software. The relationship of the auto-correlation function obtained, to time intervals is processed to provide estimates of the particle size distribution. (Healy 2010).

2.5. A COMPARISON OF LASER BASED PROCESS AND SEDIMENTATION TECHNIQUES FOR PARTICLE SIZE DISTRIBUTION ANALYSIS OF CLAY.

Laser diffraction particle size analysis is based on the forward scattering of monochromatic coherent light. According to Konert and Vandenberghe (1997), from the point of view of laboratory efficiency, accuracy and reproducibility, the laser diffraction technique is a far superior method of particle size distribution analysis of colloidal substances compared to sieving and sedimentation techniques.

The use of the pipette sedimentation method in particle size analysis of clay is based on the following assumptions–:

- Sedimentation speed is constant and not too fast. The particle Reynolds number must be smaller than one. ($Re_p < 1$).
- Particles are spheres, solid and smooth.
- Densities of the particles are equal to the density of quartz, 2.65gcm^3
- No interactions occur between the particles or between the particles and the wall of the sedimentation vessel.
- Particles do not affect the viscosity of the liquid.

However, clay minerals have been found to be mostly platy and their densities vary between 2 and 3gcm^{-3} depending on their hydration properties. (Konert and Vandenberghe 1997). Also see figure 4 below.

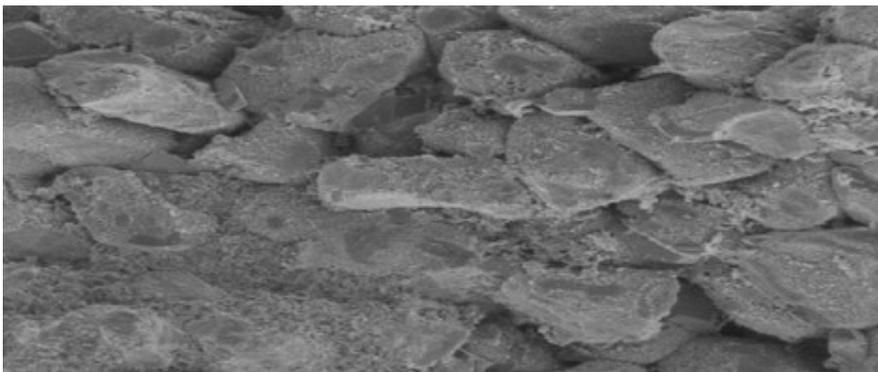


Figure 4. SEM of Nsu Clay Sample. (B.C Chukwudi 2008).

A laser diffraction spectrophotometer sees the particle as a two dimensional object and gives its grain size as a function of the cross-sectional area of the particle.

Due to the fact that the particle shape is likely to be most significant in measuring the grain size of that particle, the deviation of clay particles from sphere is a significant factor that can affect results obtained in particle size analysis by a particular method.

The influence of particle shape on grain size analysis is often hypothetical. Jonasz (1991) argues that the projected area of a non-spherical particle, averaged over the particle orientation is larger than that of a sphere with equal volume. If this is true, it will lead to coarser results by applying the laser diffraction method instead of sieves.

Syvitski etal (1991) concluded that particle size instruments should no longer have their results compared to those of the classical methods of sieving and sedimentation, because digital systems are far superior.

2.6. MODULUS OF RUPTURE

The modulus of rupture is the maximum transverse breaking stress, applied under specific conditions, that a material will withstand before fracture. It is used as a common quality control test for both ceramic raw materials and products. (Wikipedia-online encyclopaedia 2003). Floor tiles, for example, require clays with high modulus of rupture.

The modulus of rupture is a strength determination parameter used in the ceramic industry. The value of the modulus of rupture is an indication of the tensile strength of the material, but does not relate directly to the deformation properties. (G.M Reeves 2004).

The strength of a clay material defines the amount of applied stress it can sustain without failing by brittle fracture or by plastic yielding. As illustrated in figure 3 below, elastic and plastic deformation occurs before the strength is exceeded, but failure marks a pronounced change in the condition of the material and removal of the

applied stress will not restore the material to its former state. In an ideal elastic material, strain is proportional to stress and strain is recoverable. But according to Gillot (1987), the yield stress is variously defined as the point, at which there is a permanent strain, or the point at which the stress-strain graph is no longer linear, or the minimum stress for continuous plastic flow, but all these are at similar values of stress in clays.

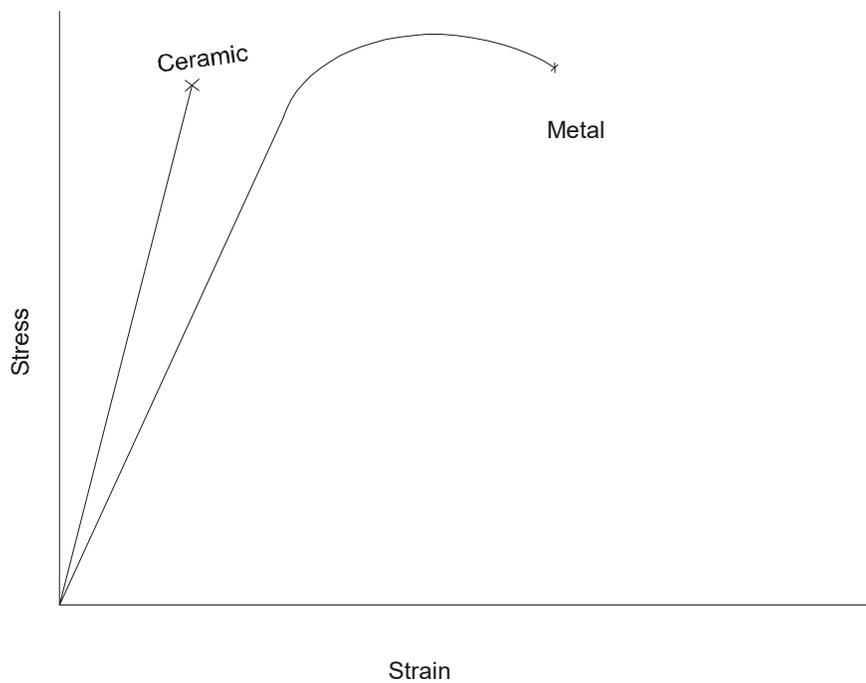


Figure 5: The Stress - Strain Behaviour of brittle materials (ceramics) Compared with that of more ductile materials (metal)

2.6.1 **TEST FOR MODULUS OF RUPTURE.**

The stress-strain behaviour of ductile materials is found by applying the tensile test. Typically the curve goes through a maximum which is where the tensile strength is located. Failure occurs at a lower stress after necking has reduced the cross-sectional area supporting the load.

However, the tensile test can not be applied to brittle materials like ceramics, for the following reasons–:

- It is difficult to prepare and test specimens having the required geometry.
- It is difficult to grip brittle materials without fracturing them.
- Surface flaws often cause premature failures.
- Ceramics fail after only about 0.1% strain thus specimens must be perfectly aligned in order to avoid the presence of bending stresses. (Shackelford 2001).

For these reasons, a more suitable transverse bending test is used. In the bend test, a bar specimen having

either a rectangular or circular cross-section is bent until fracture, using a three point or four point loading technique.

At the point of loading, the top surface of the specimen is placed in a state of compression, while the bottom surface is in tension. Stress is computed from the specimen thickness, the bending moment and the moment of inertia of the cross section.

The maximum tensile stress exists at the bottom surface of the center of the specimen, directly below the point of loading. Since the tensile strength of ceramics are about one tenth of their compressive strengths, and fracture occurs on the tensile specimen face, the bend test is a valid substitute for the tensile test. (Shackelford 2001).

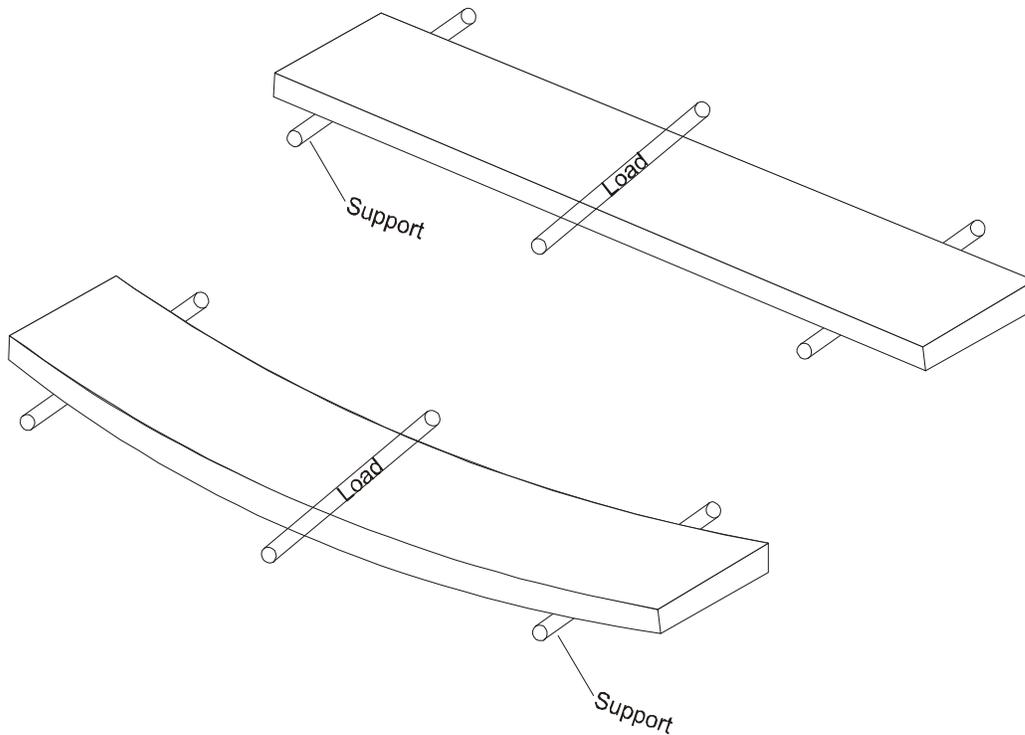


Figure 6: Bending Test 3 Point Loading

For a 3-point bend test of a rectangular bar, the stress at fracture using the bend test is known as the flexural stress or the modulus of rupture. It is given by:

$$f_s = \frac{3PL}{2BH^2} \quad \text{-----} \quad \text{(equation 2.4)}$$

where,

f_s = flexural strength,

P = fracture load,

L = length between outer supports (support span),

B = specimen width,

H = specimen height.

For a rectangular beam in 4-point loading bending test set up, where the loading span is one third of the support span,

$$f_s = PL / BH^2 \text{ ----- (equation 2.5)}$$

where,

f_s = flexural strength,

L = length of the support span,

P = load (force) at the fracture point,

B = specimen width,

H = specimen height or thickness.

For 4-point bend test set up, if the loading span is 1/2 of the support span, (i.e. $L_i = 1/2 L$ in figure 6 below),

$$f_s = 3 PL / 4 BH^2 \text{ -----(equation 2.6)}$$

If the loading span is neither 1/3 or 1/2 the support span for the 4-point bend test set up,

$$f_s = 3P(L - L_i) / 2BH_i^2 \text{ -----(equation 2.7) (ASTM}$$

2008)

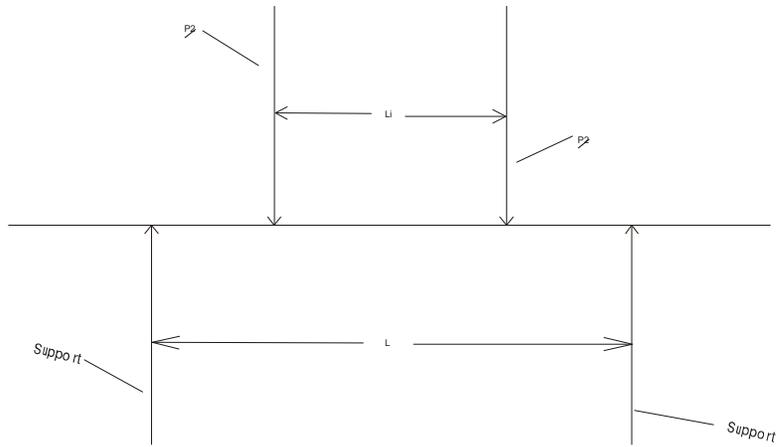


Figure7: 4 Point Bend Test Set Up

The results of the bend test are similar to strain-stress curves, except that the stress is plotted versus deflection rather than versus strain. (See fig.8).

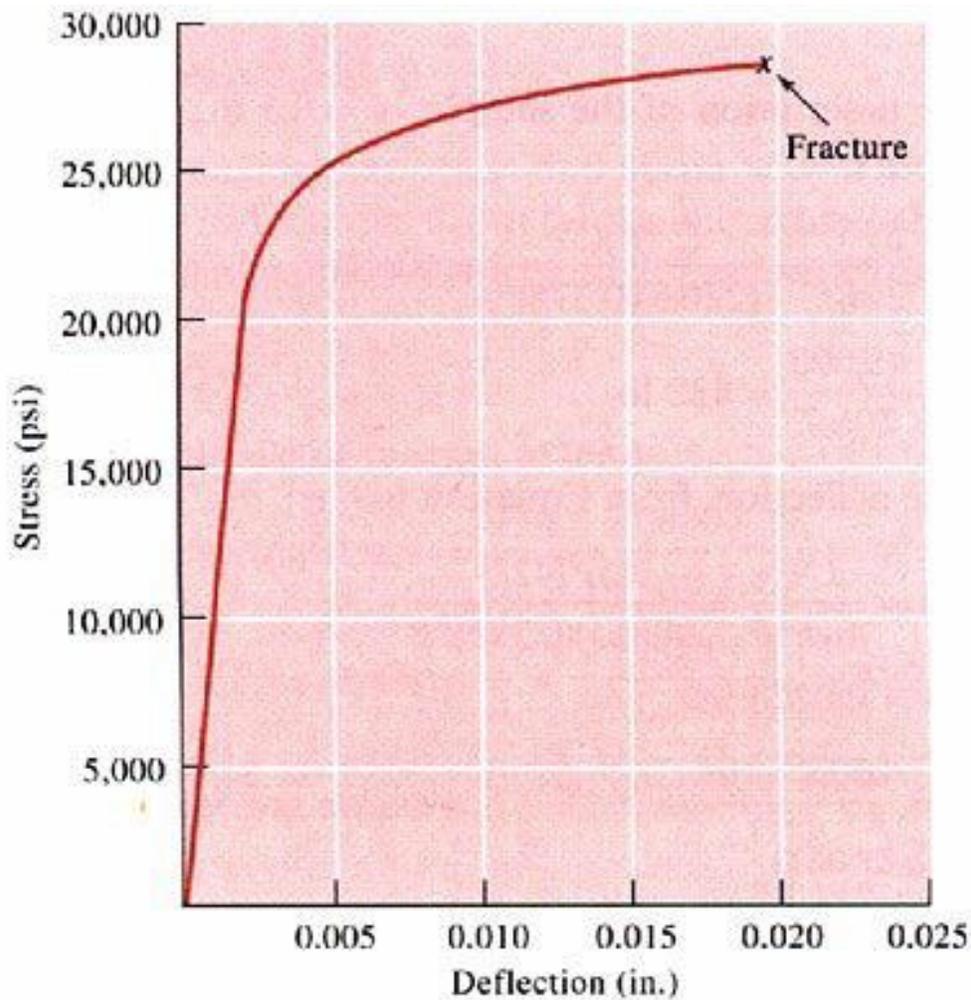


Figure 8: Stress-deflection curve for MgO obtained from a bend test. [Askeland, 1994]

The modulus of rupture test may be performed in the green state or after some sort of conditioning, as well as after firing. The values obtained gives an indication of the strength of the material in the designated state or condition.

The modulus of rupture is usually reported in units of pounds per square inch (psi), kilogram per square centimetre (Kg/cm^2) or the S.I unit of Mega Paschal (MPa).

2.7 **RELATIONSHIP BETWEEN MINERALOGY, PARTICLE SIZE AND STRENGTH OF CLAYS AND CERAMICS.**

The strength of an engineering material is dependent on its microstructure. Generally yield stress is maximised with decreasing grain size of the material according to the Hall-Petch equation,

$$\sigma_y = \sigma_0 + k_y/\sqrt{d} \text{ ----- (equation 2.8)}$$

Where,

k_y is the strengthening coefficient (a material constant);

σ_0 is a material constant for the starting stress for dislocation movement, (or the resistance of the lattice to dislocation motion); d is the grain diameter and

σ_y is the yield stress.

The particle size of clay raw materials influences their technical behaviour during processing and affects many properties of clay ceramic products. Clay particles are characterised by a high surface energy determined by the presence of negative charges, while the neutrality of the molecules is preserved inside the structure. (Maria Gorea 2002).

Consequently the properties of clays are highly influenced by the surface phenomenon, the increase of the specific surface and thus the surface energy being determined by the degree of dispersion. Grinding for example results in major structural changes in kaolin minerals. (Worasith 2012).

In practice, when establishing the fields of usage of clays and their ratio in the ceramic mass composition, not only their chemical composition but also their mineralogy, particle size distribution and their correlation with the technological characteristics are important.

The specific technological properties of clays depend first of all on their mineralogical composition, but also on other factors such as the size and morphology of the constituent particles, the crystalline degree of various minerals, the presence of organic impurities and of soluble salts. (Maria Gorea 2002).

These features also depend on the nature, ratio and size of clay particles. In fact the strength polycrystalline ceramics depend on the grain size through the Hall-Petch. As the grain size decrease, the strength increases. (Barry Carter 2007).

The grain size is determined by the size of the initial powder particles and the way in which they were consolidated or processed. It has also been shown that the mineralogical composition of clays used in ceramics has a great influence on the technical behaviour and on the final properties of fired products.

The most commonly used method of determining the mineralogical composition of clays are by using x-ray diffraction analysis and electron microscopy.

The chemical composition of clays alone can only give a rough measure of their general properties. This is due to the fact that the same oxide may be present in several mineral phases that show opposite influence on ceramics. (Teoreanu et al 1985).

For example, aluminium oxide in kaolin leads to increased plasticity and refractoriness, while in feldspars it acts as a plasticity reducing material in the process of wet preparation, or as a fluxing agent at firing. (Teoreanu et al 1985).

Consequently two clays with similar chemical composition may show different technical behaviour, according to their particular mineral compositions. The percentage of the mineral oxides, (Fe_2O_3 ; MgO ; CaO ; Na_2O ; etc), in the clay ultimately determine the areas of application of the clay such as in bricks, floor tiles paper,

etc; while the quantity of the alkaline metal oxides (Na_2O ; K_2O ; CaO ; etc), indicate their suitability for making ceramic products. (Nnuka 2001).

Up to the present, several theoretical considerations on the factors affecting the strength of porcelain (ceramics) have been proposed. Leonardo Akwilapo and Kjeell Wiik (2003) considered a theory based on the interlocking of the felt like mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) needles and another based on internal stress to be fundamental factors controlling the various properties of fired ceramics.

They found that electrical porcelains were recognised to show relatively high strength as cristobalite was produced from quartz or kaolin. It follows then that the grain size of quartz and kaolin is an important factor as far as strength development is concerned, since smaller and larger grains resulted in higher and lower strengths respectively. This can be explained by crack propagation around the large grains in the body matrix. (Akwilapo and Wiik 2003).

They stated that the physical properties of ceramics depend on the microstructure as well as the phase distributions developed during the firing process. These two properties depend on the chemical composition of the raw materials, the preparation methods and the time and temperature of firing. (Kobayashi et al 1994).

Correia et al (2002) posited that the particle size distribution of particulate substances has a direct influence on material properties including packing density and porosity, both of which have a direct correlation to the modulus of rupture of clays and ceramics.

In their research work on optimising mechanical strength and bulk densities of dry ceramic bodies through mixture design, they explained the correspondence of highest DMoR (Dry Modulus of Rupture) values to samples with high content of finer clay particles, by a particle packing effect. The finer the clay particles, the more densely packed they will be in the ceramic/clay matrix. (Correi et al 2002).

In their work to determine the relationship between the characteristics of ceramic tiles, before and after firing, and the water content of granulated powder and the compaction pressure, Boschi et al discovered that there is a linear relationship between dried density and moisture content of powder, up to a peak, and also a linear relationship between density of dried compact, modulus of rupture of dried compact, linear shrinkage on firing and modulus of rupture after firing.

They observed that the lubrication effect of water on clays leads to decrease of the yield stress and increase the degree of deformation of the granules by an applied compaction force, as moisture content is increased. Ability to absorb more water depends on the size of the pore spaces between the granules and smaller sized particles will have smaller pore spaces, while larger particles will have larger pore spaces.

Since the deformation of the granules due to the local stress distribution and sliding of the clay particles inside the granules is directed towards the inter granular

pores, the density of the dried compact increased linearly with moisture content. (Boschi et al 1998).

At the peak values of dried density, the inter granular pores have almost disappeared and the volume and size of the pores between particles inside the granules have decreased below the volume of water added, supporting the idea that more efficient particle packing, achieved by smaller sized particles, corresponds to higher densities and higher values of flexural strength or modulus of rupture.

Das et al (2004) also concluded that ceramic compositions with more of kaolinite clays showed higher shrinkage, higher densification and flexural strength than compositions with more of quartzitic clays. This they also attributed to the higher densifications due to smaller sized kaolinite particles.

Sarkar (2011) stated that particle size distribution is used in the formulation and characterisation of ceramic materials. It gives a better packing as

compared with using monosized particles. According to his findings, besides influencing packing, particle size distribution affects flow, apparent porosity and hence strength of ceramics. (Ritwik Sarkar 2011).

Viewey and Larrly (1978) also reported that fine particles shrink more, are denser and exhibit excellent mechanical properties. According to their work, it was found that the finer the particle size of ceramics, the lesser the apparent porosity and greater the bulk density. (Viewey and Larrly 1978).

Generally porosity may affect the mechanical properties of clays and ceramic materials in two ways. Firstly it reduces the effective cross-sectional (load bearing) area such that the mechanical properties will be dependent on the minimal contact solid area. The minimum solid (load bearing) area is the actual bond area between particles, in the case of stacked particles, or the minimum web cross-sectional area between pores, in the case of stacked bubbles.

Secondly porosity leads to (stress concentrations) near the pores such that under mechanical loading, the true stress in the material is higher near the pores than at a far distance from them. (Andreeva and Ordanyan 2002).

2.8 OTHER RELATED WORKS.

Research work on the properties and technical characterisation of Nigerian clays have continued to elicit the interest of many scholars in recent times, because of the obvious economic potentials the clay and ceramics industries hold for the Nigerian economy.

B.C. Chukwudi (2008) have researched on the Characteristics and Evaluations of Refractory properties of Nsu clay. From the results of his work, he concluded that although only about 50% of the sample particles have sizes finer than 400 μm , Nsu clay generally showed good suitability for refractory purpose. He also recommended the reduction of alkali impurities.

Daniel-Mkpume et al (2011) Have also researched on Blending of Nsu and Ibeku (Umuahia) clays: A Solution Towards The Replacement of GP 107-3 Refractory Brick in the Metallurgical Industry. Their results revealed that Ibeku sample enhanced the thermo-physical properties of Nsu clay, possibly due to a wider range of fine particle sizes.

Arisa (1997) have also researched on the Effect of Initial Particle Size and Size Distribution on the Physical and Mechanical Properties of some Nigerian Clays, Sintered at 1200°C. He investigated clay samples from Obowo, Ekwe-Okwelle, in Imo state, and also clay sample from Benin in Edo state.

However he carried out the particle size analysis using manual sieving technique which has since been shown to produce inconsistent results with colloidal substances. Nevertheless his results led him to conclude that the initial particle size and size distributions influenced influence the properties of the clay samples,

such as apparent porosity, bulk density, shrinkage and strength.

Having reviewed the literature on this research topic, the following chapters will deal with the materials, experimental methods, results, discussion, conclusions and recommendations.

CHAPTER THREE

MATERIALS AND EXPERIMENTAL METHODS

3.1 MATERIALS.

The three clay samples were collected as follows: Sample-A was collected from Agbaghara Nsu in Ehime Mbano Local Government Area of Imo State; Sample-B was collected from Ohiya in Umuahia North Local Government Area of Abia State; Sample-C was collected from Umuejike Awo-Omamma in Oru East Local Government area of Imo State.

Other materials include HELOS-Sympatec Particle Size Analyser. Handle-Muhlach C.H crusher, 250 μ m and 120 μ m mechanical sieves, Automated Plastometer machine, venire callipers, oven drier, Pioneer digital weigh balance, Distilled deionised water, Fulham Pottery laboratory kiln, Electric Transversal Strength Machine. (ETSM).

3.2 EXPERIMENTAL PROCEDURE.

3.3 Clay Preparation

The collected clay lumps were first crushed using the Handle-Muhlach C.H crusher. Subsequently the clay powder was dispersed in excess distilled-deionized water in a pre-treated plastic container and stirred vigorously to ensure proper dissolution. The dissolved clay was then filtered to get rid of unwanted particles and plant materials. The filtrate obtained was allowed to settle for 48 hrs after which excess water was decanted.

The settled clay at the bottom of the container was sun dried for four days to get rid of excess water molecules. After drying the clay was crushed into powder and sieved through a 120 μ m mesh sieve, the sieved clay was then mixed with appropriate amount of water to make it plastic for the molding process.

3.4 Moulding of the Test Pieces.

The slip was then molded into three types of shapes using metallic moulds and the application of lubricants to the surface of the moulds to prevent the test pieces from

sticking to the surface. The first shape is cylindrical with a width of 3.5cm and height 3cm, the second is a rectangular piece with length 8cm, width 4cm and height 1.5cm, while the third has a long rectangular shape with length 9.5cm, width 2cm and height 1.5cm.

3.5 Making Moisture Determination

This was determined by weighing the cylindrical test pieces immediately after molding and recorded as the wet weight, W_o . The test pieces were air-dried for 7 days and then dried in an oven at 105⁰C until a constant weight was recorded. After drying the test pieces were weighed and the dried weight recorded as W_i . The making moisture was then calculated.

$$\text{Making Moisture (\%)} = \frac{W_o - W_i}{W_o} \times 100$$

----- (equation 3.1)

3.6 Determination of Relative Plasticity

The relative plasticity was determined using the cylindrical test pieces. The original height, H_o of the test

pieces were obtained by the use of the venire callipers by taking the average of three specimens. Afterwards, a manual plastometer machine was used to deform the test pieces. The deformation height, H_i was recorded taking the average of three specimens. The relative plasticity was then calculated (lynne et al, 1980).

$$\text{Relative Plasticity} = H_o/H_i \text{----- (equation 3.2)}$$

3.7 Determination of Modulus of Rupture

Three long rectangular test pieces were made and air dried for 7 days, after which they were oven dried at 105⁰C until a constant weight was obtained. Two of the pieces were fired to their respective temperatures of 900 and 1100⁰C in a laboratory kiln (Fulham Pottery). The electrical transversal strength machine was used to determine the breaking load, P (Kg).

A venire calliper was used to determine the distance between support L (cm) of the transversal machine. The height, H (cm) and the width, B (cm) of the broken pieces were determined and the average value obtained from the

two broken parts was recorded. The modulus of rupture was then calculated (Akwilapo and Wiik, 2003).

$$\text{Modulus of Rupture (Kg/cm}^2\text{)} = \frac{3PL}{2BH} \text{ ----- (equation 3.3)}$$

3.8 Shrinkage Determination

Immediately after moulding of the rectangular test pieces, a venire calliper was used to insert a 5cm mark on each of them. This was recorded as the original length L_o (cm). The test pieces were then air dried for 7days and then dried in an oven at 105⁰C until a constant weight was obtained.

The shrinkage from the 5cm mark was then determined and recorded as the dried length, L_d (cm). Afterwards, two of the dried samples were fired to their respective temperatures of 900 and 1100 ⁰C, with each temperature corresponding to a particular test piece. The shrinkage of the test pieces from the 5cm mark were then determined and recorded as the fired length, L_f (cm). The shrinkage was then calculated (Lynne et al, 1980).

$$\text{Wet-Dry Shrinkage (\%)} = 100 \frac{L_o - L_d}{L_o} \quad \text{-----(equation 3.4)}$$

$$\text{Dry-Fired Shrinkage (\%)} = 100 \frac{L_d - L_f}{L_d} \quad \text{-----(equation 3.5)}$$

$$\text{Total Shrinkage (\%)} = 100 \frac{L_o - L_f}{L_o} \quad \text{-----(equation 3.6)}$$

3.9 Chemical Analysis

The Chemical analysis of sample A (Nsu clay) was obtained from Keke (2007) and that of sample B (Ohiya-Umuahia clay) was obtained from Mark (2007). The chemical analysis of sample C (Awo-Omamma clay) was done at National Root Crop Research Institute (N.R.C.R.I.) Umudike- Umuahia, using x-ray fluorescence spectroscopy.

3.10 Determination of Water of Absorption

The fired test pieces obtained from (3.8) above were then weighed and the weight recorded as dry weight, M_1

(g). Thereafter, the test pieces were soaked in water for 24hrs, then removed, cleaned and weighed immediately and recorded as soaked weight, M_2 (g). The water of adsorption was then calculated (lynne et al, 1980).

$$\text{Water of Absorption (\%)} = 100 \frac{[M_2 - M_1]}{M_1} \text{-----(equation 3.7)}$$

3.11 Porosity and Density Determination

After the procedure described in (3.10) above was completed. The suspended weight of the test pieces were then determined by the use of a lever balance and recorded as M_3 (g). The apparent porosity, apparent density and bulk density were then calculated (Akwilapo and Wiik, 2003).

$$\text{Apparent Porosity (\%)} = 100 \left[\frac{M_2 - M_1}{M_2 - M_3} \right] \text{-----(equation 3.8)}$$

$$\text{Apparent Density} = M_1 / [M_1 - M_3] \text{----- (equation 3.9)}$$

$$\text{Bulk Density} = M_1 / [M_2 - M_3] \text{----- (equation 3.10)}$$

3.12 PARTICLE SIZE ANALYSIS

The particle size analysis was done at TCR Engineering Services PVT Ltd Mumbai India, using Laser Diffraction (by wet suspension). The equipment used was HELOS sympatec Particle size analyser and the dispersion medium was distilled deionized water.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 CALCULATION OF MODULUS OF RUPTURE OF THE CLAY SAMPLES

FOR SAMPLE A (NSU- CLAY)

Table 4.1: Results of Mouldy of Rupture Test for sample A
(Nsu-Clay)

Samples no	Breaking load (kg)	Distance b/w supports	Width B. (cm)	Height H (cm)	Temp °C
A1	1.4	L (cm) 7 cm	2.01	1.44	Green
A 2	1.6	7 cm	2.00	1.45	Green
A 3	3.8	7 cm	1.93	1.43	900 ⁰ C
A 4	4.2	7 cm	1.92	1.44	900 ⁰ C
A5	5.8	7 cm	1.93	1.43	1100 ⁰ C
A 6	5.6	7 cm	1.91	1.42	1100 ⁰ C

Applying equation 3.3

$$\text{MOR (Kg/Cm}^2\text{)} = \frac{3PL}{2BH^2}$$

For A1,

$$\begin{aligned}\text{MOR} &= \frac{3 \times 1.4 \times 7}{2 \times 2.01 \times (1.44)^2} \\ &= 3.53 \text{ kg /cm}^2\end{aligned}$$

For A2

$$\begin{aligned}\text{MOR} &= \frac{3 \times 1.6 \times 7}{2 \times 2 \times (1.45)^2} \\ &= 3.99 \text{ Kg/cm}^2\end{aligned}$$

Average value for A1 & A2 (Green)

$$\begin{aligned}&= \frac{(3.99 + 3.53) \text{ Kg/cm}^2}{2} \\ &= 3.76 \text{ kg/cm}^2\end{aligned}$$

Similarly the average values of modulus of rupture for sample A3 and A4 (900⁰C) were calculated as well as for sample A5 and A6 (1100⁰C) .

The same procedure was used to calculate the modulus of

rupture values for sample B (Ohiya- Umuahia Clay) and sample

C (Umuejike-Awo-Omamma Clay) at the various temperatures;
(green, 900⁰C and 1100⁰C).

Table 4.2: Summary of the results obtained from the modulus of rupture tests of the three clay samples.

Sample	Breaking Load, P, (kg)	Distance b/w Supports L, (cm)	Width, B, (Cm)	Height, H, (cm)	Modulus of Rupture (kg/cm ³)	Temperature (°C)
Samples						
A						
A1	1.4	7cm	2.01	1.44	3.53	Green
A2	1.6		2.00	1.45	3.99	Green
A3	3.8		1.93	1.43	10.11	900 °C
A4	4.2		1.92	1.44	11.08	900 °C
A5	5.8		1.93	1.43	15.44	1100 °C
A6	5.6		1.91	1.42	15.27	1100 °C
Samples						
B						
B1	2.1	7cm	1.84	1.48	5.47	Green
B2	2.3		1.73	1.51	6.12	Green
B3	5.2		1.79	1.47	14.11	900 C
B4	5.4		1.90	1.49	13.43	900 C
B5	5.9		1.82	1.45	16.19	1100 C
B6	5.7		1.85	1.47	14.98	1100 C
Samples						
C						
C1	0.9	7cm	2.03	1.43	2.28	Green
C2	0.6	2.02	1.46	1.46	Green	0
C3	1.5	1.94	1.41	4.09	900	C ⁰
C4	1.7	1.93	1.42	4.58	900	C ⁰
C5	2.0	1.92	1.41	5.50	1100 0	C
C6	2.1	1.93	1.43	5.59	1100 C	

4.2 CALCULATION OF APPARENT POROSITY

For sample A (Nsu-Clay)

Table 4.3: Weights of Specimens of Sample A (Nsu-Clay) at various conditions.

Samples No	Soaked Weight M_2 (g)	Dried Weight M_1 (g)	Suspended Weight M_3 (g)	Temp °C
A1	102.76	77.41	51.38	Green
A 2	103.12	78.78	51.56	Green
A 3	87.51	69.67	43.79	900 ⁰ C
A 4	92.86	74.13	46.43	900 ⁰ C
A5	88.68	72.47	44.34	1100 ⁰ C
A 6	85.56	69.85	42.78	1100 ⁰ C
Applying equation 3.8				

$$\text{Apparent Porosity (\%)} = \frac{100(m_2 - m_1)}{M_2 - m_3}$$

For A1

$$\text{Apparent Porosity (5)} = \frac{100 (102.76 - 77.41)}{102.76 - 51.38}$$

$$= \frac{100 (25.35)}{51.38} = 49.33\%$$

For A2

$$\text{Apparent Porosity (\%)} = \frac{100 (103.12 - 78.78)}{103.12 - 51.56}$$

$$= 100 \left[\frac{24.34}{51.56} \right] = 47.21\%$$

Average value of apparent porosity of sample A for the green state

$$= \frac{A1 + A2}{2} \left[\frac{49.33 + 47.21}{2} \right]$$

$$= 48.27\%$$

Similarly the average values of apparent porosity for samples A3 and A4 (900⁰C), as well as samples A5 and A6 (1100⁰C) were calculated.

The same procedure was used to calculate the apparent porosity for sample -B (Ohiya Clay) and sample -C) Awo - Omamma Clay).

Table 4.4: Results obtained for porosity density and water of absorption tests of the three clay samples.

Sample no weight (g) M ₂	Soaked (g) M ₁	Dried Weight (g) M ₃	Suspended Weight (%)	Apparent Porosity n (%)	Water of Absorption Density (g/cm)	Apparent (g/cm ₃)	Bulk Density	Temp (C)
Sample A								
A1	102.76	77.41	51.38	49.33	32.75	2.97	1.51	Green
A2	103.12	78.78	51.56	47.21	30.90	2.89	1.53	Green
A3	87.51	69.67	43.79	40.29	25.25	2.68	1.60	900 C
A4	92.86	74.13	46.43	40.34	25.27	2.68	1.59	900 C
A5	88.68	72.47	44.34	36.55	22.37	2.58	1.63	1100 C
A6	85.56	69.85	42.78	36.72	22.49	2.58	1.63	1100 C
Sample B								
B1	91.63	67.73	41.82	48.00	35.29	2.61	1.35	Green
B2	89.44	64.96	40.72	50.24	27.22	2.67	1.33	Green
B3	78.01	61.32	39.01	42.79	27.22	2.75	1.57	900 C
B4	76.12	59.94	38.06	42.51	26.99	2.74	1.57	900 C
B5	74.13	58.32	37.07	42.64	27.11	2.74	1.57	1100 C
B6	76.05	60.26	33.03	36.70	26.31	2.21	1.82	1100 C
Sample C								
C1	90.13	67.23	45.07	50.81	34.06	3.03	1.49	Green
C2	92.44	68.98	46.22	50.76	34.45	3.03	1.49	Green
C3	82.19	64.02	41.09	44.21	28.37	2.31	1.56	900 C
C4	86.70	67.68	43.35	46.18	28.10	2.78	1.56	900 C
C5	78.89	63.12	39.45	39.97	24.98	2.67	1.60	1100 C
C6	80.56	65.51	40.28	37.36	22.97	2.60	1.63	1100 C

4.3 CALCULATION OF LINERA SHRINKAGE

FOR SAMPLE – A (NSU CLAY)

Table 4.5: Dried and fired length readings for samples A.

Sample No Length L ₀ (cm)	Original length L _d (cm)	Dried Length L (cm) _f	Fired	Temp C
A1	5.00	4.78		Green
A 2	5.00	4.77		Green
A 3	5.00	4.79	4.60	900 ⁰ C
A 4	5.00	4.76	4.62	900 ⁰ C
A5	5.00	4.77	4.58	1100 ⁰ C
A 6	5.00	4.78	4.57	1100 ⁰ C

Applying equation 3.6

Total shrinkage %

$$= \frac{100 (L_0 - L)_f}{L_0}$$

For A3, Total shrinkage % =

$$\frac{100 (5.0 - 4.60)}{5.00} = \frac{(0.4)100}{5.0} = 8.0 \%$$

For A4, Total shrinkage (%)

$$= 100 \left[\frac{5.0 - 4.62}{5.0} \right]$$

$$= 100 \left[\frac{0.38}{5.0} \right]$$

$$= 7.6\%$$

Average value of total shrinkage for samples A3 and A4 (900°C)

$$= (8.0 + 7.6) / 2 \%$$

Similarly, average value of total shrinkage for samples A5 and

A6 (1100°C) were also calculated. The same procedure was used to calculate the total shrinkage values for samples - B (Ohiya Clay and simply -C (Awo Omamma Clay) at 900°C and 1100°C.

Table 4.6: Shows the summary of shrinkage results for the three clay samples at various temperatures, while table 4.7 shows the summary of results for modulus of plasticity and making moisture for the three clay samples.

Table 4.6: Summary of Shrinkage results for the three clay samples at various temperatures.

Sample No	Original Length (cm)	Dried Length (cm)	Fired Length (cm)	Wet -Dry Shrinkage (%)	Dry- Fired Shrinkage (%)	Total Shrinkage (%)	Temperature (°C)
Samples A							
A1	5	4.78	-	4.4	-	4.4	Green
A2	5	4.77	-	4.6	-	4.6	Green
A3	5	4.79	4.60	4.2	3.97	8.0	900 °C
A4	5	4.76	4.62	4.8	2.94	7.6	900 °C
A5	5	4.77	4.58	4.6	3.98	8.4	1100 °C
A6	5	4.78	4.57	4.4	4.39	8.6	1100 °C
Samples B							
B1	5	4.74	-	5.2	-	5.2	Green
B2	5	4.69	-	6.2	-	6.2	Green
B3	5	4.72	4.54	5.6	3.80	9.2	900 °C
B4	5	4.73	4.55	5.4	3.81	9.0	900 °C
B5	5	4.69	4.51	6.2	3.84	9.8	1100 °C
B6	5	4.70	4.53	6.0	3.62	9.4	1100 °C
Samples C							
C1	5	4.62	-	7.6	-	7.6	Green
C2	5	4.65	-	7.0	-	7.0	Green
C3	5	4.68	4.44	6.4	5.13	11.2	900 °C
C4	5	4.63	4.50	6.4	2.81	10.0	900 °C
C5	5	4.64	4.42	7.2	4.74	11.6	1100 °C
C6	5	4.65	4.41	7.0	5.16	11.8	1100 °C

Sample No	Original Height (cm)	Deformation Height (cm)	Modulus of Plasticity	Wet Weight (g)	Dry Weight (g)	Making Moisture (%)
Sample A						
A1	4.50	3.28	1.37	61.64	45.18	26.70
A2	4.50	3.27	1.38	61.76	45.61	26.16
Sample B						
B1	4.50	3.12	1.44	58.95	40.88	30.65
B2	4.50	3.27	1.38	60.18	41.58	30.91
Sample C						
C1	4.50	3.54	1.27	60.32	43.65	27.64
C2	4.50	3.35	1.34	62.55	45.09	27.91

Table 4.7: Summary of results for Modulus of Plasticity and making moisture for the three clay samples.

4.4. CHEMICAL ANALYSIS

The results of the chemical analysis of the three clay samples are given in table 4.8 while table 4.9 shows the summary of the thermo-physical analysis of the three clay samples.

Table 4.8: Chemical Analysis of the Three Clay samples

Adapted from Keke¹ (2007), Mark² (2007); Done at N.R.C R. I³

COMPOSITION	WEIGHT PERCENT		
	Sample A NSU ¹	Samples B Ohiya ²	Samples C Awo-Omamma ³
SiO ₂	46.01	48.23	50.42
Al ₂ O ₃	31.32	29.45	26.01
TiO ₂	0.34	-	0.23
Fe ₂ O ₃	4.78	3.58	5.68
MnO	2.66	-	-
MgO	1.45	1.49	0.96
CaO	-	0.22	-
Na ₂ O	0.98	0.29	1.53
K ₂ O	0.61	2.56	0.49
H ₂ O (ignition Loss at 1000 ⁰ C	10.82	13.40	14.68

Table 4.9: Summary of the Thermo-Physical analysis of the three clay samples.

Parameter/ Sample	A=Nsu Clay			B= Ohia Clay			C=Awo-Omamma Clay		
	Green 100°C	900 °C	1100 °C	Green 100°C	900 °C	1100 °C	Green 100°C	900 °C	1100 °C
Temperature (0C)	Green 100°C	900 °C	1100 °C	Green 100°C	900 °C	1100 °C	Green 100°C	900 °C	1100 °C
Wet-Dry Shrinkage (%)	4.5	4.5	4.5	5.7	5.5	6.1	7.3	6.9	7.1
Dry-Fired Shrinkage (%)	-	3.46	4.19	-	3.81	3.73	-	3.97	4.95
Total Shrinkage (%)	4.5	7.8	8.5	5.7	9.1	9.6	7.3	10.6	11.7
Apparent Porosity (%)	48.27	40.32	36.64	49.12	42.65	39.67	50.79	45.20	38.67
Apparent Density (g/cm ³)	2.93	2.68	2.58	2.64	2.75	2.48	3.03	2.55	2.64
Bulk Density (g/cm ³)	1.52	1.60	1.63	1.34	1.57	1.60	1.49	1.56	1.62
Water of Absorption (%)	31.83	25.26	22.43	31.26	27.11	26.71	35.76	28.10	23.97
Modulus of Rupture (Kg/Cm ²) N/mm ² (Mpa)	3.76 0.369	10.6 1.04	15.36 1.51	5.8 0.569	13.77 1.35	15.58 1.53	1.87 0.183	4.34 0.426	5.55 0.544
Modulus Plasticity	1.375			1.41			1.304		
Making Moisture (%)	26.425			30.78			27.775		

4.5 PARTICLE SIZE ANALYSIS.

Figures 4.1, 4.2 and 4.3 show the particle size results of the three clay samples respectively.

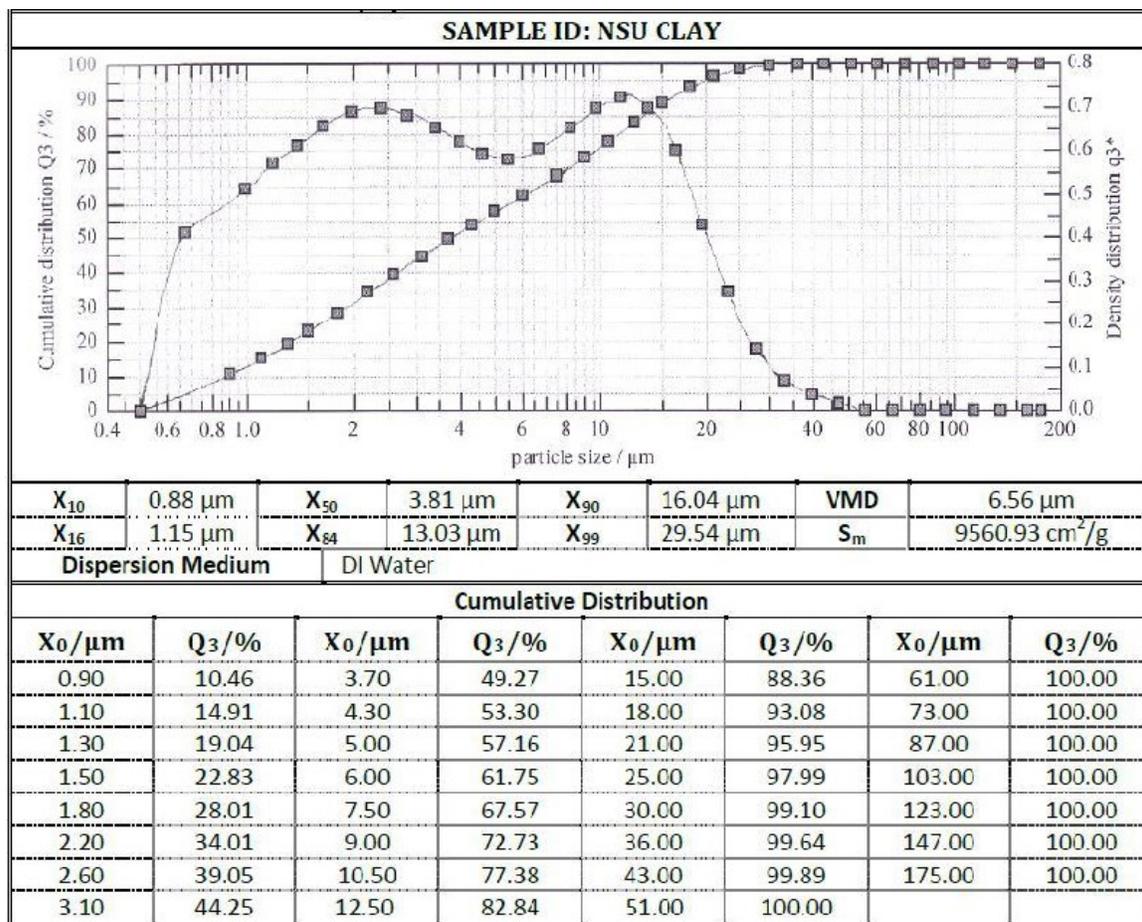


Figure 4.1 Particle size analysis of samples A (Nsu Clay)

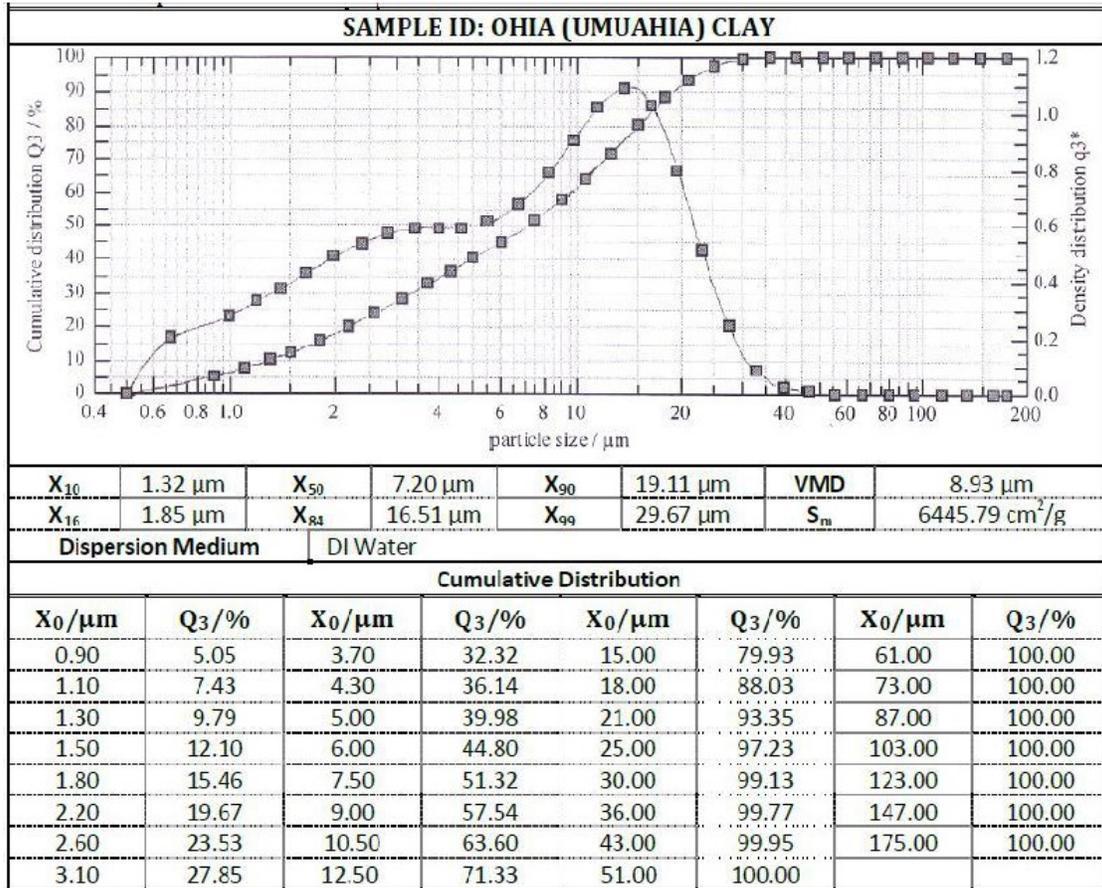


Figure 4.2 particle size analysis of samples B. (Ohiya clay)

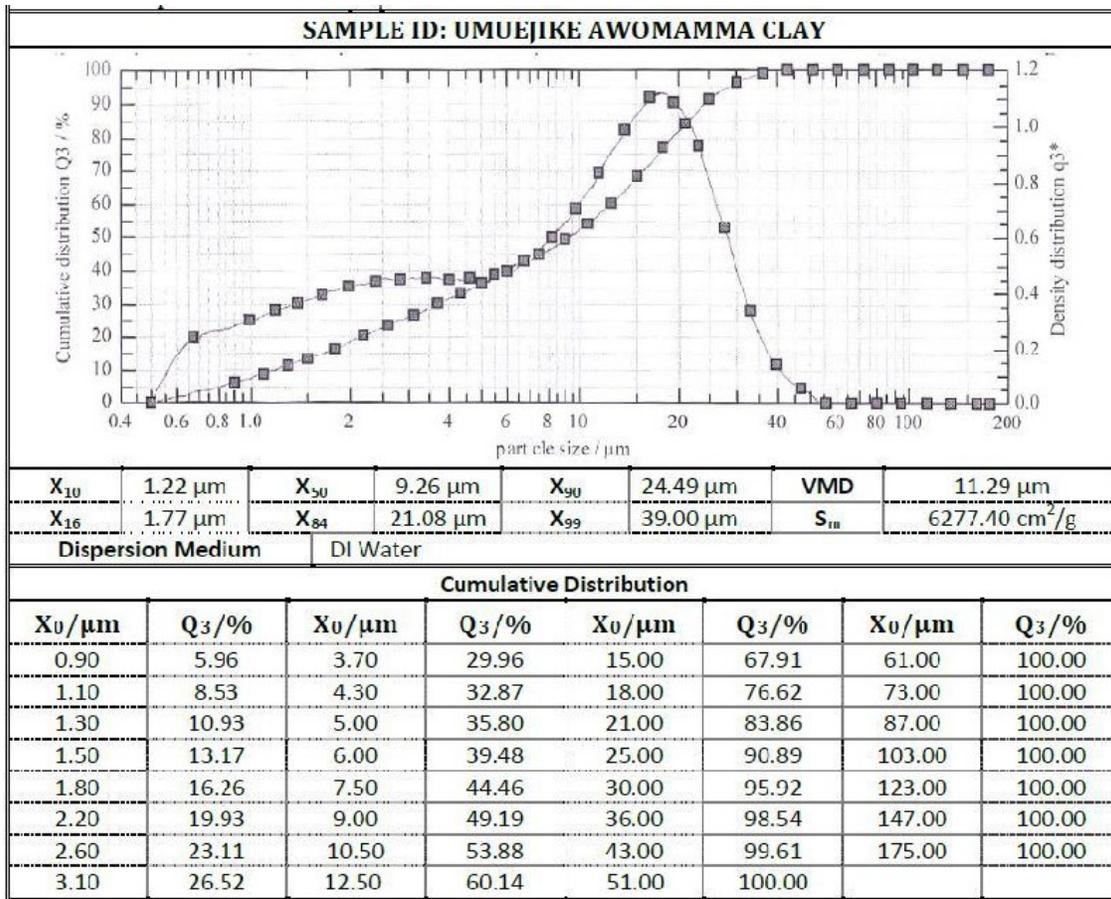


Figure 4.3 particles size analysis of sample- C (Awo - Omamma Clay)

From the particle size results of the three clay samples, it can be observed that Awo-Omamma Clay contains a high proportion of the larger sized particles (21 μm -51 μm), compared to Nsu clay and Ohiya clay, (Awo -Omamma - 16.14%; Nsu - 4.05%, Ohiya - 6.65%). Also the volume mean diameter (VMD) of Awo-Omamma clay is much

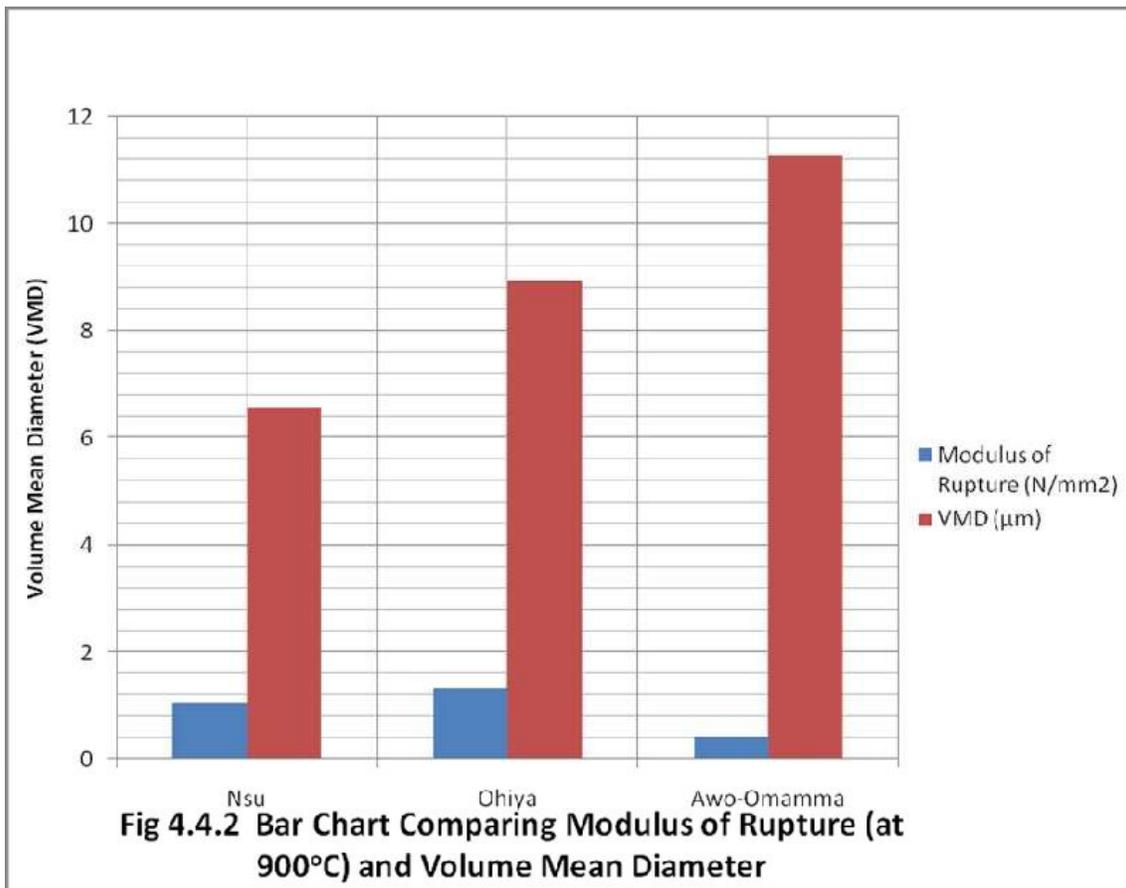
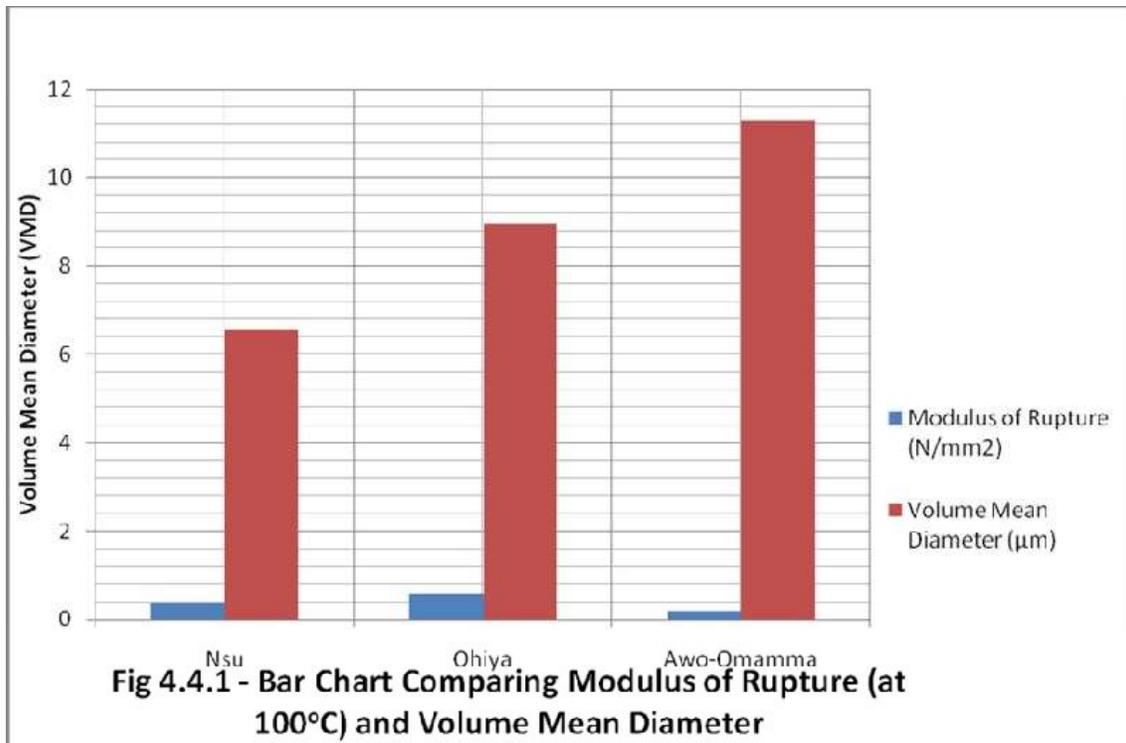
higher than that of Nsu clay and Ohiya clay, (Awo-Omamma - 11.29 μm ; Nsu - 6.56 μm ; Ohiya - 8.93 μm).

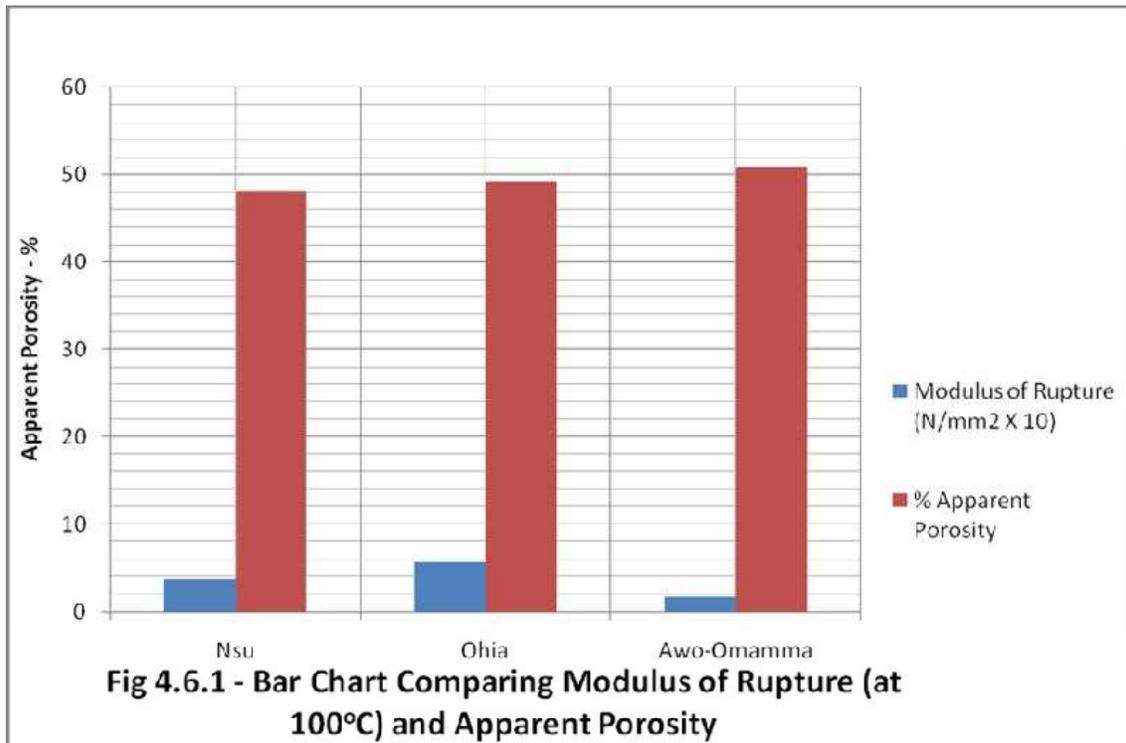
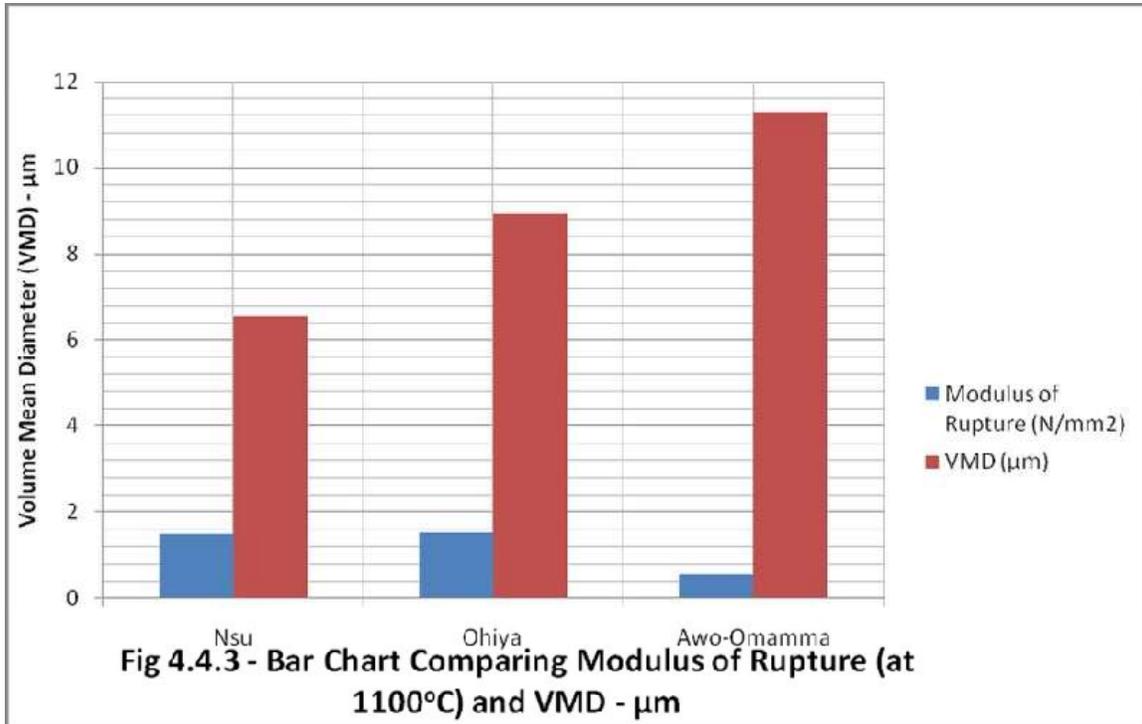
This resulted in a much lower value of modulus of rupture for Awo-Omamma clay, possibly due to the particle packing effect as reported by Correia et al (2002). This particle packing effect becomes more obvious when you compare X_{50} , X_{84} and X_{99} values for the three clay samples.

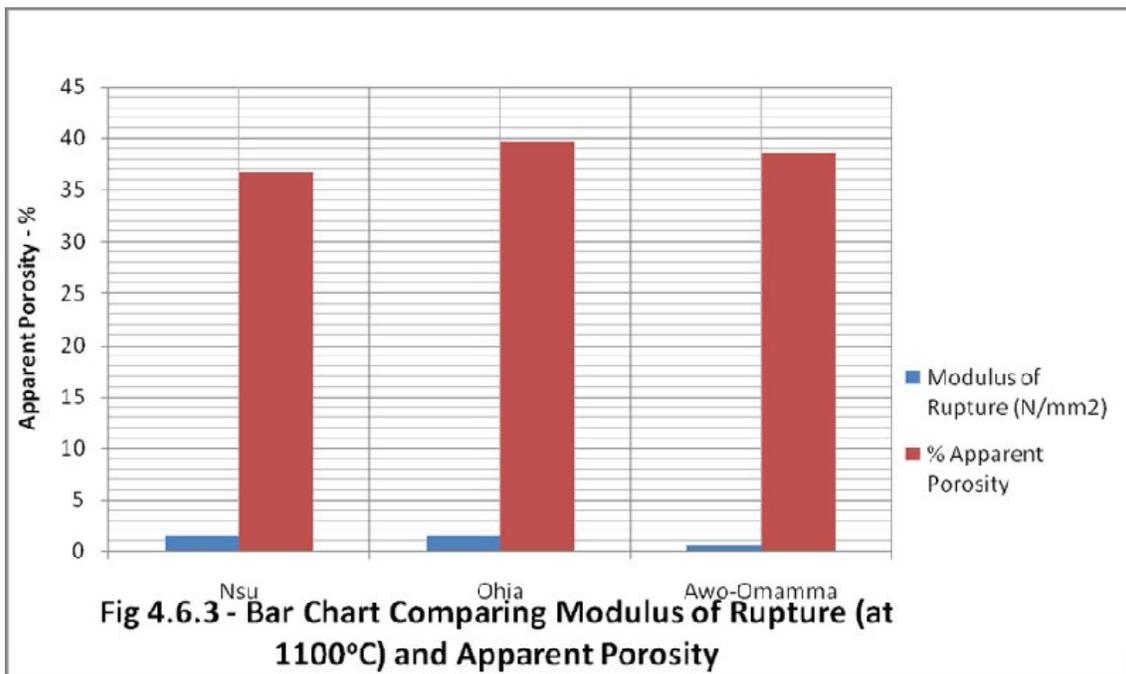
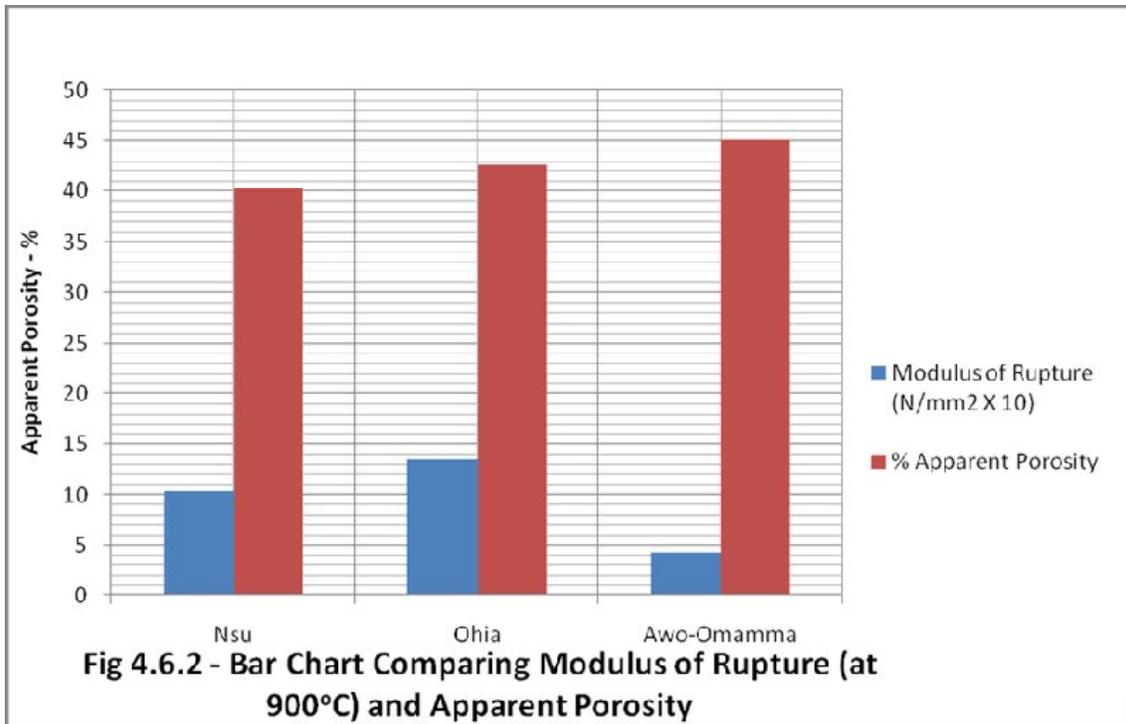
It can also be observed that Ohiya clay has a slightly higher modulus of rupture than Nsu clay at green conditions and at 900⁰C. This can be attributed to the slightly higher proportions of medium sized particles, (3.70mm-12.50mm). Ohiya Clay contains 39.01% of this particle size range while Nsu clay and Awo-Omama clay contain 33.57% and 30.18% respectively. Differences in the vitrification temperature of the clay samples will also need to be taken into account. Nsu clay appear to have a higher vitrification temperature than Ohiya clay and this led to the increase of the modulus of rupture of Nsu clay at higher sintering temperatures.

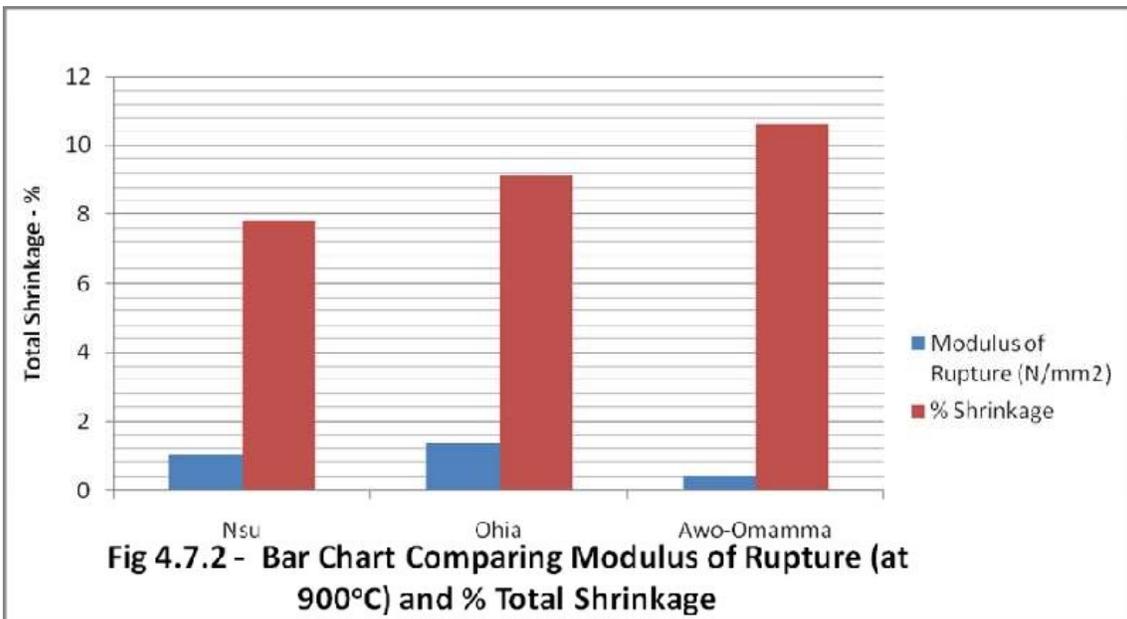
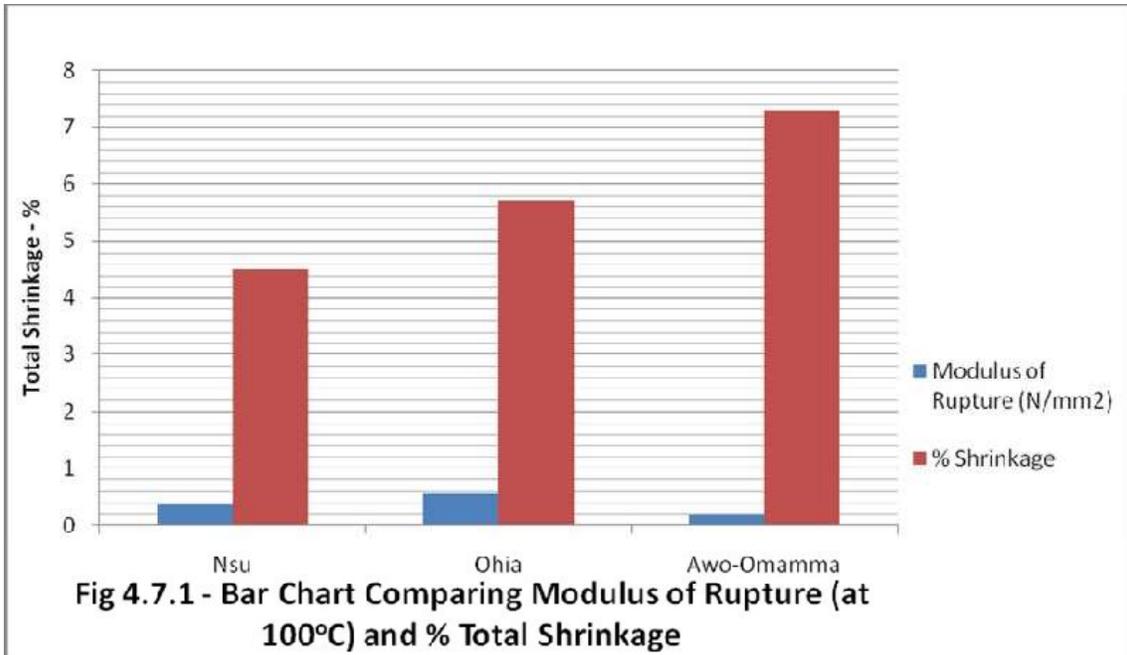
It can also be observed that a linear relationship exist between shrinkage and modulus of rupture as suggested by Correa et al (2002). Also it can be observed that the proportion of the various particles size ranges has a marked effect on the modulus of rupture. It is detrimental to have a high concentration of a particular size range, at the expense of other particle size ranges. However a nearly even distribution could be beneficial as reported by Ritwik Sarkar (2011).

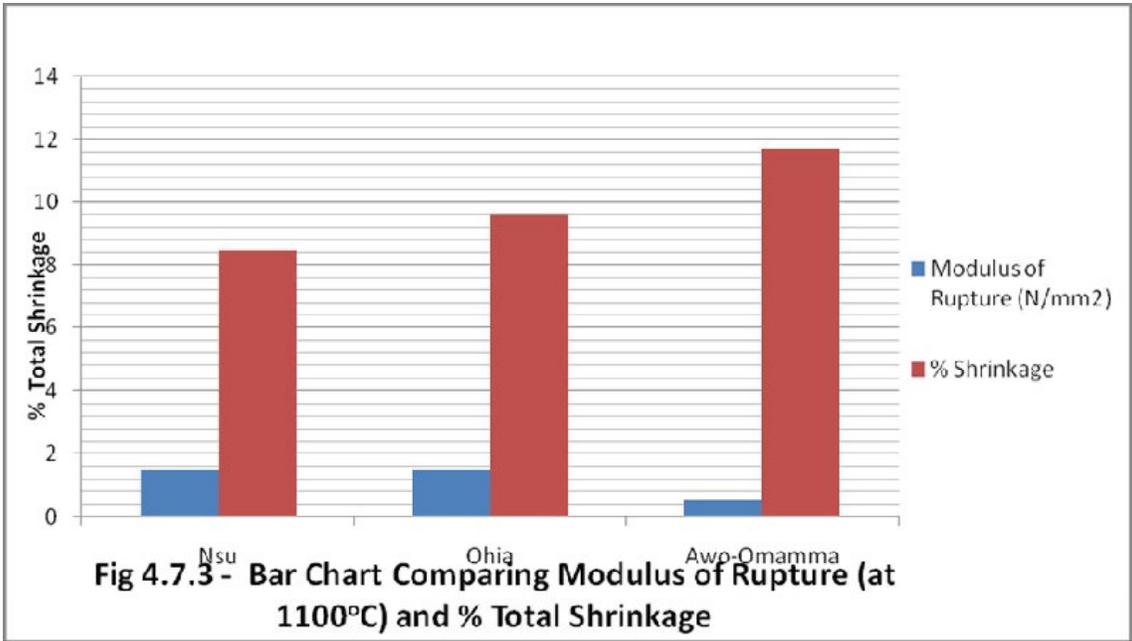
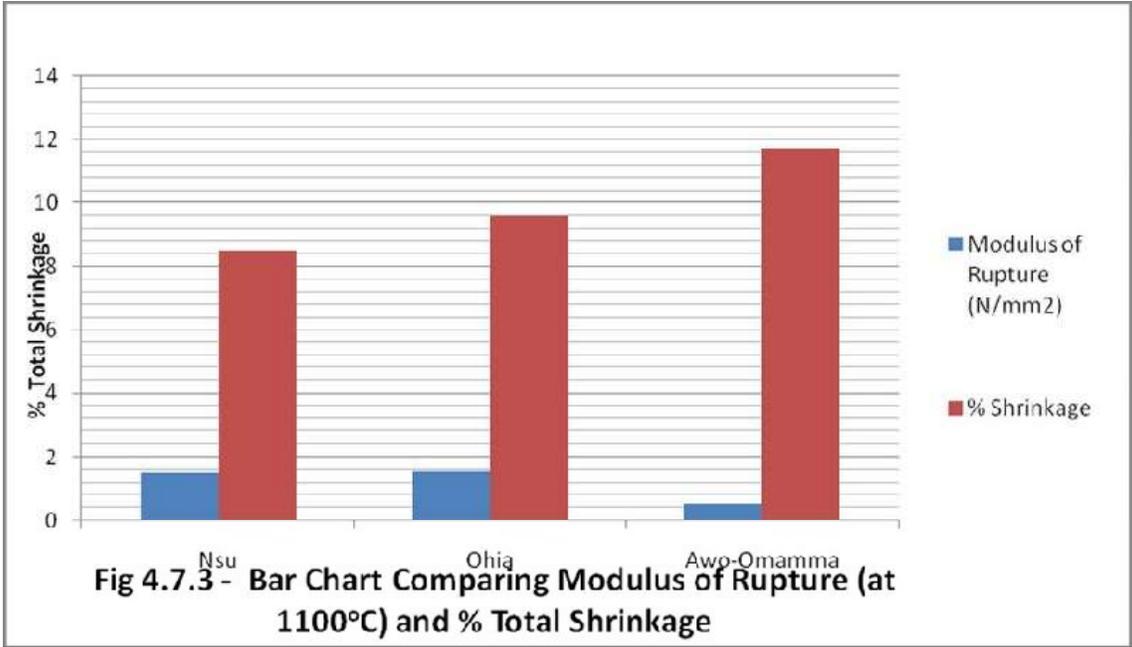
The thermo-physical behaviour of Ohiya clay and Nsu clay were also in good agreement with results obtained by Mark (2007) and Chukwudi (2008), as bulk density increased with firing temperature, due to closure of internal pores. However, because of the incorporation of some inert additives (grog) in their clay slip and also the application of molding/extrusion pressure, the shrinkage and porosity values obtained in their work do not compare well with the results obtained in this work.

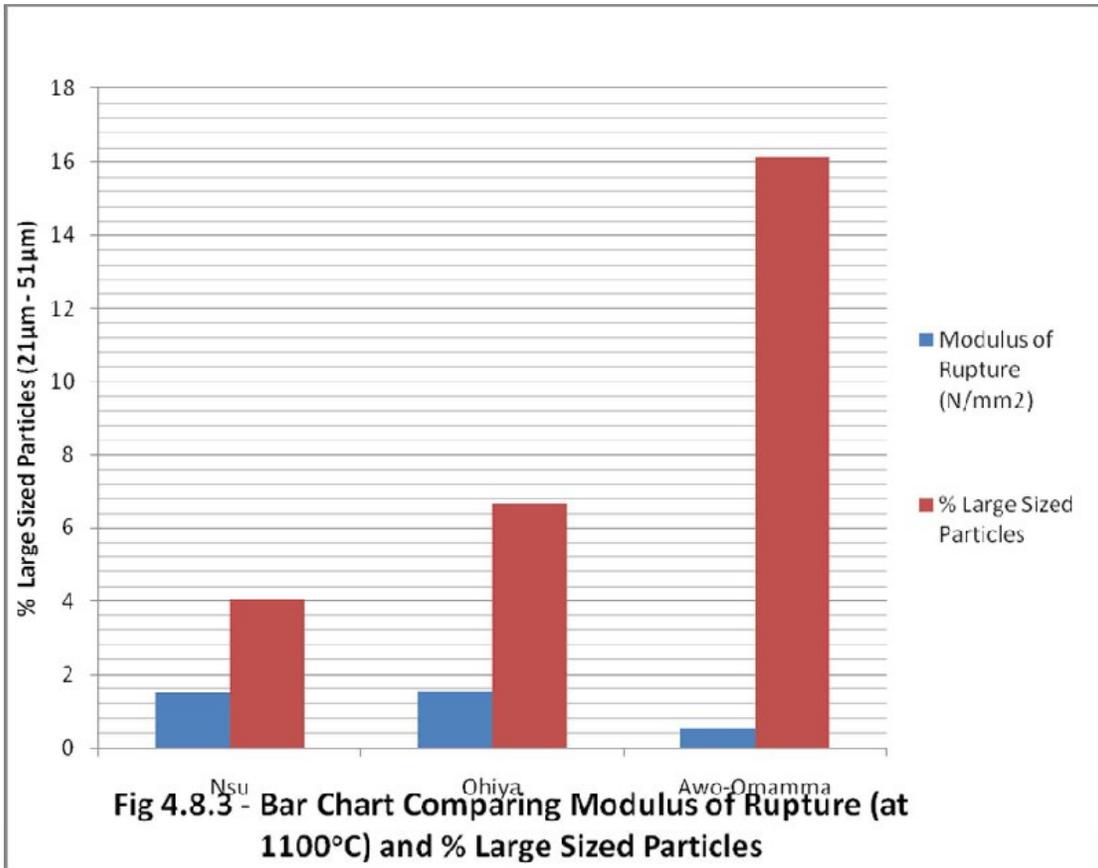
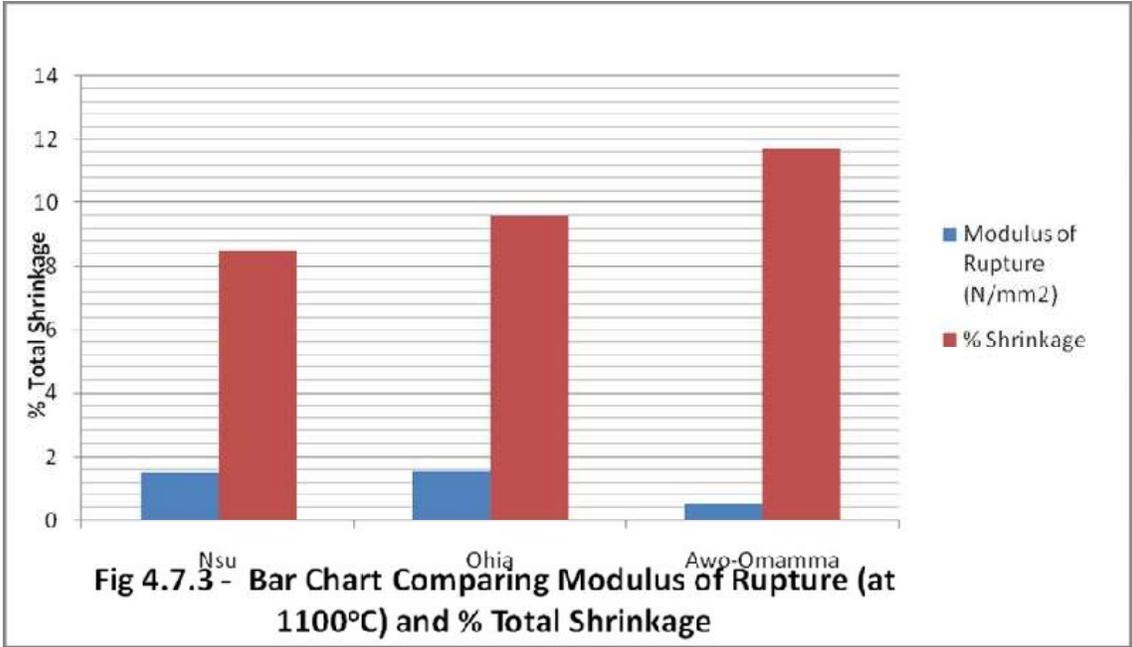


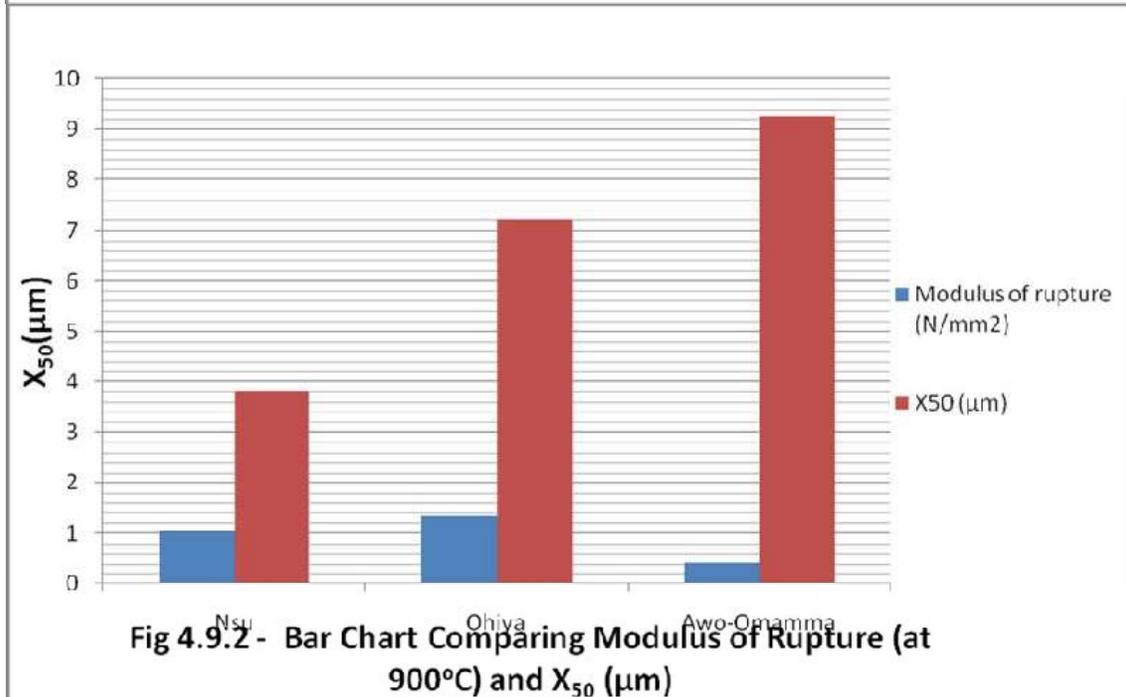
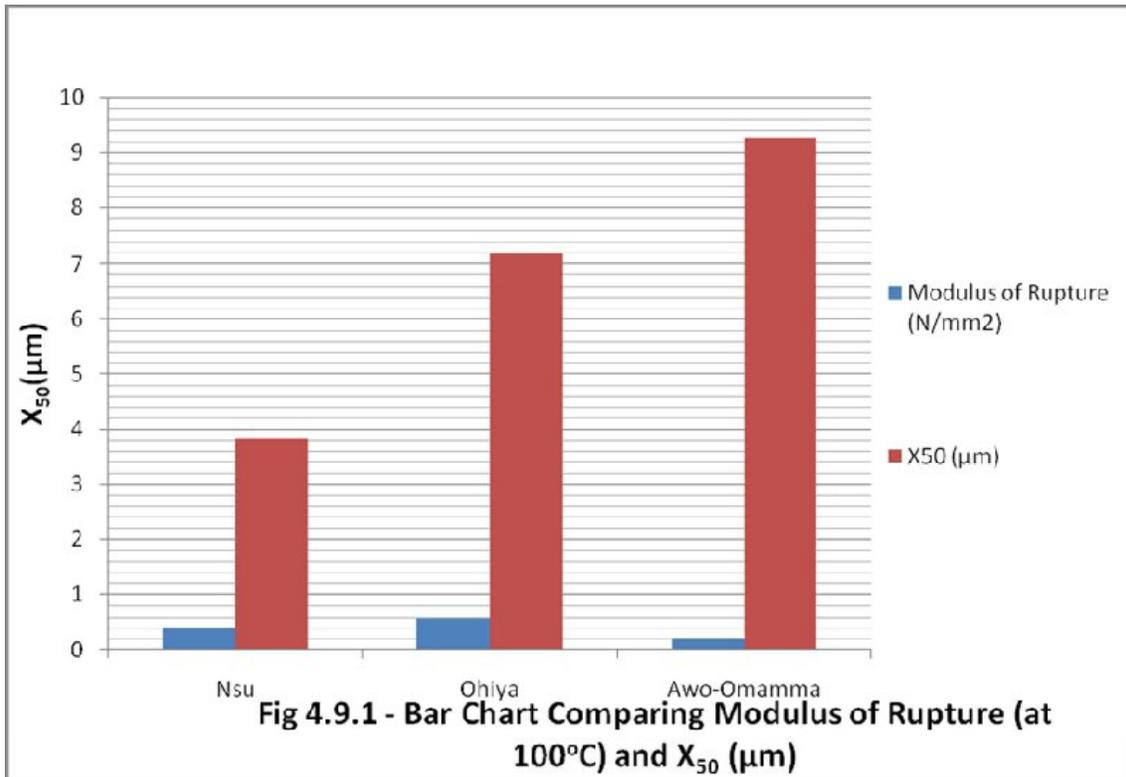


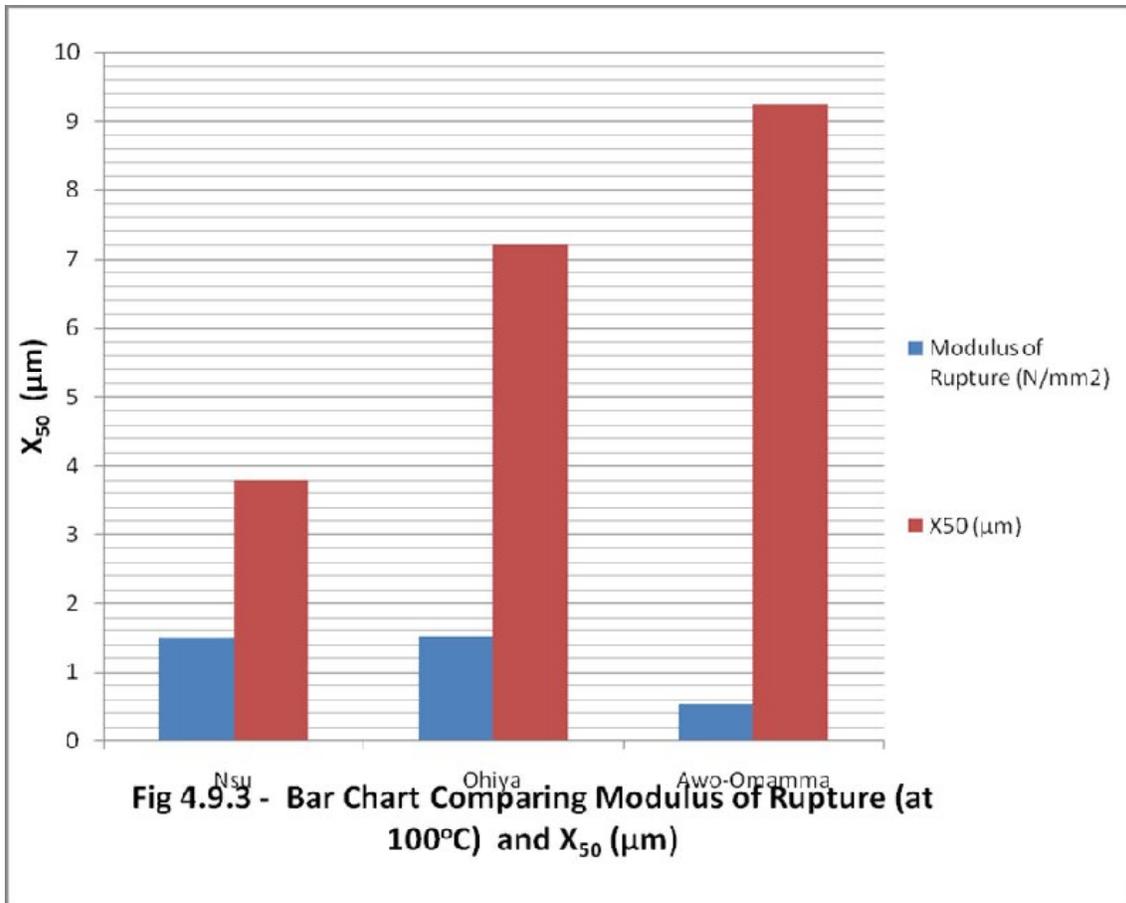


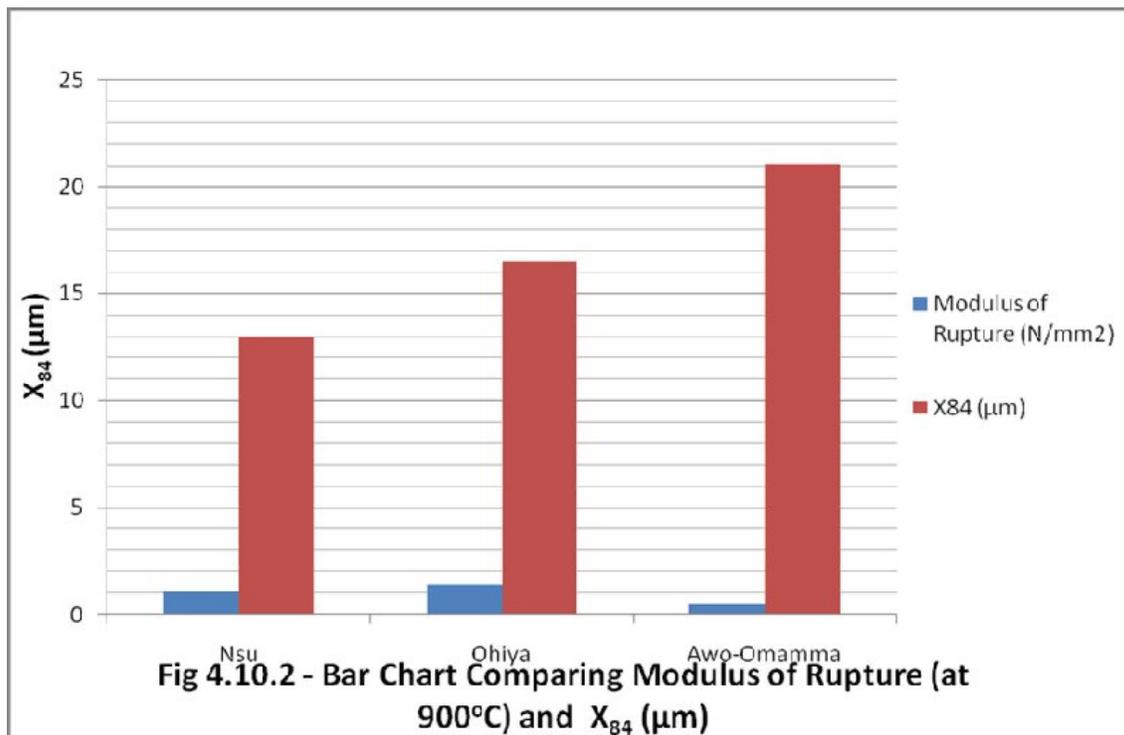
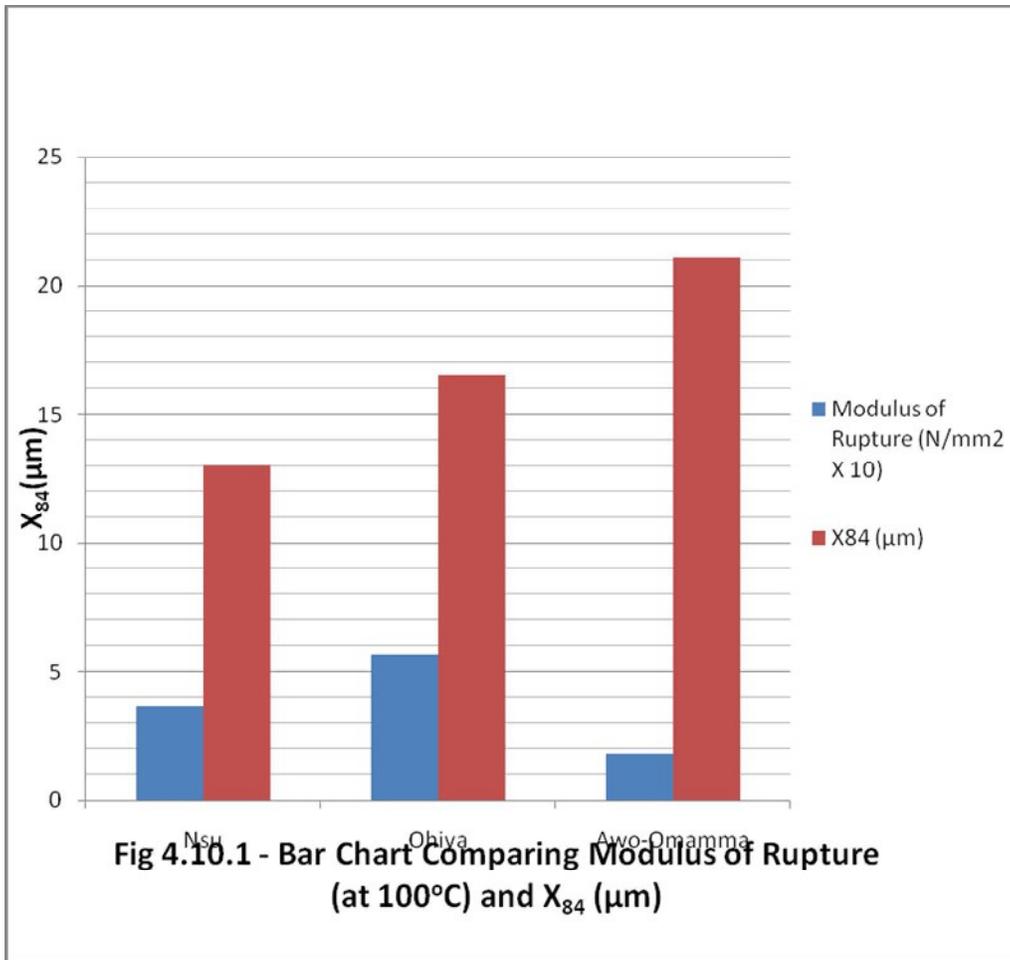


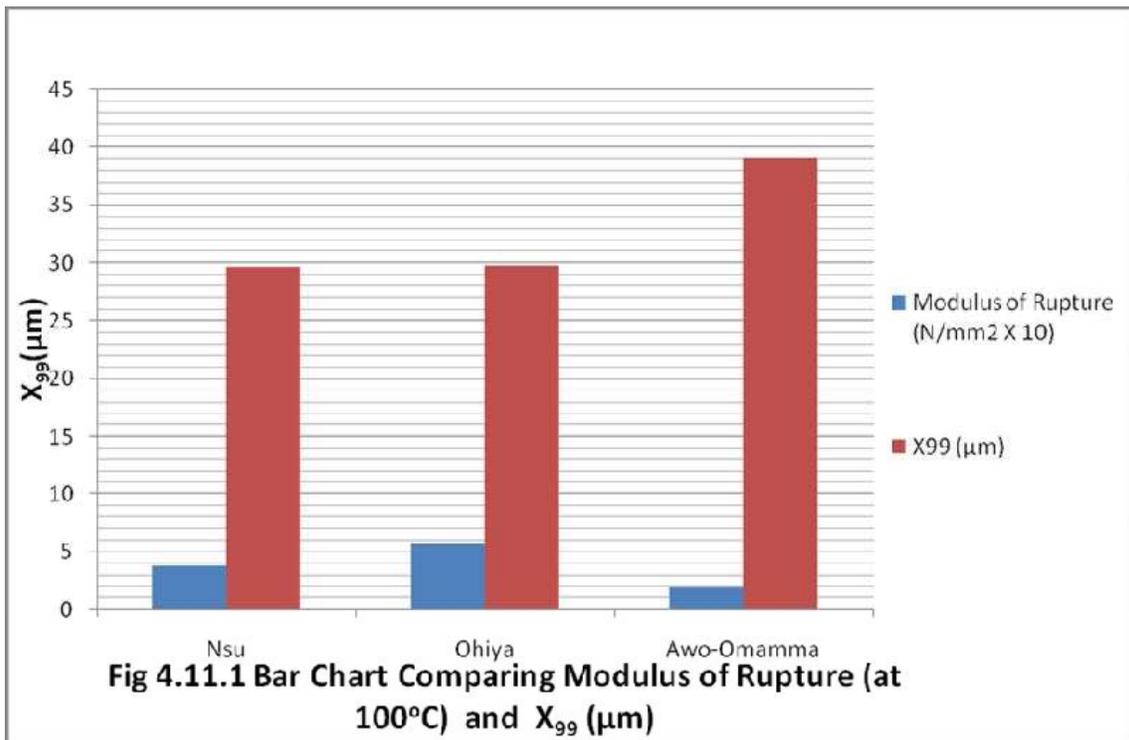
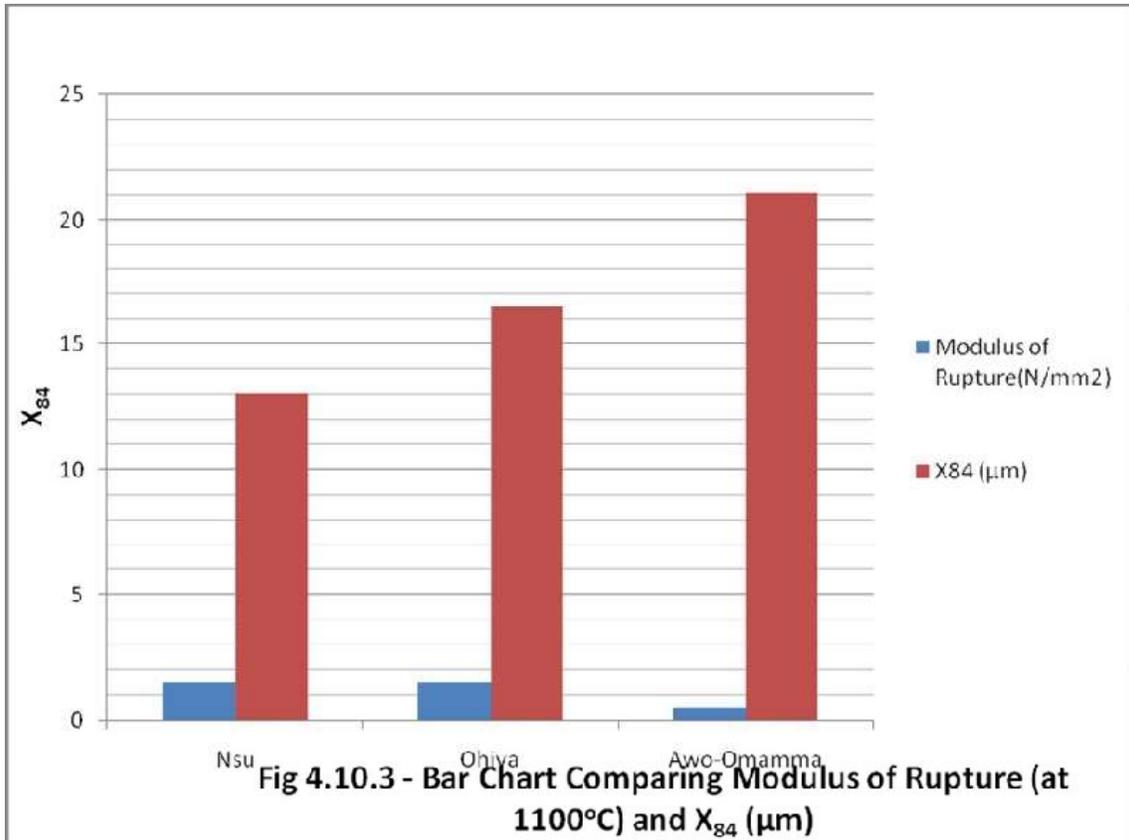


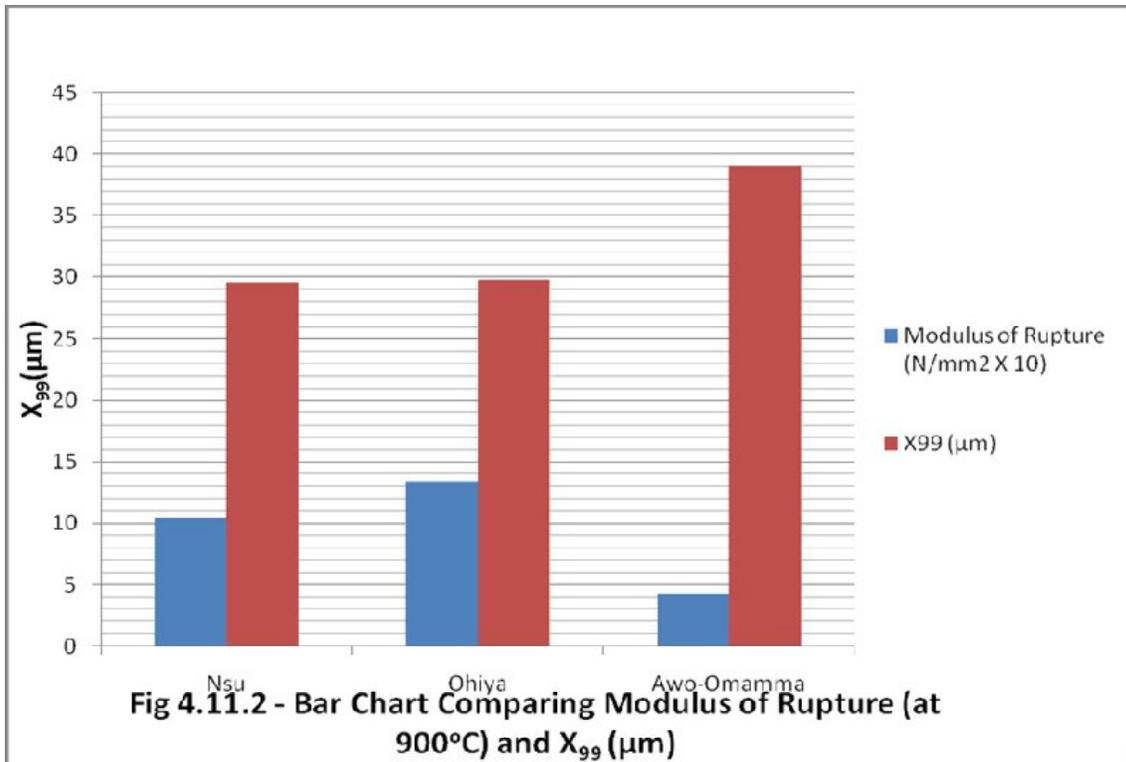


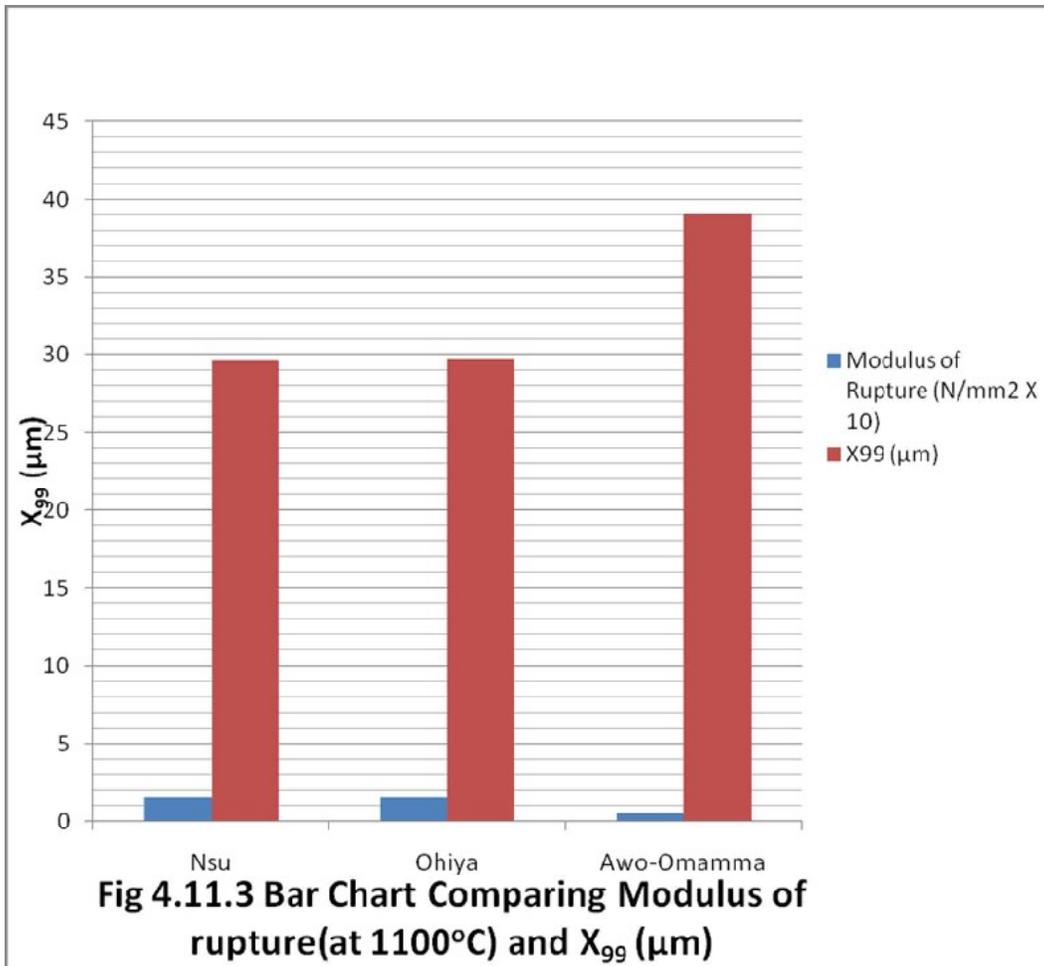












CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY

From the results obtained in this research work, it can be seen that different clay deposits will have different particles sizes and size distributions. These differences could be as a result of variations in the compositions of the parent rocks and the weathering mechanisms.

The particle size distributions of a clay mineral will have a marked influence, not only on the mechanical behaviour of that clay, (as indicated by the modulus of rupture), but also on the thermo-physical behaviour such as porosity and shrinkage.

5.2 CONCLUSION

From careful observations, results and analysis of the data generated in this research work, it can be concluded that contribution to knowledge has been made as follows:

1. Nsu clay and Ohiya clay have high modulus of rupture in both the dry and fired conditions.
2. The three clay samples have a volume mean diameter (VMD) of 6.56 μm ; 8.93 μm and 11.29 μm for Nsu clay, Ohiya clay and Awo-Omamma clay respectively.
3. The volume mean diameter of 11.29 μm for Awo-Omamma clay indicates that it contains a high proportion of large sized particles.
4. High content of the larger sized particles, in the range of 21 μm -51 μm will lower the modulus of rupture of the clay due to poor particle packing.

The poor mechanical behaviour of Awo-Omamma Clay, as indicated by the low modulus of rupture and high shrinkage can be attributed to this factor.

5.3 RECOMMENDATIONS

From the findings made in this research work, it is recommended that Nsu Clay and Ohiya Clay are very suitable for the production of ceramic wares because of their relatively high modulus of rupture and moderate shrinkage. The modulus

of rupture of the two clays fall within the 0.5 N/mm² to 50 N/mm² range given in literature for commercial clays. Awo-Omamma Clay will require further beneficiation processing and possibly blending with other clays.

Further research is required to ascertain the optimum proportion of particle sizes that will produce the best mechanical behaviour.

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APPENDIX



Plate 1: **The Electric Transversal Strength Machine. (ESTM)**

This is a machine used in testing for the breaking load, and consequently the modulus of rupture of a

particular clay sample. The picture is as shown in fig 1.2. Rectangular test pieces are made from the clay sample. Then, after drying and also firing the testpieces to different temperatures, they are subjected to a breaking-load test in the ETSM. The working principle is as follows:

The testpiece is made to lie horizontally and perpendicularly on a wooden rod which is made to hang on a weighing balance attached to a stringed lever system, and lying in-between two parallel metal bars fixed at a set distance between each other. When the machine is plugged into the electrical system, and switched on, the pulley system on the string begins to pull it up. Thus, the testpiece lying on the wooden bar starts to move up until it encounters the two parallel and fixed metal bars, which tends to keep the testpiece on the wooden bar static. As a result of the opposing forces of the wooden rod which is till trying to push up in response to the pulley system, and the two static metal bars which tend to impede the motion of the testpiece and the wooden bar, a stress is introduced on the testpiece, and the pointer on the weighing scale attached to the string begins to read. This stress increases on the testpiece, and the pointer continues to move over the face of the weighing scale until the testpiece breaks.

The point at which the testpiece broke is known as its 'breaking load (in kg)' and is useful in determining the 'modulus of rupture' of a clay material as will be shown later.



Plate 2: **Fulham Pottery laboratory Kiln**



Plate 3: **Samples in Green State**



Plate 4: **Sample Preparation**



Plate 5: **Marking of the Sample**



PLATE 6. HELOS – Sympatec Particle Size Analyser



Plate 7: **The Metallic Moulds**

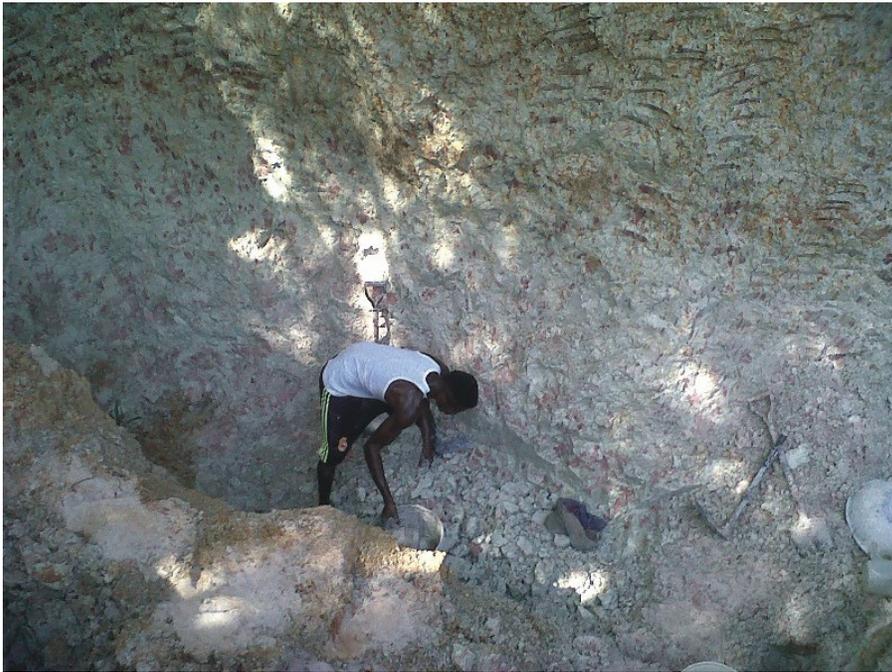


Plate 8: **Mining of Clay at Nsu**



Plate 9: **Mining of Clay at Ohiya-Umuahia**



Plate 10: **Mining of Clay at Awo-Omamma**

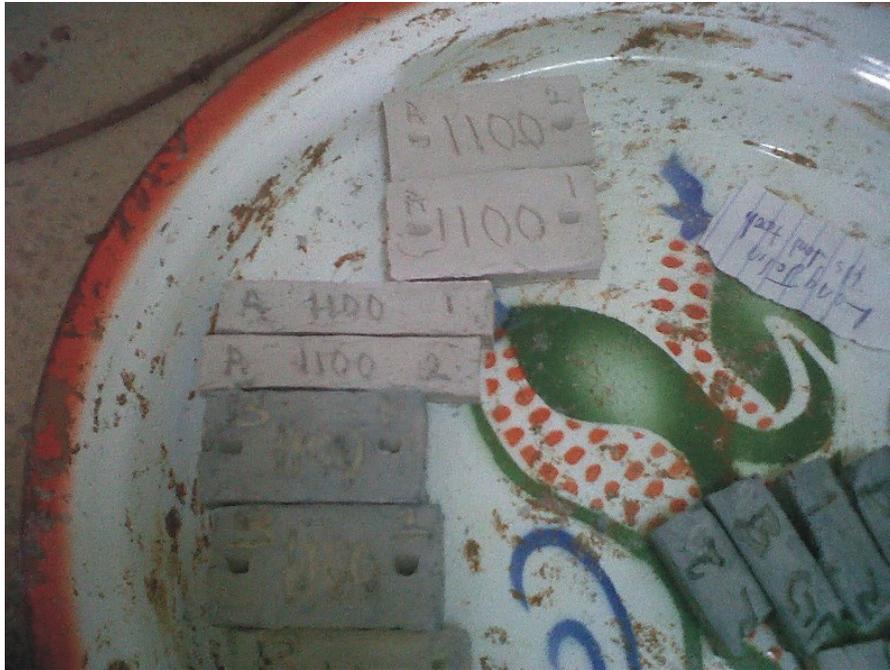


Plate 11: **Dried Samples**



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 35, Pragati Industrial Estate, Ground Floor,
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 Tel : 23087921, 23087923, 23092347, 23091938
 Fax : 23080197

TEST REPORT

Report No: AU/5823 Page 1 Date: 17.06.2013

To,
Department of Materials & Metallurgical Engg.
 Nigeria.

Test: Particle Size analysis By Laser Diffraction (By Wet Suspension)

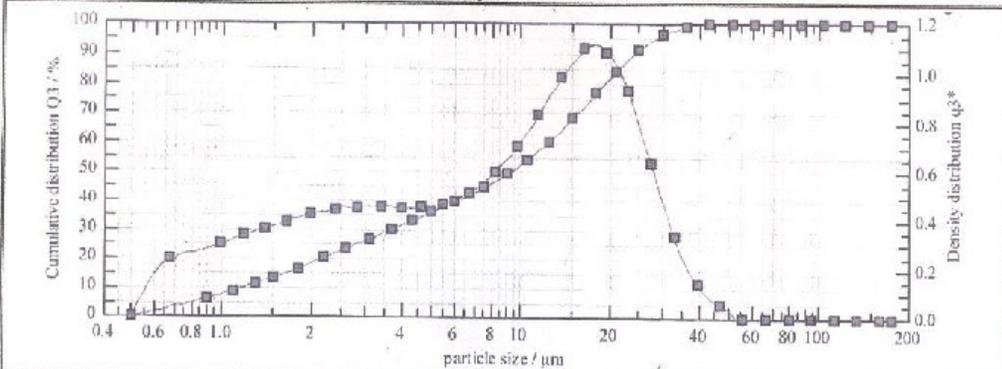
Instrument : Sympatec particle size analyser Model : HELOS

Party's Reference : Letter dated: 11.06.2013

Sample received on : 12.06.2013

Date of completion of test : 15.06.2013

SAMPLE ID: UMUEJIKE AWOMAMMA CLAY



X ₁₀	1.22 µm	X ₅₀	9.26 µm	X ₉₀	24.49 µm	VMD	11.29 µm
X ₁₆	1.77 µm	X ₈₄	21.08 µm	X ₉₉	39.00 µm	S _m	6277.40 cm ² /g
Dispersion Medium		DI Water					

Cumulative Distribution							
X ₀ /µm	Q ₃ /%	X ₀ /µm	Q ₃ /%	X ₀ /µm	Q ₃ /%	X ₀ /µm	Q ₃ /%
0.90	5.96	3.70	29.96	15.00	67.91	61.00	100.00
1.10	8.53	4.30	32.87	18.00	76.62	73.00	100.00
1.30	10.93	5.00	35.80	21.00	83.86	87.00	100.00
1.50	13.17	6.00	39.48	25.00	90.89	103.00	100.00
1.80	16.26	7.50	44.46	30.00	95.92	123.00	100.00
2.20	19.93	9.00	49.19	36.00	98.54	147.00	100.00
2.60	23.11	10.50	53.88	43.00	99.61	175.00	100.00
3.10	26.52	12.50	60.14	51.00	100.00		

CHECKED BY

 Checked by
 Signatory

Authorized

AVINASH TAMBRE NAGH
 (Lab in - Charge)

1. The results relate only to the sample tested. 2. Test certificate shall not be re-produced except in full without the written approval of laboratory. 3. TCR has made the best endeavors to provide accurate and reliable information. TCR is not responsible for any financial liability due to any act of omission or error made. 4. Samples are preserved for 15 days. Any ambiguity at last results should be brought forward to the lab management within this period.



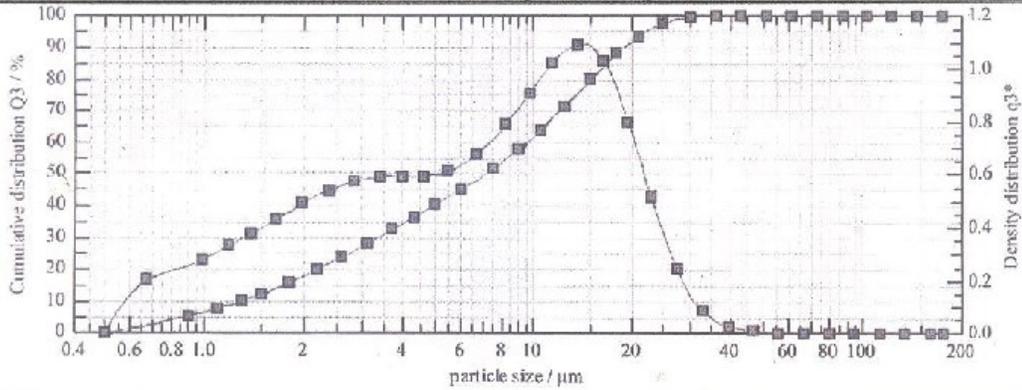
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 Tel : 23097921, 23097923, 23092347, 23091938
 Fax : 23080197

TEST REPORT		
Report No: AU/5822	Page 1	Date: 17.06.2013
To, Department of Materials & Metallurgical Engg. Nigeria.		
Test: Particle Size analysis By Laser Diffraction (By Wet Suspension)		
Instrument : Sympatec particle size analyser Model : HELOS		
Party's Reference	: Letter dated: 11.06.2013	
Sample received on	: 12.06.2013	
Date of completion of test	: 15.06.2013	

SAMPLE ID: OHIA (UMUAHIA) CLAY



X ₂₀	1.32 μm	X ₅₀	7.20 μm	X ₉₀	19.11 μm	VMD	8.93 μm
X ₁₅	1.85 μm	X ₈₄	16.51 μm	X ₉₉	29.67 μm	S _n	6445.79 cm ² /g

Dispersion Medium : DI Water

Cumulative Distribution

X ₀ /μm	Q ₃ /%						
0.90	5.05	3.70	32.32	15.00	79.93	61.00	100.00
1.10	7.43	4.30	36.14	18.00	88.03	73.00	100.00
1.30	9.79	5.00	39.98	21.00	93.35	87.00	100.00
1.50	12.10	6.00	44.80	25.00	97.23	103.00	100.00
1.80	15.46	7.50	51.32	30.00	99.13	123.00	100.00
2.20	19.67	9.00	57.54	36.00	99.77	147.00	100.00
2.60	23.53	10.50	63.60	43.00	99.95	175.00	100.00
3.10	27.85	12.50	71.33	51.00	100.00		

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 AVINASH KUMBEWAGH
 (Lab in - Charge)

1. The results relate only to the sample tested. 2. Test certificate shall not be re-produced except in full without the written approval of laboratory. 3. TCR has made their best endeavors to provide accurate and reliable information. TCR is not responsible for any financial liability due to any act of omission or error made. 4. Samples are preserved for 15 days. Any ambiguity in test results should be brought forward to the lab management within this period.



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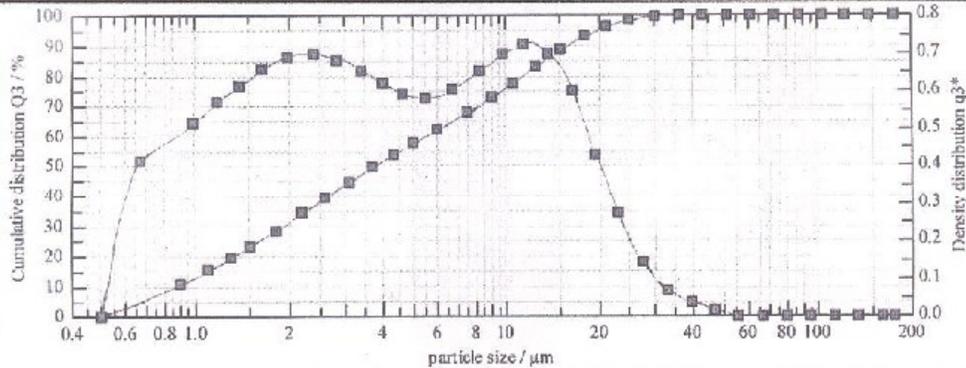
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 Fax : 23080197

TEST REPORT		
Report No: AU/5821	Page 1	Date: 17.06.2013
To, Department of Materials & Metallurgical Engg. Nigeria.		
Test: Particle Size analysis By Laser Diffraction (By Wet Suspension)		
Instrument : Sympatec particle size analyser Model : HELOS		
Party's Reference	:	Letter dated: 11.06.2013
Sample received on	:	12.06.2013
Date of completion of test	:	15.06.2013

SAMPLE ID: NSU CLAY



X_{10}	0.88 μm	X_{50}	3.81 μm	X_{90}	16.04 μm	VMD	6.56 μm
X_{36}	1.15 μm	X_{64}	13.03 μm	X_{99}	29.54 μm	S_m	9560.93 cm^2/g
Dispersion Medium		DI Water					

Cumulative Distribution

$X_0/\mu\text{m}$	$Q_3/\%$	$X_0/\mu\text{m}$	$Q_3/\%$	$X_0/\mu\text{m}$	$Q_3/\%$	$X_0/\mu\text{m}$	$Q_3/\%$
0.90	10.46	3.70	49.27	15.00	88.36	61.00	100.00
1.10	14.91	4.30	53.30	18.00	93.08	73.00	100.00
1.30	19.04	5.00	57.16	21.00	95.95	87.00	100.00
1.50	22.83	6.00	61.75	25.00	97.99	103.00	100.00
1.80	28.01	7.50	67.57	30.00	99.10	123.00	100.00
2.20	34.01	9.00	72.73	36.00	99.64	147.00	100.00
2.60	39.05	10.50	77.38	43.00	99.89	175.00	100.00
3.10	44.25	12.50	82.84	51.00	100.00		



Authorized
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DEFINITION OF TERMS AND SYMBOLS.

μm ----- micrometers(10^{-6} meters.).

mm ----- millimetres.

MoR ----- Modulus of Rupture.

DMoR ----- Dry Modulus of Rupture.

MoP-----Modulus of Plasticity.

d ----- Diameter of particle.

v ----- velocity of fall of particle in the fluid medium.

k ----- constant.

2-D ----- Two dimensional.

3-D ----- Three dimensional.

ρ_s ----- density of sphere.

ρ_f ----- density of fluid.

η ----- Viscosity of fluid.

g ----- Acceleration due to gravity.

x ----- Distance.

t ----- Time.

%w/w ----- weight percent.

f_s ----- Flexural strength.

P ----- Fracture load.

L ----- Length between outer support (support span).

B ----- Specimen width.

H ----- Height of specimen.

psi ----- pounds per square inch.

MPa ----- Mega paschal.

N/mm^2 . -----Newton per square millimetre.

K_y ----- strengthening coefficient.

σ_y ----- yield stress.

σ_0 -----resistance of lattice to dislocation movement.

Re----- Reynold's

number. (a dimensionless number that gives the ratio of inertial forces to viscous forces for a given flow condition).

Cumulative distribution (Q_3).-----Statistical

function that describes the probability that a random variable X with a given probability distribution will be found at a value less than or equal to x.

Density distribution (q_3).-----

Statistical function that describes the relative likelihood for a continuous random variable to take a given value.

LASER ----- (Light Amplification by Stimulated Emission of Radiation). A device that produces and amplifies light.

VMD.-----Volume Mean Diameter. (Relates to weight based comparison of particles).

S_m.-----Surface Area Mean. (Relates to the mean surface area of particles).

X10. ----- 10% of particles.

X16. -----16% of particles.

X50. -----50% of particles.

X84. ----- 84% of particles.

X90. ----- 90% of particles.

X99. ----- 99% of particles.



