

KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY

COLLEGE OF SCIENCE

FACULTY OF PHYSICAL SCIENCE

DEPARTMENT OF PHYSICS

TOPIC

**THE USE OF LOCAL CLAY IN THE MANUFACTURE OF HONEYCOMB IN CATALYTIC CONVERTOR OF
AUTOMOBILE EXHAUST SYSTEM.**

**A DESSERTATION SUBMITTED TO THE DEPARTMENT OF PHYSICS IN A PARTIAL FULFILMENT OF THE
REQUIREMENT OF THE MASTER OF SCIENCE DEGREE IN PHYSICS**

BY

ASARE BOAKYE-ANSAH

SUPERVISOR

DR. BRIGHT KWAKYE- AWUAH

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DECLARATION

I declare that the study was carried out under the strict supervision of Dr. Kwakye- Awuah and that this project was done to the best of my knowledge and believe, it does not contain any material previously published or written by another person where due references is not made in the text.

NAME :

SIGNATURE

ASARE BOAKYE-ANSAH

(.....)

(Student)

DR. BRIGHT KWAKYE - AWUAH

(.....)

(Supervisor)

PROF. S. K. DANOUR

(.....) (Head

of Department)

KNUST



DEDICATION

This piece of work is wholeheartedly dedicated to my parents for their support and prayers in ensuring that I attain the highest level in my education. Also to my supervisor Dr. Bright

Kwakyee-Awuah for his encouragement and support and to Mr. I. Nkrumah for his time and advice.

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I express my outmost appreciation to the almighty God for his divine protection and love for me, throughout my two year stay in Kwame Nkrumah University of Science and Technology.

I am also grateful to my Supervisor. Dr. B. Kwakyee- Awuah for his guidance, suggestions and his immense advice he gave me towards this research.

My appreciation also goes to Mr. Naab of the Ceramic Department KNUST.

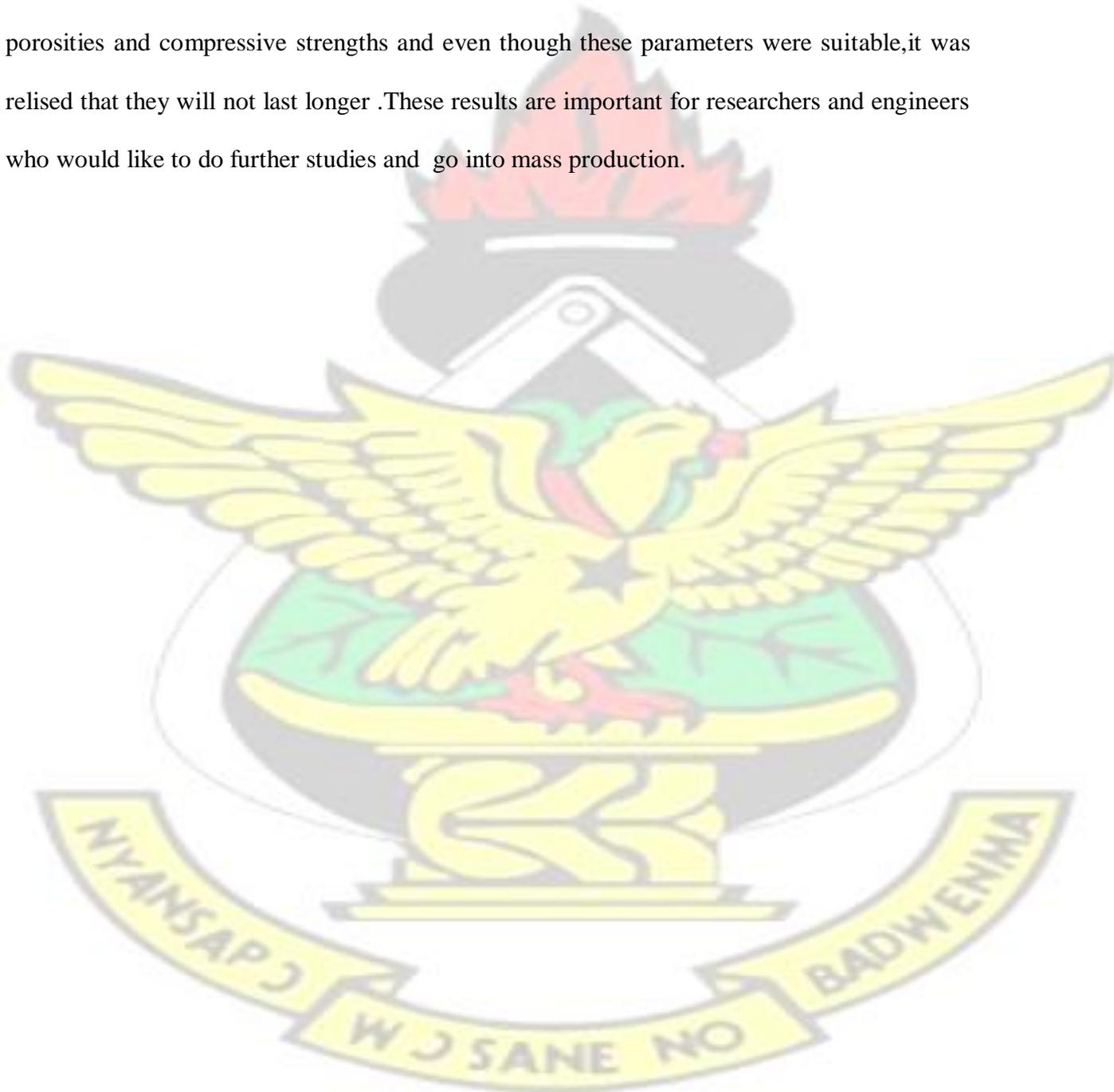
Also my appreciation also goes to all lecturers, non-teaching staff and all the students of the Physics Department.

Lastly, I would like to express my appreciation to Mr. M. O. Yeboah and family, Assumptamarie and loved ones.

ABSTRACT

The study was aimed at investigating on how our local clay can be used in the manufacturing of honeycomb, in a catalytic convertor of automobile exhaust system. The viability of the clay fetched from Fosu a village in the central region of Ghana is ascertained using the various methods below. After series of initial processing techniques to get fine grain clay; it was then soaked and left at a prevailing temperature overnight until a workable consistency was achieved. The clay was then molded into cylindrical and rectangular dimensions of different series. The honeycombs were dried slowly in an open air for some hours at room temperature

to prevent cracking. The physical and mechanical properties of the green ware and the bisque were determined using porosity, dry and fired shrinkage and compressive techniques. After these, the recommended honeycomb fired to 1150 °C had its porosity to be 30.5 % and it indicates an appreciable number of pores that could absorb water, since water and smoke are all fluids. Its average fired shrinkage is 14.0% and its average compressive strength is 7.86 KNmm⁻². Other test samples fired at different temperatures also gave fired weights, shrinkages porosities and compressive strengths and even though these parameters were suitable, it was realised that they will not last longer .These results are important for researchers and engineers who would like to do further studies and go into mass production.



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CHAPTER ONE

1.0. INTRODUCTION

A catalytic honeycomb or substrate is found in the exhaust of automobiles. It is precisely found in the converter of the exhaust. By definition it is a device used to reduce the toxicity of emission from an internal combustion engine. It is made of clay and has the ability to convert the poisons gases emitted from the engine of automobile, lawn and garden equipments and other non-road engines to useful environmental gases (Csab et al., 1988). The substrate together with the metal part forms the catalytic converter. A catalytic convector is the centerpiece of the motor vehicles emission control program. It was first introduced in the United State in 1975 to comply with the tightening environmental protection agency regulation on auto exhaust. Over the past twenty five (25) years catalyst technology has continued to advance to meet

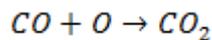
increasingly tighter emissions standards and greater durability equipments (Houdry, 2011).A catalytic converter consists of a stainless steel box mounted in the exhaust system. Inside is the auto catalyst, ceramic substrate. The ceramic substrate is protected from shock by a resilient ceramic on metal mat (Houdry, 2011)There are two main types , they are :

1. Two way catalytic converter
2. Three way catalytic converter

The two way catalytic converter performs two main functions. These functions are simultaneously performed (Ullman et al., 1976).

These are ;

1. Oxidation of carbon mono-oxide to carbon dioxide



2. Oxidation of unburnt Hydrocarbons to carbon dioxides and water.



This type of converter is widely used on diesel engines to reduce hydrocarbons and carbon monoxide emissions.

The three way catalytic converter performs three simultaneous tasks (Ullman et al.,1976.)

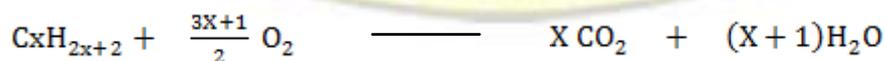
1. Reducing of nitrogen oxides to nitrogen and oxygen.



2. Oxidation of carbon monoxide to carbon dioxide



3. Oxidation of unburnt hydrocarbons (HC) to carbon dioxide and water.



These three reactions occur most efficiently when the catalytic converter receives exhaust from an engine running slightly above the stoichiometric point. This point is between 14.6 and 14.8 parts air to 1 part fuel, by weight, for gasoline. The ratio for Autogas (or liquefied petroleum gas (LPG)), natural gas and ethanol fuels is slightly different, requiring modified fuel system settings when using those fuels. Generally, engines fitted with 3-way catalytic converters are equipped with a computerized closed-loop feedback fuel injection system using one or more oxygen sensors, though early in the deployment of three-way converters, carburetors equipped for feedback mixture control were used (Wright, 2009). When there is more oxygen than required, then, the system is said to be running lean and thus the system is in oxidizing conditions. In this case the converters two oxidizing reactions are favored at the expense of the reduction reactions. When there is excessive fuel, then the engine is running rich. The reduction of NO_x is favoured at the expense of the carbon mono oxide and hydrocarbons (CO and HC). Oxidation, when an engine could be operated with infinitesimally small, oscillations, that is about the stoichiometric point for the fuel, then this is theoretically possible reach 100 % conversion efficiency (Brant et al., 2000). In the world today, in which Ghana is a stakeholder, been a global village and are together fighting a wealthy course of global warming which is on the increase as a result of excess pollutants released into the atmosphere , there is the need to find effective ways to the reduction of poisonous gases. These converters when used for a longer periods has its honey comb sealed with excess carbon and affect the functioning of automobile. Hence mechanical engineers on revealing remove this substrate which is ceramic and lay pipes in the converter and sometimes buy the whole converter which is very expensive. When the substrate is removed without replacement, the result is that the HC and CO that come out of combustion come directly into the environment. The Environmental Protection Agency of Ghana (EPA) reported that over 20 % of air pollution is emitted from exhaust of automobiles (<http://www.ghanaweb.com>, 2003). In order to offset this effect the ceramic substrate must be replaced by clay since ceramic substrate are easily damaged.

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1.1. BACKGROUND OF STUDY

One of the activities of man in many years which has contributed in no better way to improving the environment of men in pollution. Pollution has been a major environmental hazard. It takes place in so many forms. The most common type of pollution which has assumed global dimension is air pollution. Research has shown that the rate at which the air around us has been polluted has lead to the outbreak of diseases such as throat inflammation and cardiovascular diseases (Sheppard et al., 2004) . Gases released into the atmosphere are from the exhaust of automobiles forms about 10 % of the worlds air pollution (<http://w.w.w.epa.gov/ebt/airpollution.html>). In Ghana alone the amount of poisonous gases emitted by the automobiles as recently released by the environmental protection agency is about 35 % of the total air emissions (www.ghanaweb.com). Automobiles have in their exhaust system a catalytic converter which is responsible for the conversion of poisonous gases into somehow useful environmental gases. These convertors have a ceramic material which converts carbon monoxide emitted during combustion into carbon dioxide and water. These ceramic materials are damaged with time as the carbon fills the holes in them and also covers the surfaces of the hole where chemical reaction takes place, therefore leading to the ineffective functioning of the honeycomb (Csaba, 1988).

When these ceramic materials are damaged, the local mechanic cut open the convertor system to remove the ceramic honeycomb. This leads to the release into the atmosphere poisonous carbon monoxide. The ceramic product is not replaced because it is not manufactured here in Ghana. It is made of clay and clay is also abundant in Ghana, the country stands a chance to benefit , by producing this substrate.

1.2. STATEMENT OF PROBLEM

Pollution is the introduction of contaminants into a natural environment that causes instability, disorder, harm or discomfort to the ecosystem i.e. physical systems or living organisms (Merriam-Webster.com). Pollution can take the form of chemical substances or energy, such as noise, heat, or light. Pollutants, the elements of pollution, can be foreign substances or energies, or naturally occurring; when naturally occurring, they are considered contaminants when they exceed natural levels. Pollution is often classed as point source or nonpoint source pollution. The Blacksmith Institute issues annually a list of the world's worst polluted places. In the 2007, the worst polluted places in the world included; Azerbaijan, China, India, Peru, Russia, Ukraine, and Zambia (Blacksmith institute,2007). In order to reduce air pollution and cut down the risk of airborne diseases, a locally manufactured honeycomb should be constructed so as to intermittently replace the ineffective honeycombs.

Local materials would be used so as to reduce cost.

1.3. RESEARCH

The main purpose of this project is to produce a catalytic honey comb using locally processed clay. The product is found in catalytic convertors, so as to replace, the original ones placed in the catalytic convertor exhaust. The product will help in the continual effective process of reducing toxic pollutants that automobiles emit into the atmosphere and also to reduce noise

produced by the engine. The following specific objectives were also determined alongside the main objectives.

- a) Drying shrinkage of the product,
- b) Porosity of fired product,
- c) The compression strength of fired honeycomb,
- d) Durability of the fired honey comb.

The clays used in this work, vary considerably in physical properties like colour, porosity hardness, etc and mineralogical content. Aside their varying physical properties, certain properties are common in them. That is, they have the ability to be crushed and mixed with water to form a plastic material which can be molded into various shapes and sizes. This can then be fired to a high temperature during which it can attain a high, hard weathered resistant characteristic. Insulating is then considered on the sides of the product. The two direct faces, that is the front and the back of the product are not insulated.

1.4. JUSTIFICATION

As described in section 1.0, a catalytic convertor consist of three main parts: a precious metal such as platinum, palladium or rhodium, a wash coat and a substrate or core. As emission of gases passes through the convertor the pores in the substrate become choked with time. Furthermore, because auto mechanics do not have any idea of replacing the substrate when damaged (since convertors are produced overseas) they cut open the metal casing, remove and throw away the damaged substrate . When this is done, toxic gases are emitted directly into the environment and this can lead to serious respiratory diseases such as asthma. Excessive noise is also produced. Using a clay substrate, can reduce pollution caused by automobiles as mentioned above ,create employment and also cut costs in terms of purchasing new convertors when old ones are damaged or stolen.

1.5. IMPORTANCE OF RESEARCH

The importance of this research might include;

- To reduce the amount of automobile toxic released into the environment.
- To make use of our local natural resource (clay).
- To minimize and prevent the theft of catalytic converter.
- To create employment for those who will be working at the catalytic industry.

CHAPTER TWO

2.0. LITERATURE REVIEW

Ceramic plays an important role in addressing various environmental needs. One most important function of ceramic nowadays in automobile is its ability to help decrease pollution. In recent times, air pollution, which is the introduction of poisonous chemicals and particulate matter in the environment has increased Global warming. Reduction in air pollution is currently a major problem to the world to which Ghana is included. Researchers and other stakeholders are therefore working around the clock to help decrease pollution in any other form so as to make the earth a healthy habitat for all. As man cannot leave without producing these poisonous gases that pollute the environment antidotes should also be put in place to help check, reduce and if possible find ways of stopping these toxic gases. Automobiles were found to be one of the main contributors to this canker. Researchers and manufactures saw the need to reduce the emission of carbon monoxide that is produced during combustion in the engine of the automobile and also some fuel using equipments such as lawn mowers. In 1975, catalytic convertors were widely introduced on series production in the United States of America market to comply with tightening. Environmental Protection Agency regulations on auto exhaust (Brant et al., 2000). They were made to provide an environment for a chemical reaction wherein toxic combustion by products are converted to less toxic substances. Emission regulations vary considerably from jurisdiction to jurisdiction. In North America most spark ignition engines of

over 25 break horsepower (19KW) output built after January 1, 2004 are equipped with three-way catalytic converters (Crutsinger, 1982) .In Japan, a similar set of regulations came into effect in January 1, 2007, while the European Union had not yet enacted analogues regulations. Most automobile spark ignitions engines in North America have been fitted with catalytic convertors since the mid 1970s, as stated earlier and the technology is generally based on automotive technology.

Diesel engine regulations are similarly varied with some jurisdiction focusing on NO_x (Nitric Oxide and Nitrogen dioxide) emissions and others focusing on particulate (soot) emission. The emission of nitric oxide and soot into the environment can cause problem for the engine manufacturer as it may not be economical to design an engine to meet two sets of regulations. Regulation of fuel quality varies across jurisdiction. In North America, Europe, Japan and Hong Kong, gasoline and diesel fuel are highly regulated while CNG and LPG are being reviewed for regulation too. In most of Asia and Africa this is not so in some places, sulphur content of the fuel can reach 20,000 parts per million (2 %) (Houdry, 2009). Any sulphur present may be oxidized to SO₂ (Sulphur dioxide) or SO₃ (Sulphur trioxide) in the combustion chamber. If sulphur passes over a catalyst, it may be oxidized in the catalyst. Sulphur oxides are precursors to sulphuric acid, a major component of acid rain. While it is possible to add vanadium to the catalyst wash coat to combat sulphur oxide formation, such addition will reduce the effectiveness of the catalyst. The most effective solution is to further refine fuel that contains sulphur. Regulations in Japan, Europe and North America tightly restrict the amount of sulphur permitted in motor fuels (Crutsinger, 1982). However, the expense of producing such clean fuel makes it not practical for use in many developing countries such as Ghana. As a result cities in developing countries like Ghana , with high levels of vehicular traffic suffer from acid rain causing damages to stone and wood work buildings and deleterious effects on the local ecosystem.

2.1. CLAY

Clay is defined as a naturally occurring material composed of fine grained minerals which shows plasticity through a variable range of water content and which can be hardened when dried or fired (Dadson, 2006). Basically, clay is derived from the disintegration of granite and other feldspatic or pegmatite rocks which as they decompose deposit alumina and silica particles. The latter two minerals, combined with water to form pure clay. The composition is expressed chemically as $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$. (Worrall, 1986). This is an ideal formula, however, nearly all clay contain some impurities and variations in the basic formulae that accounts for the different characteristics of the numerous clay types. Clay minerals are typically formed over long range of time by the gradual chemical weathering of rocks with concentrations of carbonic acid and other diluted solvents being low. These acid solvents migrate through the weathering rocks after leaching through upper weathered layers. Also clay minerals are formed by hydrothermal activities. In addition the decomposition activities also occur under the Weatherly of the wind, rain or erosion by running water or rivers. Clays which decompose upon their site of their original rock are known as primary clay (Clews, 1969) and it is characterized by relatively purity with lack of plasticity. They may not hold their shape during drying and firing but tend to crack. They are relatively refractory and form white or light cream in colour. Clays which have been transported from the site of decomposition and deposited on the beds of rivers or lakes is known as secondary clay. They are far more plastic but relatively impure. This is because, during passage, they would have taken up impurities present in the rocks, which have similarly been decomposed. Nevertheless, the two types of clay are given the standard chemical formula $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$ (Worrall, 1986). They are broadly categorized as aluminium-silicates, and from the chemical formula it shows that they include chemically combined water.

2.1.1. TYPES OF CLAY

Basically there are two main types of clay and they are

- Primary Clay,
- Secondary Clay.

2.1.2 PRIMARY CLAY

This is a type of clay which is formed as a result of weathering, where the decomposed rock is usually not transported from the parent original rock. Primary clays share remain close to their original source and have large grain size. An example of primary clay is Kaolin or China clay which is the parent clay.

2.1.3 SECONDARY CLAY

Secondary clay, also known as sedimentary clay are those that, by the action of the wind or running water, have been transported far from the site of the parent rock. This action usually reduces the clay particles to the finest size and therefore sedimentary or secondary clay are the more plastic of the two types. Clays of this sort are usually found mixed with other minerals such as iron and mica, which gives the clay a shining or reddish property.

2.2. CLAY MIXTURES

2.2.1 KAOLIN

Kaolin is a white clay found at the base of mount Kau-ling in China. It is a very pure form of clay approaching the ideal formula $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2 \cdot 2 \text{H}_2\text{O}$ and it serves as a source of $\text{SiO}_2 + \text{Al}_2\text{O}_3$ (Perkins, 1984). Although it is never used alone as a body, it serves as a standard of which other clays' are compared. Kaolin is white in colour and it can be fired to an extremely high temperature. Kaolin provides a source of alumina and silica for glazes and is an important ingredient in high fire whiter ware and porcelain bodies. The wide variety of kaolin types

available is indicative of the difficulty in classifying clays. In the United States, the major commercial deposits are in the South East. North Carolina produces a residual type of kaolin with many coarse rock particles, while the deposits in South Carolina and Georgia are of sedimentary types. Florida deposits are even more plastic and are termed ball kaolin (Walter, 1986).

2.2.2. BALL CLAY

Chemically Ball Clay looks similar to kaolin after firing. In its uncoloured state however, the colour is dark gray due to the presence of organic material. Although weathered from a granite type of rock much like that which produces. Kaolin, the ball clay particles are deposited in swampy areas where the organic acids and gaseous compounds released from decaying vegetation. Serve to breakdown the clay particles into even finer sizes than those of the sedimentary Kaolin Ball Clay impacts increased plasticity and dry strength when used as a body component. It has a high maturing temperature. If a clay body contains 10 to 20 percent ball clay, its throwing qualities are gently improved.

2.2.3. STONEWARE CLAY

Stoneware clay is of particular interest to us because they are generally plastic and fire a range of cone 6 to 10 (840 °C-1400 °C). Depending upon the atmospheric conditions during firing, the colour will vary from New York and New Jersey westward to Illinois and Missouri and also in pacific coast (Dadson, 2006). In comparison with Kaolin, they contain impurities such as, feldspar and iron that lower the maturing temperatures and impact colour to the clay.

2.2.4. FIRE CLAY

Fire clay is high firing clay commonly used for insulating brick and kiln furniture. The physical characteristics of fire clay vary from one clay to another; that is, while some of them have a fine plastic quality others are coarse and granular and are suitable for throwing. They generally

contain some iron as an impurity but seldom have calcium or feldspar. They can be high in either flint or alumina and have industrial uses. They are found in most states and absent in only a few mountainous regions in U.S.A. .

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2.2.5. EARTHENWARE CLAYS

Earthenware clays constitute a group of low firing clays that mature at temperatures ranging from cone 2 to cone 8. They contain a relatively high percentage of iron oxide which serves as a flux (a substance that lowers the maturing temperature of the clay) so that when fired they are rather fragile and quite porous (5 to 15 percent) stoneware would be about 3 %.

Earthenware deforms and often bloats and blisters at temperatures above 1150 °C.

2.2.6. SLIP CLAY

These are clays that naturally contain sufficient fluxes to function as glaze without further additions. Although white and even blue slips exist, the most common ones are tan, brick red, or brown, black. Most slip clays fire between a range from cone 6 to 10.

2.2.7. BENTONITE

Bentonite is usually a clay that is used in small amounts as plasticizers. It has the finest particle sizes from the airborne dust of volcanic eruptions. It is composed largely of silica. Deposits are found in most of the western mountainous states, the Dakotas and in several Gulf States (John, 2009).

2.3. PROPERTIES OF CLAY

Before a new clay or clay body is purchased for use, a few simple tests should be made. It ensures that the right raw material is being used to produce the product of desired qualities.

This brings into play the exact features and characteristics of the clay being used.

The properties of clay may be either physical as well as chemical and they include

- Plasticity,
- Porosity,
- Shrinkage,
- Particle size distribution,

2.3.1. PLASTICITY

Plasticity refers to how flexible clay or clay body is. Any particular clay's plasticity is greatly influenced by the clay's particle size, water content, and aging. (Nelson et al., 2000) Plasticity is an essential property to throwing clay. A standard simple test for plasticity is to loop a pencil size roll of clay around ones finger. If the coil cracks excessively, it probably will not throw well. The ultimate test is however, to throw several pieces. In comparing bodies the porter should make sure that all samples have been treated with water for equal length of time. Three weeks is adequate for clay to improve appreciable qualities. At this time, the finest particles become thoroughly moist and the slight chemical breakdown caused by the organic matter contained in all clays can occur if it is necessary to use an alkaline body. The addition of small amount of vinegar to the throwing water will prove helpful. Wedging, a process by which the clay is kneaded to remove air pockets, has a considerable effect in increasing plasticity. Water of plasticity refers to the amount of water needed to bring dry, powdered clay into a plastic state suitable for throwing. The finer the particle size the more plastic clay will be and the more the water it will absorb.

2.3.2. SHRINKAGE

Shrinkage is the rate at which a clay body shrinks during drying and firing. (Lawrence, 1972). Shrinkage of the clay body occurs first as the clay formed dries in air. It occurs again when the formed clay is put through the bisque firing and the glaze firing. The most plastic clay will

always shrink the most. The test for shrinkage is always simple. To go through the test, firstly, a plastic clay slab is rolled out and either cut or marked to a measure; when the slab is totally dry, a second measurement is taken. A final measurement is made after firing. Clay shrinkage rates generally ranges between 5 % to 12 %. In the drying state , with an additional 8 % to 12 % shrinkage during firing. Therefore the porter can expect a total shrinkage of at least 13 % and an extreme of 24 % with a medium of 15 % to 20 % between the wet clay and the final glaze ware (Hopper, 1994).

2.3.3. POROSITY

The porosity of fired clay is directly related to the hardness and verification of the clay. The porosity of a body is defined as the total proportion of air spaces contained between the solid particles of which the body is composed (Glasbey, 1991). Porosity is a fraction between 0 and 1, typically ranging from less than 0.01 for solid granite to more than 0.5 for peat and clay. It may also be represented in percentage terms by multiplying the fraction by 100. The porosity of a rock , is an important consideration when attempting to evaluate the potential volume of water or hydrocarbons it may contain. Consequently sedimentary porosity is a complex function of many factors, including the following properties ; rate of burial, depth of burial, the nature of the connate fluids, the nature of overlying sediments . One commonly used relationship between porosity and depth is given by the equation;

$$\theta(z) = \theta_0 \cdot e^{-kz}$$

Where: θ_0 is the surface porosity, k is the compaction coefficient (m^{-1}) and z is depth (m). A value for porosity can alternatively be calculated from the bulk density (ρ_{bulk}) and particle density (ρ_{particle}).

$$\theta = 1 - \frac{\rho_{\text{Bulk}}}{\rho_{\text{Particle}}}$$

As a general rule, fired clay bodies fall within the following porosity ranges, earthenware, (4 - 10 %). Stoneware (1 - 6 %) (Horgan, 1999). A higher firing will reduce the porosity, but

normally a specific firing temperature would have been chosen already. The pores located in a particular material may be categorized into six different types.

- a. Closed or sealed pores
- b. Channel pores connecting separate pores
- c. Blind alloy pore
- d. Loop pores
- e. Pocket pores-some with narrow necks.
- f. Micro pores, which are so small as not to be filled with liquid in any ordinary period of soaking.

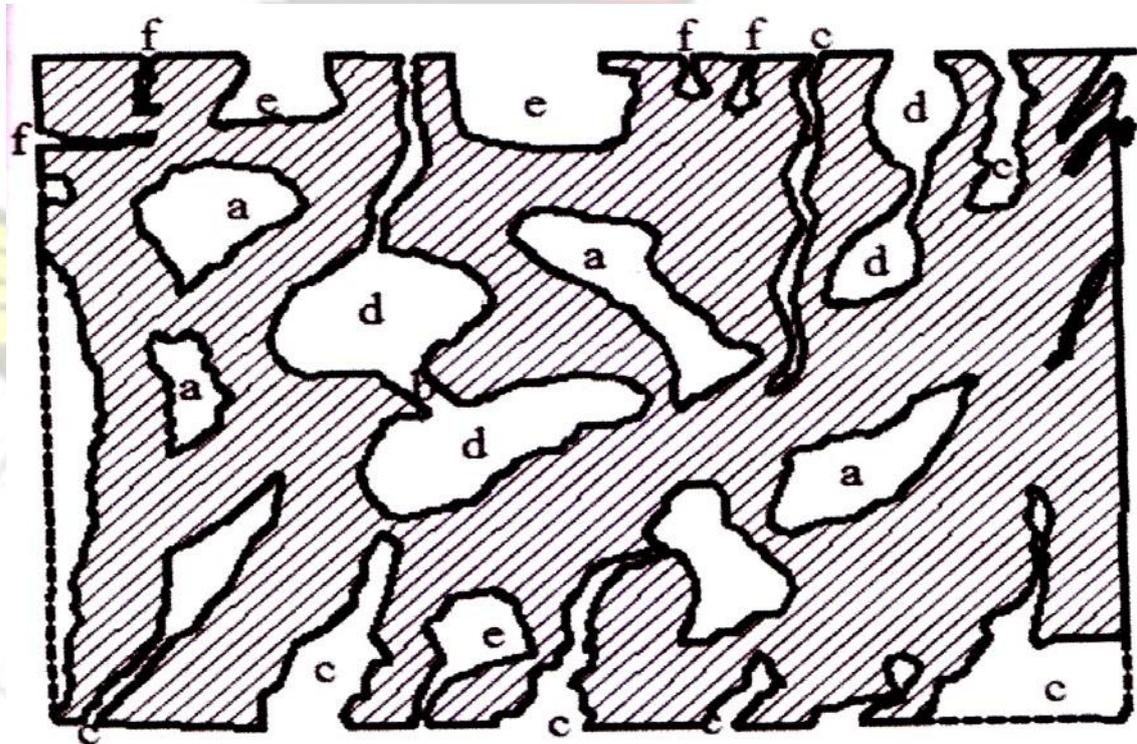


Figure 2.1 : Types of pores present in a clay material (John, 2009)

When the porosity of a material is determined experimentally by observing these types of different kinds of pores two sets of values are produced: True porosity and apparent porosity.

2.3.3.1. Measurement of porosity

There are several ways by which porosity can be measured, some of the methods include;

2.3.3.1.1 Direct method

This is done by determining the bulk volume of the porous sample, and then determining the volume of the skeletal material with no pores. That is pore volume = total volume – material volume.

2.3.3.1.2. Optical methods

With this method the area of the material versus the area of the pores visible under the microscope are determined. The "areal" and "volumetric" porosities are equal for porous media with random structure (Ball et al., 1994).

2.3.3.1.3 Gas expansion method

A sample of known bulk volume is enclosed in a container of known volume. It is connected to another container with a known volume which is evacuated (i.e., near vacuum pressure). When a valve connecting the two containers is opened, gas passes from the first container to the second until a uniform pressure distribution is attained (Horgan, 1999). Using ideal gas law, the volume of the pores is calculated as

$$v_v = v_t - v_a - v_b \times \frac{p_2}{p_2 - p_1}$$

Where

\mathcal{V}_v = the effective volume of the pores,

\mathcal{V}_{tt} = the bulk volume of the sample,

\mathcal{V}_a = the volume of the container containing the sample,

\mathcal{V}_b = the volume of the evacuated container, P_1

= the initial pressure in volume \mathcal{V}_a and \mathcal{V}_v ,

and P_2 = final pressure present in the entire

system.

The porosity can therefore be defined as $\theta = \frac{v_v}{v_t}$

In practice, the equation above means that, the pores must not be closed cavities.

2.4. PARTICLE SIZE DISTRIBUTION

Particle size distribution of clay is very important in the manufacture of clay honeycomb. This is because the bonds affect some of the chains features of honeycomb. The proportions of materials within contained grain size ranges can be found by dispersing the clay with some dispensing agent. This can be done by allowing the clay to sediment. The particle size distribution has an effect on the drying strength. It is dependent on the size of the grain particle involved.

2.5. FELDSPAR

Feldspars are groups of rock-forming tectosilicate minerals which make up as much as 60 % of the earth crust (Blatt et al., 2007). Feldspar crystallize from magma in both intrusive igneous rocks, as veins and are also present in many types of metamorphic rocks (Harvey et al., 1996). Rocks formed entirely of plagioclase feldspar are known as anorthosite. Feldspar is also found in many types of sedimentary rock. Composition of major elements in common feldspars can be expressed in terms of three end members. They are:

1. Potassium Feldspar (K-spar) end member $[\text{KAlSi}_3\text{O}_8]$.
2. Albite end member $[\text{NaAlSi}_3\text{O}_8]$.
3. Anorthite end member $\text{CaAl}_2\text{Si}_2\text{O}_8$

Solid solutions between K-feldspar and albite are called alkali feldspar. Solid solutions between albite and anorthites are called plagioclase or plagioclase feldspar. Only limited solid solutions occur between K-feldspar and anorthite. In two other solid solutions immiscibility occurs at temperatures common in the crust of the earth.

Albite is considered both as plagioclase and alkali feldspar. In addition to Albite, barium feldspars are also considered both as alkali and plagioclase feldspars. Barium feldspars form as the result of the replacement of potassium feldspar.

2.5.1. USES OF FELDSPAR

Feldspar is a common raw material in the ceramic and geopolymers. They are also used for thermoluminescence dating and optical dating in earth science and archaeology.

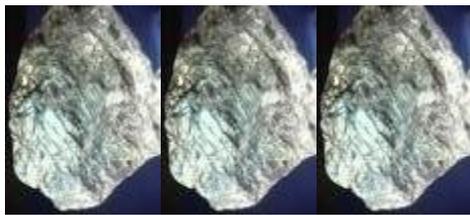


Figure 2.2 : A photograph of feldspar taken at different positions (Minas et al, Brazil)

2.6. SILICA (Silicon dioxide)

Silicon dioxide also known as silica, it is an oxide of silicon with a chemical formula SiO_2 and has been known for its hardness since antiquity. Silica is most commonly found in nature as sand or quartz as well as in the cell wall of diatoms (Iller, 1979). Silica is also the most abundant mineral in the earth's crust. Silica is manufactured in several forms including crystal, aero gel, fumed silica and colloidal silica. It is also a common addition in the production of foods, where it is used, primarily as a flow agent in powdered foods or to absorb water in hygroscope applications. In its capacity as a refractory, it is useful in fibre form as high temperature thermal protection fabric.

2.6.1 CRYSTAL STRUCTURE

In the vast majority of silicates, the Si atoms show tetrahedral coordination with 4 oxygen atoms surrounding a central atom. The most common example is seen in the quartz crystalline

form of silica, (SiO_2), each is thermodynamically stable. Crystalline forms of silica on average only two out of the four of each of the vertices of the Si tetrahedral are shared with others, yielding, the net chemical formula SiO_2 as shown below:

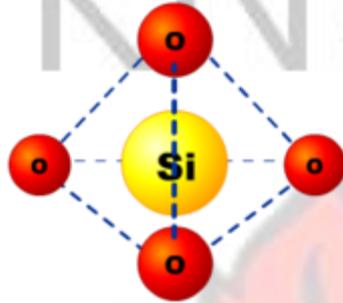


Figure 2.3: Tetrahedral structural unit of silica (SiO_4), the basic building block of most ideal glass former (Holleman et al., 2001)

SiO_2 has a number of distinct crystalline forms in addition to amorphous forms. With the exception of stishovite and fibrous silica, all of the crystalline forms involve tetrahedral SiO_4 units linked together by shared vertices in different arrangements. The Si – O – Si angle varies between a low value of 140° in α -tridymite, up to 180° in β -tridymite. In α -quartz Si angle is 144° (Holleman et al., 2001). Molten Silica exhibits several peculiar physical characteristics that are similar to the ones observed in liquid water: negative temperature expansion, density maximum and a heat capacity minimum (Scott et al., 2002). When molecular silicon monoxide, (SiO) is condensed in argon matrix, cooled with helium along with oxygen atoms generated by microwave discharge, molecular SiO_2 is produced which has a linear structure. Dimeric silicon dioxide (SiO_2)₂ is prepared by reacting oxygen gas with matrix isolated dimeric silicon monoxide. In dimeric silicon dioxide there are two oxygen atoms bridging between the silicon atoms with an Si -O -Si angle of 94° and bond length of 164.6 pm and the terminal Si – O bond length is 150.2 pm.

The Si – O bond length is 148.3 pm which compares with the length of 161 pm in α -quartz. The bond energy is estimated at 621.7 kJ/mol (Jutzi et al., 2003).

Silicon dioxide is formed when silicon is exposed to oxygen (or Air). A very thin layer of so called native oxide is formed on the surface when silicon is exposed to air under ambient conditions. Higher temperatures and alternative environments are used to grow well – controlled layers of silicon dioxide on silicon. For example at temperatures between 600 °C and 1200 °C, using the so called dry or wet oxidation with water or oxygen gas, respectively. The depth of the layer of silicon replaced by the dioxide is 44 % of the depth of the silicon dioxide layer produced.

2.7. CERAMIC HONEYCOMB/SUBSTRATE

A ceramic honeycomb is a material or substance made of clay. It basically performs the following function

- a) To reduce the noise produced by the combustion engine
- b) To convert the carbon monoxide that is produced during combustion to carbon dioxide and water

Since carbon monoxide is a poisonous gas, its conversion quite environmental friendly, helps to reduce the amount of toxic gases produced during combustion, thus saving the environment from its adverse pollution condition. Apart from the exhaust of automobile, plans are being made to use the ceramic honeycombs in equipment such as weeding mowers and other smaller combustion devices that are also known. The substrate is usually formed by pressing moist clay into mold in the early states. Currently they are formed by pouring slip (liquid clay) into a porous mold and allowing it to stiffen. Basically when forming the substrate, it is treated into liquid form. A metal mould is prepared and the liquid clay is poured into the mould, so as to take the shape of the mould. The space in between stands of metal in the mould is between 0.12 mm and 0.17

mm. Thus the partition wall thickness of the ceramic honeycomb may also fall within that range or better if less. Environmental issues in recent years along with even stricter exhaust gas restrictions are requiring that catalysts should be able to function immediately the engine starts, even when the exhaust is cold, that is cold start. The skin of the substrate wall is less or made less so as to reduce cracks. When the material is well dried, the outside walls are sealed leaving only two portions of air spaces (that is the where the gas will first reach into the substrate and where it will go out of the substrate. The outside is sealed to prevent gases from leaving through other parts.

The substrate is then covered with a metal mat before placed in non corrosive metal and then fixed in the exhaust compartment. The size of the substrate differ in terms of operational purposes. For instance, a Mercedes Benz C-class uses double ceramic honeycomb with an oval shape while a BMW 5.20 i uses a single round honeycomb. Traditional ceramic such as the ceramic honeycomb are basically formed from powders made from minerals such as clay, talc, silica, kaolin and feldspar. Most industrial ceramic, however are formed from pure powders of specialty chemicals such as silicon carbide, alumina and barium titanate. The minerals used to make ceramic are dug from the earth and are then crushed and ground into fine powder.



Figure 2.4: A pictorial diagram of a used ceramic honeycomb.

2.7.1. MOLDING

After purification, small amount of wax are often added to bind the ceramic powder and make it more workable. Plastic may also be added to the powder to give the desire pliability and softness. The powder can then be shaped into different objects by various molding processes.

These molding processes include: slip casting, pressure casting, injection, molding and extrusion. After molding a heating process called densification is applied to make the material stronger and denser.

2.7.2. SLIP CASTING

It is a molding process used to form hollow ceramic objects. Here, the ceramic powder is poured into a mold that has porous walls, and then the mold is filled with water. The capillary action

(that is force created by surface tension and by wetting of the sides of a tube) of the porous walls drains water through the powder and the mold, leaving a solid layer of ceramic inside.

2.7.3 PRESSURE CASTING

In pressure casting ceramic powder is poured into a mold, pressure is then applied to the powder, the pressure condenses the powder into a solid layer of ceramic that is shaped to the size of the mold.

2.7.4. INJECTION MOLDDING

This is another type of molding used in making small intricate objects. This method uses a piston to force the ceramic powder through a heated tube into a mold where the powder cools and hardens to the shape of the molding. When the object has solidified, the mold is opened and the ceramic piece is removed.

2.7.5. EXTRUCSION

This is a ceramic process in which ceramic powder is heated in a long barrel. A rotating screw then forces the heated material through an opening of the desired shape. As the material emerges from the die opening, the form cools, solidifies and is cut to the desired length. Extrusion is used in for making of products such as ceramic pipes, ceramic leads of plugs in automobile engine and pipes. In densification, intense heat is used to condense a ceramic object into a strong dense product. After being molded, the ceramic object is heated in an electric furnace to temperatures between 1000 °C and 1700 °C. As the ceramic heats, the powder particles coalesce, much as water droplets join at room temperature. As the ceramic particles merge, the object becomes increasingly dense, shrinking by up to 25 % of its original size. The goal of this heating process is to maximize the ceramic strength by obtaining an internal structure that is compact and extremely dense.

2.8. FIRING

Clay bodies cannot be discussed without considering firing. Firing of clay bodies has been in existence since time immemorial. The difference between a white translucent porcelain tea cup and a common red brick is created not only by the type of clay but also by the temperature to which it is fired. Firing is therefore a process by which the clay of which ceramic are made is induced to retain its shape permanently. The ceramic ware is heated either in an open fire or in one of the many varieties of Kiln to a point where the particle structure cannot be altered by water or pressure. The clay ware has to be raised to a temperature of about 330 °C at least , this drives off the water which remains in the clay after it has been sun dried. The firing properties that are of great interest are ;

1. The colour
2. The shrinkage
3. Porosity

2.8.1 BISQUE FIRING

This is a low temperature firing which is done to strengthen the clay ware to endure normal handling in glaze operation after sufficient absorbent to permit glaze adhesion. Bisque firing temperature is generally between cone 010 and cone 05, depending upon the clay body used. Ware bisque below cone 012 may crack during the glaze fire if too much flux is absorbed into the porous clay body. The stacking of a bisque kiln is quite different from that required for a glaze fire. In each situation , however at least, one inch (2.54 cm) of free space must be left inbetween the electrical elements and the ware. In a gas kiln a minimum of three inches (7.62 cm) between the kiln wall and ware is a desirable margin to allow free passage of heat and gases and also to avoid hot and cold spots. The green ware must be completely dry before it is loaded into the bisque kiln. It is possible to stuck one piece inside or on top of another, building

to a considerable height if the ware is strong enough. The porter must take care to make the rims coincide for support and to avoid placing heavy pieces on more fragile ones.

Before the start of the bisque firing, we should understand that raw clay contains much moisture, even though it seems dry so firing should proceed at a very low temperature for a long time.

Kiln doors should be left open jar or peepholes left open for an hour to allow the moisture inside to escape. Large heavy pots or sculpture pieces must be fired slowly to prevent the moisture contained in the clay or in hidden air pockets from being converted into steam, which would cause the piece to explode. After considering all these precaution the material can now be fired at the required temperature.

2.8.2 REDUCING FIRING

Reducing firing, sometimes called reducing the kiln, means that part of the firing cycle is conducted with an adequate amount of oxygen in the kiln to burn up all the fuel. As a result, the free hydrogen and carbon monoxide (CO) in the kiln atmosphere unite and thus reduce the oxygen content of the metallic oxides in the body.

Table 2.1; Below is a summary of reaction that occur during firing (sintering) of typical clay (Dadson, 2009)

Temperature (°C)	Reaction
500	Removal of free water the clay dries and volume changes. Organic matter burns off clay loses water of hydration volume changes again.

600	α - Quartz (a polymorph of quartz) transforms to β - Quartz (another polymorph of quartz) large volume change
900 – 1000	The clay particles partially sinter. The density decreases and the volume also decreases.
1000 – 1100	Silicate reacts with example feldspar to create a glass forming liquid, sintering is accelerated. Mullet is formed. Glass forms from the liquid or cooling.
1250 – 1400	Liquid assisted sintering yields approximately 100% dense ceramic. Glass forms from the liquid on cooling.
1250 – 1400	Firing the ceramic consists of 60% glass 20% millet 20% quartz

2.9. TEMPERATURE OF FIRED CLAY

Since the firing to which clay materials are subjected to, are very high, specific thermometer are engaged in measuring of such temperature. Some of these thermometers are the pyrometer and the thermocouple.

2.9.1. THE PYROMETER

Pyrometers are thermometers used to measure very high temperature up to 3000 °C, such as temperature of an oven or furnace such as Kiln. Bodies with very high temperatures are extremely hot and such bodies give off heat radiations. These hot radiations come out in colours. The hottest radiation has indigo colour and the least hot radiation comes in red colour. The pyrometer measures the temperature of very hot objects using the colour of the heat emitted from the body. The thermometric substance is the heat radiation from the body and the colour

of the heat radiation from the body is the thermometric property. There are two types of pyrometers and they are: Optical and total radiation pyrometer.

2.9.2 MODE OF OPERATION

The pyrometer is arranged to face the hot body and the heat radiation from the hot body is focused onto the thermometer by the converging lens. The colour of the radiation is viewed through the telescope and the bulb appears dark in the background. The key is then closed and the bulb lights up. The rheostat is adjusted until the colour of the bulb matches with the colour of the radiation. At this point, the colour of the bulb blends with the colour of the radiation and the filament bulb appears from the background. The temperature of the filament bulb and this is the same as the temperature of the hot body (Paker et al., 1995).

2.9.3 THE THERMOCOUPLE

The thermocouple works with the idea of the Seebeck's effect. The courses are the thermometer substance and the electromotive force (emf) is the thermometric property. It consists of two different metal wires that is, copper and zinc joined together at their ends. One junction is kept cold at 0 °C and the other junction known as the test junction is used to measure the temperature of the body, a galvanometer is connected to the wires to measure the emf generated. The emf is however measured accurately when potentiometers are used. The pyrometer has a temperature range of - 200 °C to 1500 °C. (Parker et al, .1995)

2.10. THEORY

2.10.1. APPARANT POROSITY

Apparent porosity refers to the amount of pores within a volume of sediment or porous solid. In the determination of apparent porosity, the water assesses only the open pores and not the closed pores. To determine the apparent porosity of a sample, the sample is fired to its required temperature and weighed, its weight W_a is noted. Water is made to boil on fire for some time,

the samples are then immersed for twenty four hours to ensure that water completely fills all unsealed pores. The saturated sample is removed wiped and then weighed in air and its weight W_s , noted. The saturated sample is again weighed in water and its weight W_w , is recorded.

CALCULATION OF APPARANT POROSITY

W_a = Weight of dry sample in air

W_w = Weight of saturated sample in water

W_s = Weight of saturated sample in air

$$\% \text{ Apparent Porosity} = \frac{W_s - W_a}{W_s - W_w} \times 100 \%$$

$$\% \text{ Apparent Porosity} = \frac{\text{Volume of water in the open pore}}{\text{Bulk volume of sample}} \times 100\%$$

2.10.2. SHRINKAGE

Shrinkage is a defect thought about by the reduction in volume of a material as it cools and solidifies. Bodies experience different amount of shrinkage. It depends upon the clays particle size and the amount of impurities present in the clay body. When a clay body is wet and very pliable, it contains a great amount of water. The clay particles ride within the water, which is what makes clay plastic or easily workable. As the clay dries the water evaporates, escaping from those spaces inbetween particles. The particles are more closer together resulting in the entire sample shrinking .How much a clay sample shrinks depend on the characteristics of the clay .Highly plastics wet clay have a very fine particle size and will shrinks more on the other hand. Clays with large particles will shrink less. Also clay bodies that include non-plastic additives such as sand will shrink less.

Shrinkage due to dry is generally between 4% and 10% when clay is fired at a high temperature. It begins to gradually vitrify. This process of melting and fusing also compacts the clay body. The clay shrinks as the particles size slowly decreases as they fuse. In addition, the particles also compress into a tighter, more dense configuration within the glassy material that fills up all the nooks and crannies. The amount of shrinkage due to vitrification is very dependent on the type of clay involved.

2.10.2.1 CALCULATION OF THE SHRINKAGE OF A CLAY SAMPLE

Wet length of line = W

Fired length of line = F

Shrinkage = S

$$\% \text{ shrinkage} = \frac{F}{W} \times 100 \%$$

VITRIFICATION

Vitrification is the process of melting that clays and glazes go through as they are fired to maturity. In a fully matured clay body, the spaces between refractory particles are completely filled up with glass, fusing the particles together and making the clay body impervious to water. Vitrification takes place at different temperatures for different clay bodies.

2.10.3. COMPRESSIVE STRENGTH

Compressive strength is the capacity of a material or structure to withstand axially directed pushing forces. When the limit of compressive strength is reached, materials are crushed. Compressive strength is usually measured on a universal testing machine. Mechanical testing measuring maximum and minimum amount of compressive load a material can receive before fracturing. The testing piece in the form of a cube is compressed between the plates of a compression testing machine by a gradually applied load. Materials such as brick, concrete

exhibit a great compressive strength before fracture. The top and bottom areas of the sample are measured by measuring the length and breath of the sample and hence the compressive strength can be calculated.

DIAGRAM

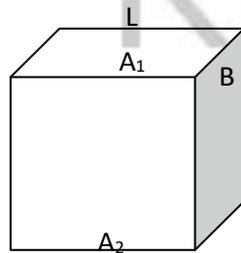


Figure 2.5

- L = length
- B = Breath
- A1 = Top Area
- A2 = Bottom Area

Area = length x breath

$$\text{Compressive strength} = \frac{\text{Maximum load at failure (KN)}}{\text{Average area of sample face (mm)}} \quad \text{or}$$

$$\text{Compressive strength} = \frac{\text{Crushing load}}{\text{Area of sample}}$$

Compressive strength is measured in Kilo Newton per millimetre square (KNmm⁻²) or megapascal (Mpa)

These crushing machines ranges from very small table top systems to ones with over 53 MN capacity (Mikelt et al., 2002). There are several ways of determining the compressive strength of a material, some examples are: spring testing and top load crushing. When a material is exposed to a compressive force, they show initially, a linear relationship between stress and strain. This is a physical manifestation of Hooke's law. That is,

$$\text{Youngs modulus} = \frac{\text{Tensile stress}}{\text{Tensile strain}}$$

This value shows how the material will deform under applied compressive loading before plastic deformation occurs. The compressive strength of a material helps one to have data on the integrity and safety on material components and products, thus helping manufacturers to ensure that products are fixed for a particular purpose. It also helps to determine the batch quality. Knowing the compressive strength helps to ensure compliance with international standards.

CHAPTER THREE

3.1. MATERIALS

The materials used were divided into two and they are; raw materials 1 and raw materials 2. This is because two different samples were produced but one was recommended after the production. Apart from the raw material itself, emphasis was also given to the apparatus used in the processing and preparation of the product.

3.1.1. RAW MATERIALS 1

Fosu Clay

Feldspar

Sand (Silica)

Water

3.1.2 RAW MATERIALS 2

Fosu Clay

Feldspar

Sand (silica)

Saw dust (very fine)

Water

3.1.3. OTHER MATERIALS

1. Plaster of pirates (P.O.P)
2. Swing mesh (size 60mm)
3. Moldings
4. Metal strands (sewing pins)

The clay (Fosu clay) was obtained from Assin Fosu a town located in the Central Region of Ghana. Feldspar and silica were also obtained in their raw states from the Ceramic Department, KNUST. Other materials which were obtained from the ceramic department includes; plaster of pirates (P.O.P), swing mesh, molding, kiln and water. The metal strands (sewing pins) were bought from the Kejetia Market, Kumasi. The sawdust (mixture) was obtained from Kojovi carpentry shop, Anloga-Kumasi. The production of the honey comb and testing of samples were carried out at the College of Arts (Ceramic Department, KNUST).

3.2. CHARACTERISTICS OF CLAY CONSIDERED

1. The clay was readily available and was easily obtained from the earth with a minimum physical effort.
2. Plasticity of the clay was considered. Plasticity was determined by mixing clay with small amount of water. With this, I mean that when the clay was mixed with small

amount of water, it became pliable and responded to the human hand by taking different shapes.

3. It developed some strength upon drying and firing.

3.3. METHODOLOGY

3.3.1. PREPARATION OF RAW MATERIALS

3.3.2. CLAY WINNING AND PREPARATION

The clay obtained from Fosu was dried for seventy-two hours (72 hours) under the sun. It was then crushed into fine particles using a ball mill. The crushed clay was then grounded and then sieved with a mesh of 60 mm to obtain very fine particle. Size of clay was not uniform, that is some particle sizes were not greater than 60 mm.

3.3.3. FELDSPAR PREPARATION

The feldspar was crushed from its mother rock, grounded, and sieved to obtain the desired size. The grounded feldspar was sieved with a 60 mm mesh and thus, the required size was obtained.

3.3.4. SAND (SILICA) PREPARATION

The sand was also grounded and sieved to obtain the required sizes. The method used was similar to the one used in section 3.3.2.

3.3.5. SAWDUST PREPARATION

The dust has already been prepared but was again sieved into the required sizes (60 mm mesh) as in the method used in section 3.3.2.

3.3.6. METHOD OF PREPARATION OF RAW MATERIALS

For the first sample (Fosu Clay, Feldspar and Sand). The raw materials were mixed together after which 250 cm³ of water was added. The mixture was well stirred until an even mixture

was obtained. The mixture was then poured into a P.O.P, which aided in getting rid of excess water in the mixture. This made the clay mixture thick and sticky. The second Sample, (Fosu Clay, Feldspar, Sand and Saw dust) was also mixed with water and also went through the same preparation as it was done for sample one above. The mixture in different P.O.P's were removed and then placed in a clean container and then moved to the honey comb forming site.

Table 3.1: The various composition of raw materials in gramms and also expressed in percentages of raw materials one.

Material	Composition (gramms)	Composition (%)
Fosu Clay	188.0	59.87
Sand	63.0	20
Feldspar	63.0	20

Table 3.2: The various composition of raw materials 2 in gramms and also expressed in percentages.

Materials	Composition (gramms)	Composition (%)
Fosu Clay	115.0	50.9
Sand	38.0	16.8
Feldspar	38.0	16.8
Sawdust	38.0	16.8

3.4. MAKING OF HONEYCOMB

The already prepared clay mixture is brought to a table where different moulds have been prepared for casting of the product. Since the honey comb differs in size from one automobile to the other different sample shapes were made for the different samples used. (The shape of the honey comb found in the exhaust of BMW 5-series is different from the one found in the exhaust of a Mercedes C-Class Model). Also strands which are circular in shape and of diameter 0.12 mm were used in the creation of the holes for the passage of the burnt gases. This was done manually with the aid of sewing pins. The required body size and hole size were obtained as a result of the processes mentioned above. Before the honeycomb was fired much moisture needs to be removed as possible to prevent the honeycomb from exploding in the kiln. Drying involves the removal of the water from the wet material in such a way as to take enough water out from them evenly from inside out. If the outer skin of the honeycomb is to dry first, that is if we try firing immediately after molding without drying, the outer will dry up first, which will then prevent the water inside from coming out. In the kiln, the extreme temperature will force dry the sample and this will lead to the occurrence of cracks. In areas where rainfall is regular, it is best to provide covering from the newly formed honeycomb to prevent the rains from wetting it. The covering had no side and this aided air to move freely around the honey comb. After the honeycomb has been dried for at least six days (6 days), it was then ready to be fired. At this stage it was observed that honeycomb can be handled without deforming or crumbling. During this drying stage, the honeycombs were turned in different positions to speed up drying.

The following factors controlled the rate of drying.

1. Naturally available heat
2. Humidity
3. Amount of free particles in the air.

It was necessary to provide at least a full day to ensure complete drying.

The product formed from this drying process is called *bisque*.

An electrical kiln was used in firing the honeycomb. The kiln has electrical input of 220 V which can generate heat up to a temperature of 1500 °C. The kiln used was an electrical one and it was set to the required temperature that is 1000 °C and 1150 °C for both samples.

Table 3.3: Shows the temperatures to which various samples were fired.

SAMPLE	TEMPERATURE °C
A1	1000
A2	1150
B1	1000
B2	1150

Loading of the honeycombs were carefully done with the hand to prevent damage to the substrate. The firing process took 72 hours for the samples which were set to 1000 °C and 79 hours for the samples which were set to 1150 °C

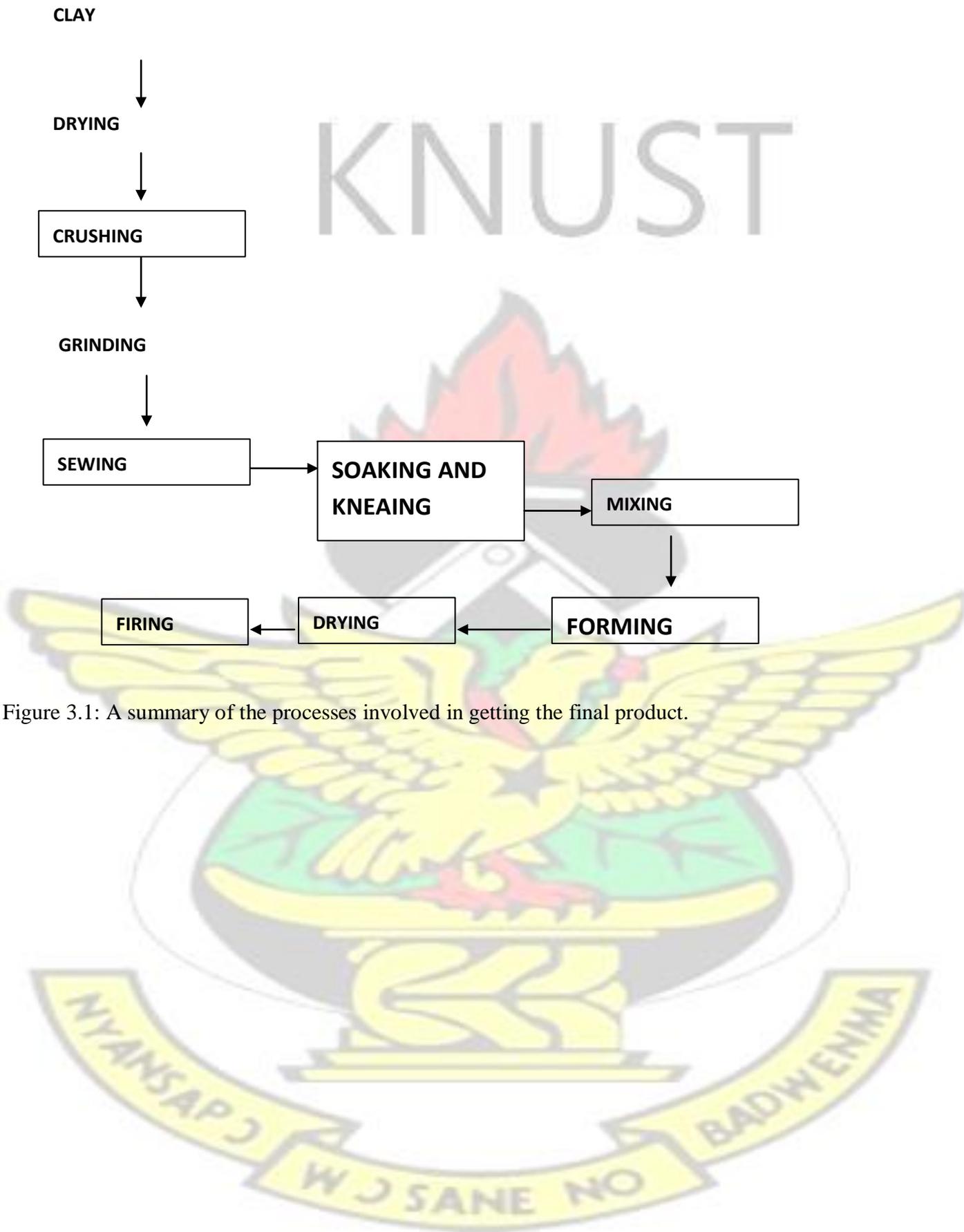


Figure 3.1: A summary of the processes involved in getting the final product.

3.5. PHYSICAL TEST

Below are series of tests that were conducted on the clay bodies after preparation and the following are the series of tests that were conducted:

1. Weighing,
2. Shrinkage test,
3. Apparent Porosity test and
4. Compressive test

These tests were performed using materials which were of the product produced. These materials were casted and labelled as Sample A and Sample B. Sample A was made up of two portions A₁ and A₂, sample B was also made of B₁ and B₂. Five separate samples of A₁, A₂, B₁ and B₂ were made. The samples were then labelled as A₁ (A₁₁, A₁₂, A₁₃, A₁₄, A₁₅), A₂ (A₂₁, A₂₂, A₂₃, A₂₄, A₂₅), B₁ (B₁₁, B₁₂, B₁₃, B₁₄, B₁₅) and B₂ (B₂₁, B₂₂, B₂₃, B₂₄, B₂₅).

Sample A is the product which was made up of clay, Feldspar and Sand (Silica). Sample B was also made up of clay, feldspar, sand (Silica) and saw dust.

3.5.1 WEIGHING

The two samples were weighed and their weights recorded.

3.5.1.1. DRY WEIGHT

The weights of the sample were obtained by using a spring balance. This was after the samples have been left to dry on its own for five days. Their corresponding weights were then determined.

3.5.1.2 FIRED WEIGHT (1000 °C)

The fired weight of the samples were also determined after the samples have been left in the kiln for 72 hours, brought out, cooled and was weighed using electronic balance.

3.5.2. SHRINKAGE

Shrinkage is a defect thought about by the reduction in volume of a material at it cools and solidifies. In this study the shrinkage test was done for the dry and fired samples. This test was also determined using Sample A and B.

3.5.2.1. DRY SHRINKAGE

The dry shrinkage of the Samples (A1, A2, B1 and B2) was determined by the percentage decrease in the average dimension of the sample. Here a ruler was used to draw two lines, the lines were made diagonally on the top face of the samples and their dimensions were noted. After drying for 72 hours, their dimensions were also taken and the results recorded. There was supposed to be reduction in the average length, width and thickness of the samples before and after drying. The result gives lineal shrinkage values in three directions at right angles.

3.5.2.2 FIRED SHRINKAGE (AT 1000 °C)

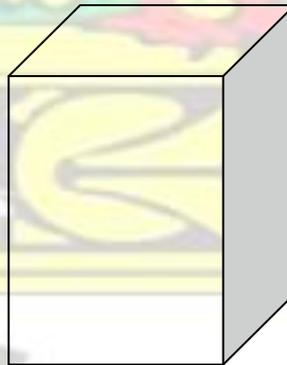
When the samples were processed through the firing stage, they were observed to have shrunk. Normally the shrinkage of a fired clay product will amount to as much as ten percent of its original size. The average difference in dimensions of the sample before and after firing gave the firing shrinkage. The difference in dimension was measured using rule.

3.6. APPARANT POROSITY

To determine the apparent porosity, a suitable length of inextensible string was used in suspending the fired sample whose weight was taken using a spring balance. The sample was lowered gently into hot water which has been made to boil on fire for some time, and brought off the fire. The samples are made to remain in the water for twenty four hours. The samples are wiped, weighed in air and their weights W_s are recorded. The weight of the saturated sample is again taken when immersed completely in water, its weight W_w is recorded from a spring balance. All the other samples are taken through the process as described above and in each case the dry weight, the saturated weight in air and the saturated weight in water are determined and recorded. The apparent porosity is then calculated as shown in page 28.

3.7. COMPRESSIVE STRENGTH

The compressive strength test was performed by first, measuring the length and breath of the samples. at top and bottom regions of the samples, this was done with a steel meter rule. The area at the top and bottom regions of the samples were also found for each sample and the average was calculated as shown.



$$\text{Top Area} = \text{Length} \times \text{width}$$

$$\text{Bottom Area} = \text{Length} \times \text{Width}$$

Figure 3.2

$$\text{Average Area} = \frac{\text{Top Area} \times \text{Bottom Area}}{2}$$

This was done for all samples. That is sample A and B.

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After finding the area, the samples were placed on a compressive strength testing machine. That is one sample at a time. A plate was placed on top of the sample and the machine was switched on. When the upper part of the machine on which a scale is attached comes into contact with the sample, the crushing process begins as shown below



Figure 3.3



Figure 3.4



Figure 3.5

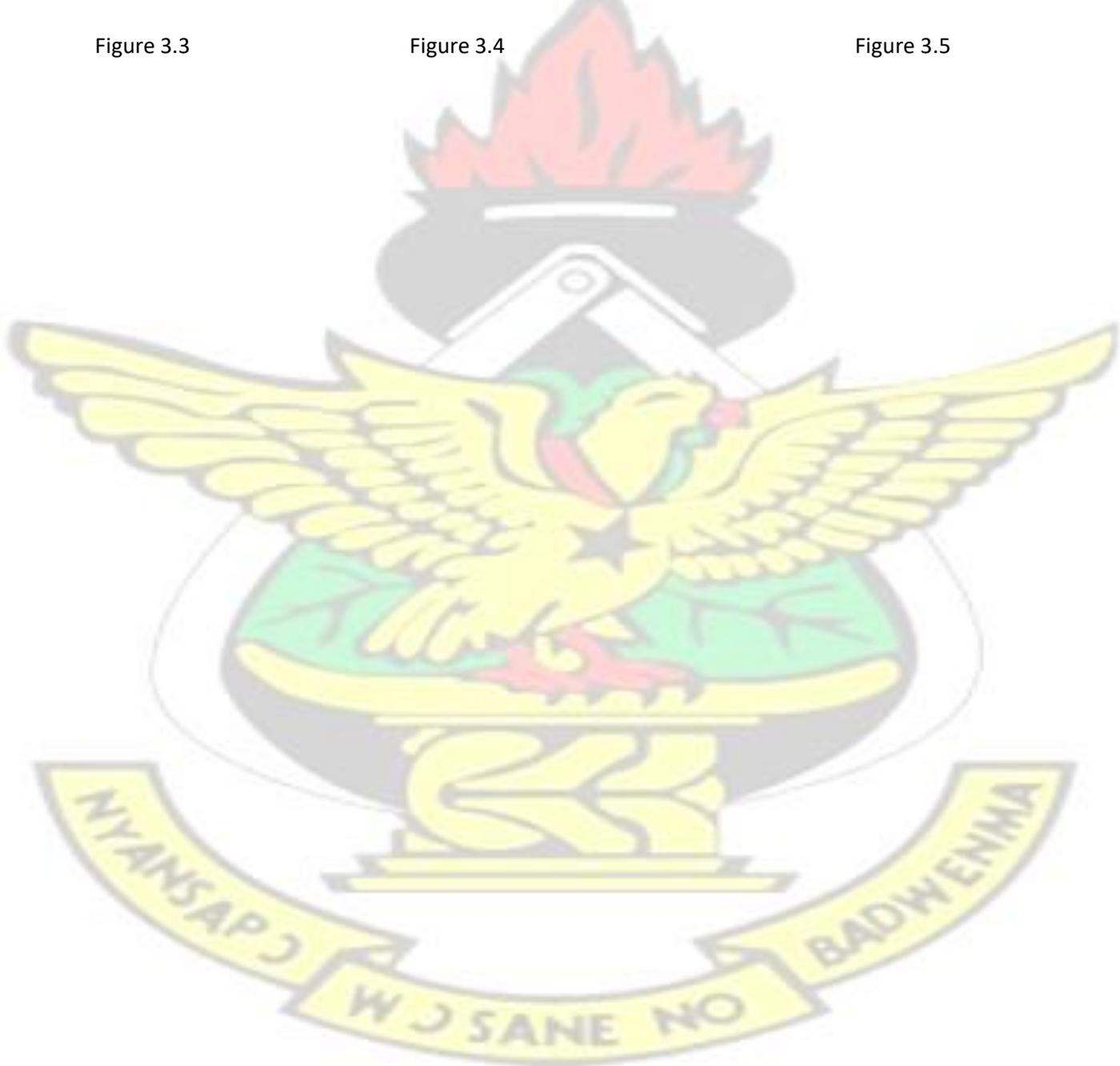




Figure 3.6



Figure 3.7



Figure 3.8



Figure 3.9



Figure 3.10



Figure 3.11

As crushing continues, the scale continues to read until at a particular point when cracks were observed all over the sample. At this same point the movement of the pointer on the scale reduces. At the failure point, that is when the sample is not able to withstand the compressive forces, the pointer on the scale stops and the scale was read and recorded. This gives the failure or the crushing load. The compressive strength is calculated. The procedure was repeated for all other samples and in each case the compressive strength was calculated, as shown in page

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CHAPTER FOUR

4.0. EXPERIMENTAL RESULTS AND DISCUSSION

4.1. AVERAGE MECHANICAL AND PHYSICAL PROPERTIES OF SAMPLE A AND B AT 1000°C AND 1150°C.

The four tables (table 4.1, table 4.2, table 4.3 and table 4.4) below show the various physical and mechanical properties of the test sample (A and B) that were considered before the clay was finally realized that it was viable and can be used for the manufacture of a catalytic honeycomb

4.1.1 TABLE 4.1. AVERAGE MECHANICAL AND PHYSICAL PROPERTIES OF SAMPLE A AT 1000 °C.

Sample of clay	Av. Dry weight/g	Av. Fired Weight/g	Av. Soaked weight /g	Dry Shrinkage /cm	Fired Shrinkage %	Apparant Porosity %	Compressive Strength x 10^{-3} KNmm ⁻²
Fosu	283	267	307.1	5.00	10	36.5	5.87

4.1.2 TABLE 4.2- AVERAGE (AV) MECHANICAL AND PHYSICAL PROPERTIES

OF SAMPLE A AT 1150 °C

Sample of clay	Av. Dry weight /g	Av. Fired Weight/g	Av. Soaked weight /g	Dry Shrinkage /cm	Fired Shrinkage %	Apparant Porosity %	Compressive Strength x 10 ⁻³ KNmm ⁻²
Fosu	283	265	299	4.9	12	32.3	5.99

4.1.3 TABLE 4.3 - AVERAGE MECHANICAL AND PHYSICAL PROPERTIES OF

SAMPLE B AT 1000°C

Sample of clay	Av. Dry weight /g	Av. Fired weight /g	Av. Soaked weight /g	Dry Shrinkage /cm	Fired Shrinkage %	Apparant Porosity %	Compressive Strength x10 ⁻³ KNmm ⁻²
Fosu	192	159.2	200.4	4.64	11	31.5	6.92

4.1.4 TABLE 4.4 - AVERAGE (AV) MECHANICAL AND PHYSICAL

PROPERTIES OF SAMPLE B AT 1150 °C

Sample of clay	Av. Dry weight /g	Av. Fired weight /g	Av. Soaked weight /g	Dry Shrinkage /cm	Fired Shrinkage %	Apparant Porosity %	Compressive Strength $\times 10^{-3}$ KNmm ⁻²
Fosu	192.0	157.0	200.0	4.6	14	30.5	7.86

4.2. AVERAGE DRY WEIGHT OF SAMPLE A AND B

All test samples of the catalytic honeycomb were left to dry in a place for more than seventy two hours (72-hours). The dry weight of Sample A and B after being left to dry for more than

72 hours were 283g and 192 g respectively as shown in figure 4.1. Even though two samples were made with equal proportion of materials, the sawdust accounted for the extra decrease in weight of Sample B after air drying.

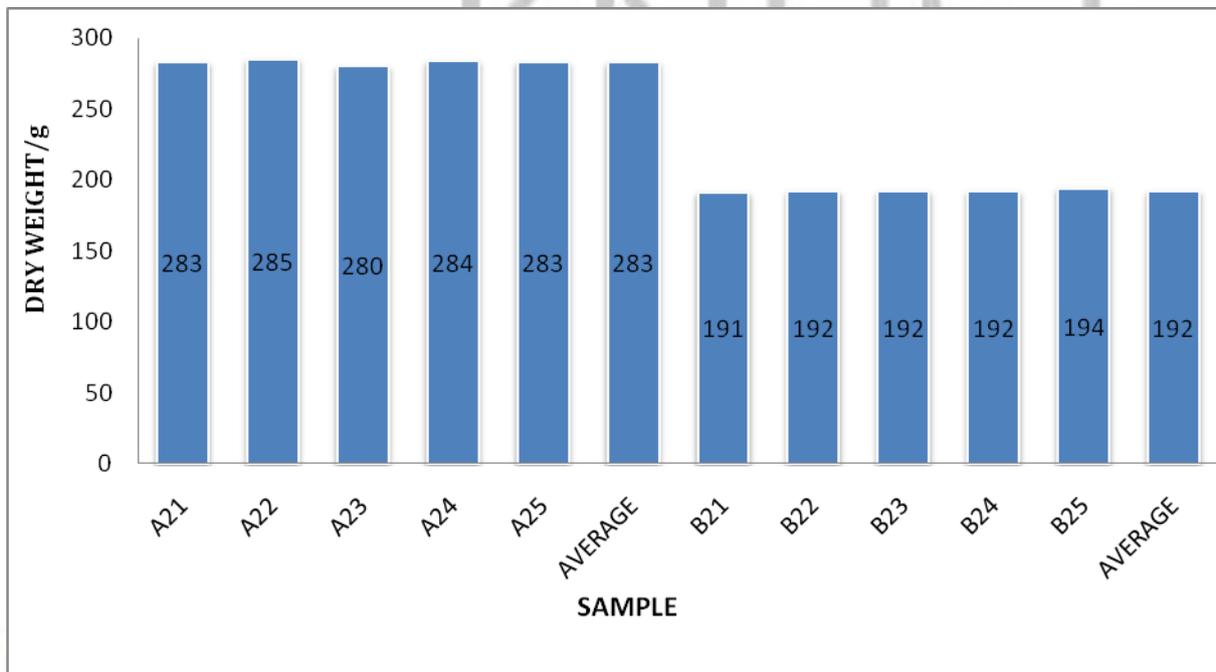


Figure 4.1: A bar graph showing average dry weight of sample A and B.



4.3. AVERAGE FIRED WEIGHT OF SAMPLE A AT 1000 °C AND 1150 °C

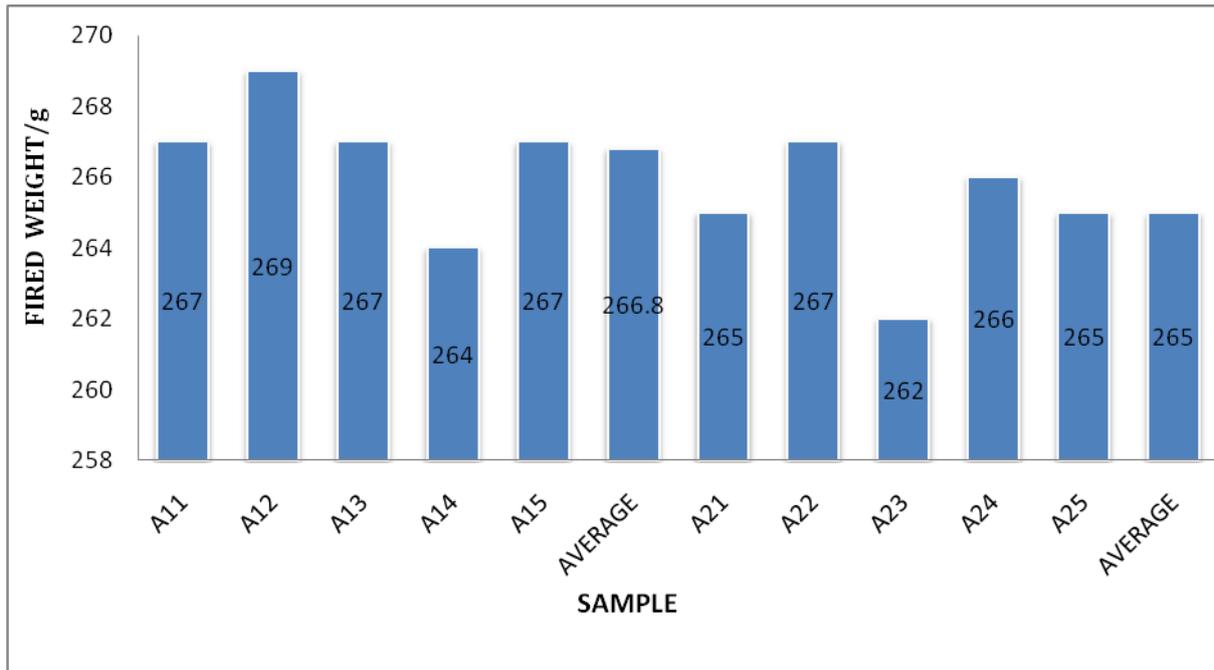


Figure 4.2: A bar graph showing average fired weight of sample A at 1000 °C and 1150 °C

After firing test Sample A at 1000 °C the average fired weight was found to be 267 g which is higher than the average fired weight of Sample A which has being fired again to 1150 °C of value 265 g as shown in figure 4.2. This difference in weight would have resulted from the fact that at 1000 °C the Sample still have some amount of volatile clay mineral component such as sulphate irons or lime which contributed to the increase in weight. With the test Sample at 1150 °C the decrease in weight would have resulted from the escape of most volatile clay minerals through the pores of the kiln

4.4. AVERAGE FIRED WEIGHT OF SAMPLE B AT 1000 °C AND 1150 °C.

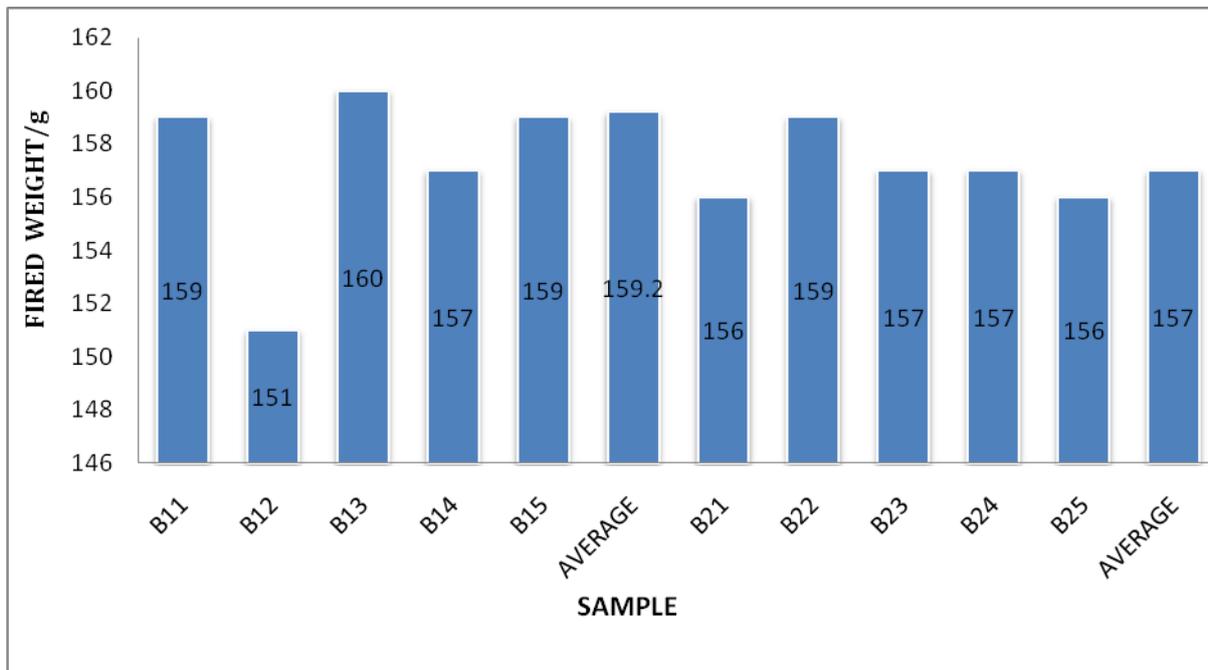
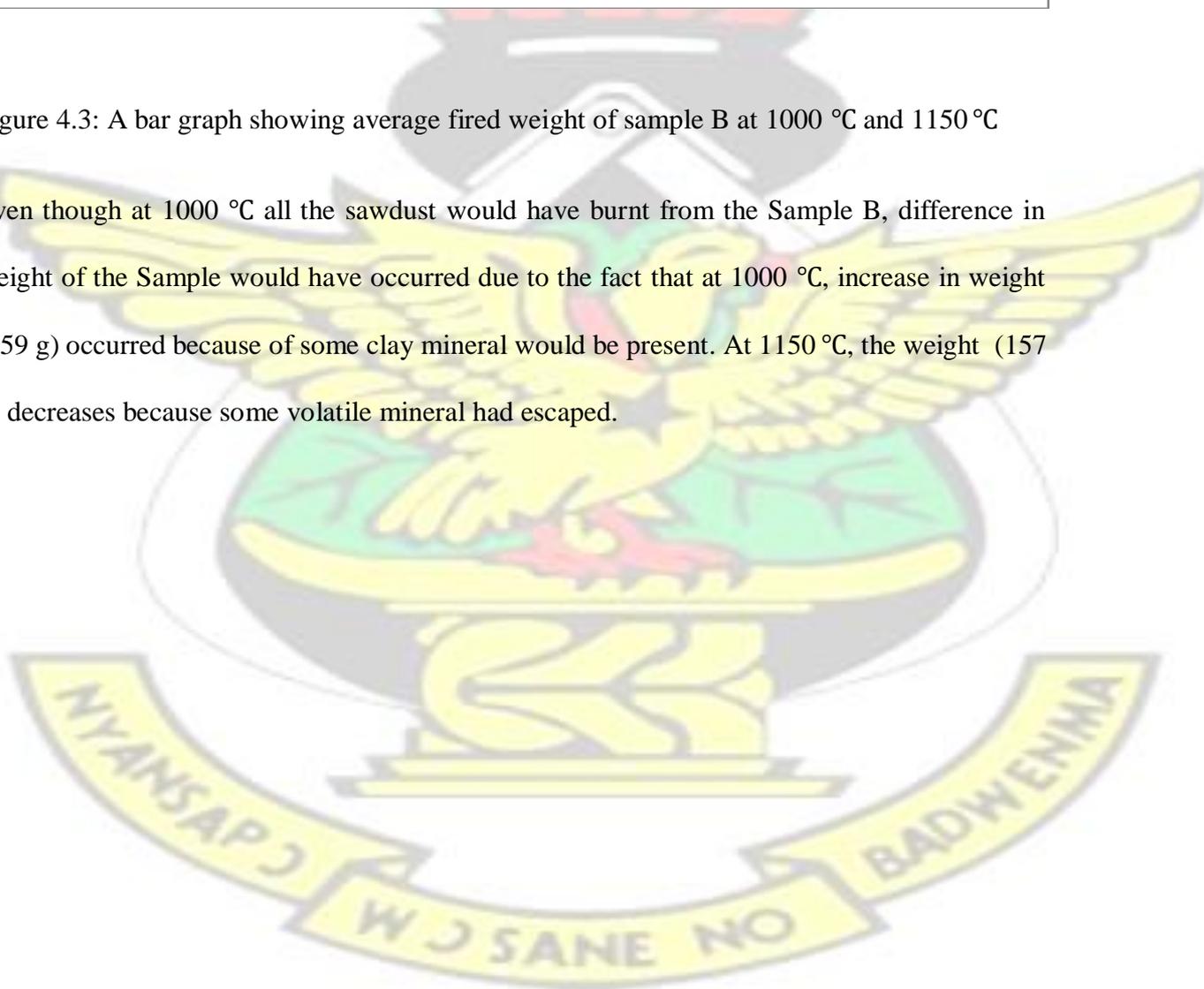


Figure 4.3: A bar graph showing average fired weight of sample B at 1000 °C and 1150 °C

Even though at 1000 °C all the sawdust would have burnt from the Sample B, difference in weight of the Sample would have occurred due to the fact that at 1000 °C, increase in weight (159 g) occurred because of some clay mineral would be present. At 1150 °C, the weight (157 g) decreases because some volatile mineral had escaped.



4.5. AVERAGE FIRED WEIGHT OF SAMPLE A AND B AT 1000 °C

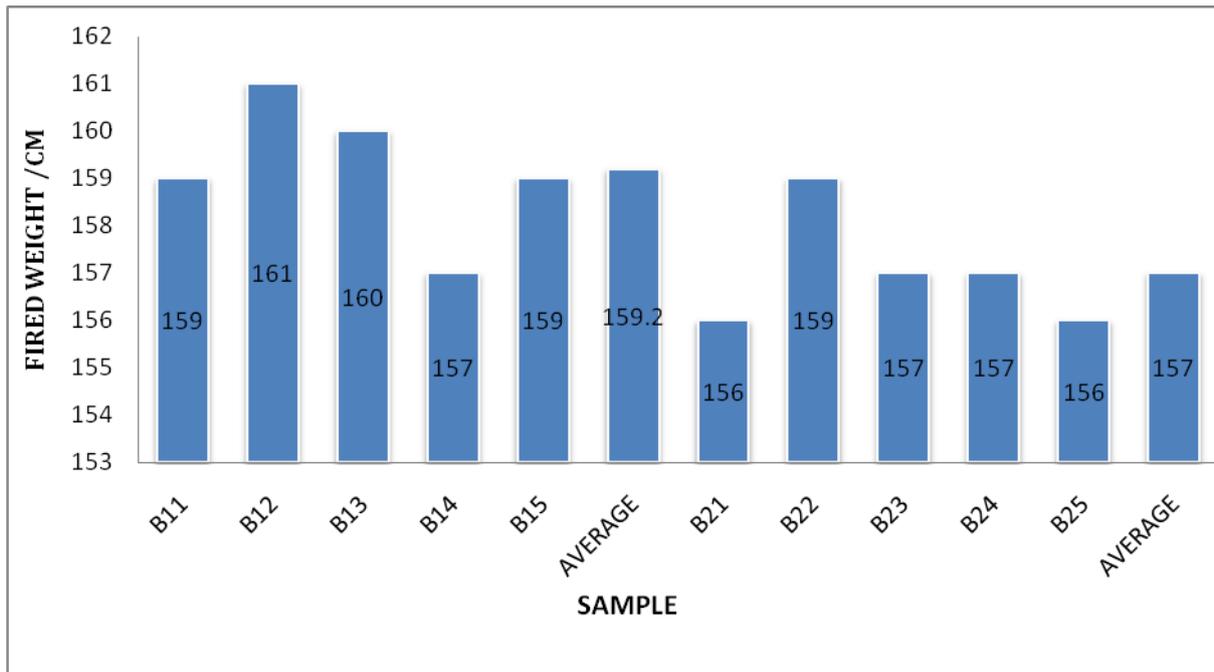


Figure 4.4: A bar graph showing average fired weight of test samples A and B at 1000 °C .

At 1000 °C the fired weight of test Sample A was found to be 267 g and that of test Sample B was also found to be 159 g as shown in figure 4.4. Even though the same proportion of material was used in the manufacture of each Sample, the difference in weight would have resulted from the following:

- a) The sawdust in Sample B would have burnt off at 1000 °C leaving more voids in test Sample B thus reducing the manufacturing weight to that drastic level.
- b) Test Sample A is found to be more dense, after most of the water and other minerals have escaped the weight may remain higher than that of test Sample B.

4.6. AVERAGE FIRED WEIGHT OF SAMPLE A AND B AT 1150 °C

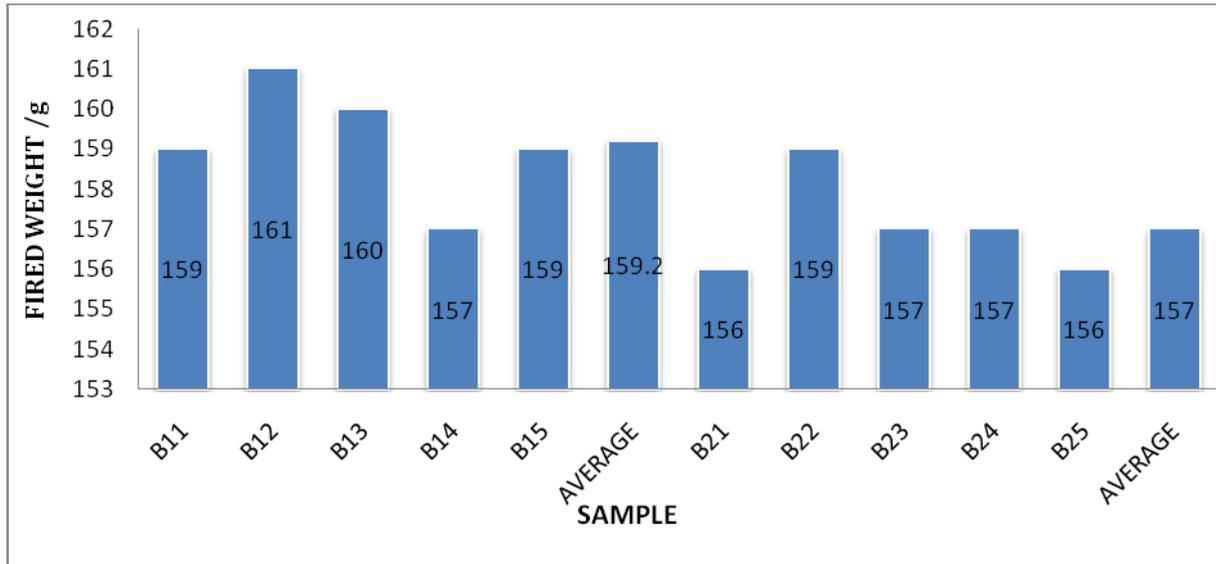


Figure 4.5: A bar graph showing average fired weight of test samples A and B at 1150 °C.

The fired weight of Samples A and B at 1150 °C were found to be 265 g and 157 g respectively as shown in figure 4.5. At 1150 °C there is a decrease in weight of the two Samples and this would be as a result of escape of some extract volatile clay mineral found in the Samples.

4.7. AVERAGE DRY SHRINKAGE OF SAMPLES A AND B.

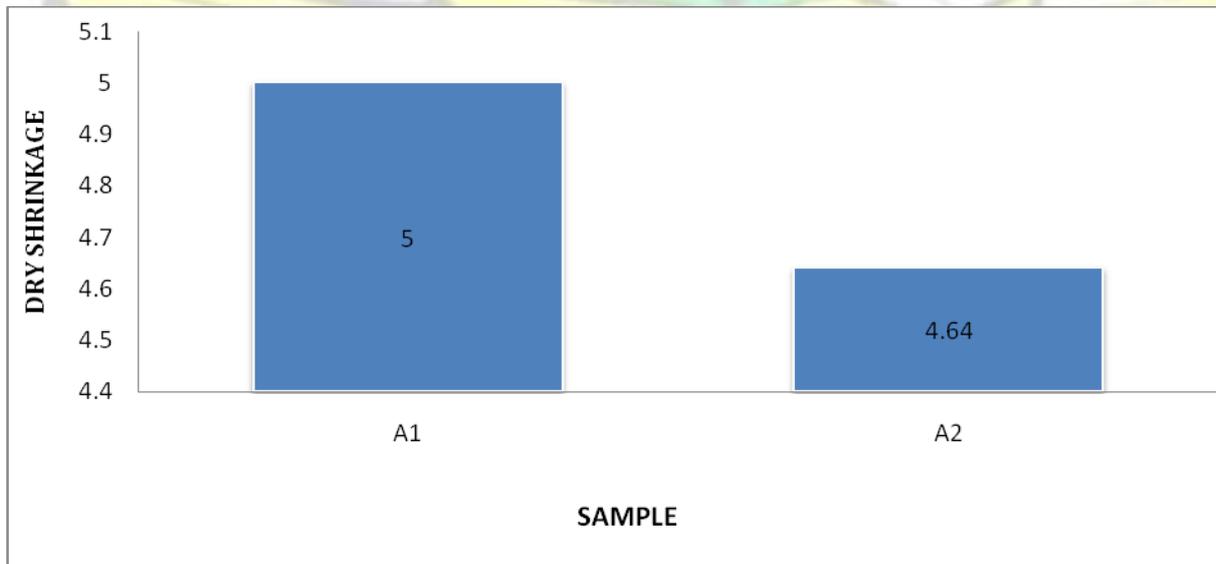


Figure 4.6: A bar graph showing average dry shrinkage (%) of sample A and B

During the drying process, at the same temperature (room temperatures) Sample A shrank by 2.0 % while Sample B shrank by 8 % as shown in figure 4.6.

Since the two Sample manufactured from the portion of water. But the difference in percentage is as a result of the sawdust incorporated in the Sample B. Sample A retains much water than sample B, thus if they are all given the same temperature today, Sample B will dry most since its quite lighter, and this lead to its high shrinkage.

4.8. AVERAGE FIRED SHRINKAGE OF SAMPLE A AT 1000 °C AND 1150 °C.

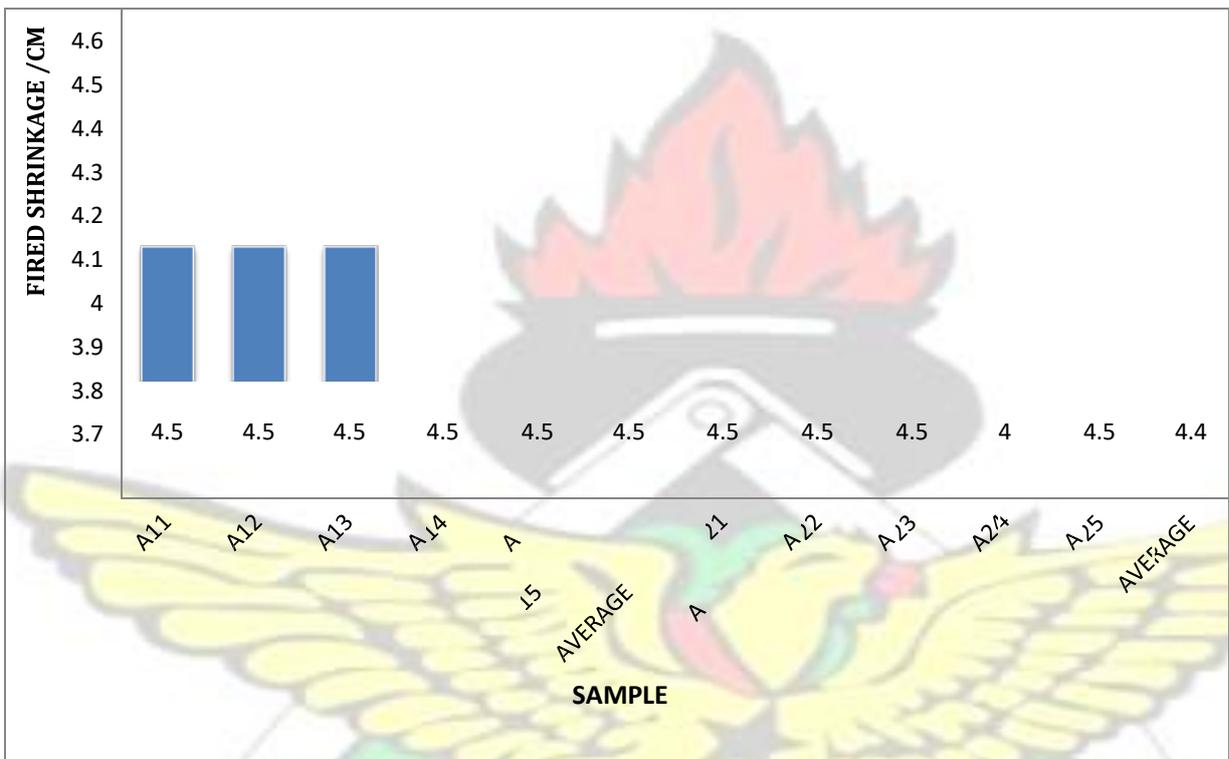


Figure 4.7: A bar graph showing average fired shrinkage (%) of sample A at 1000 °C and 1150 °C

All test Samples of Catalytic honeycomb shrank after firing. During the firing process, at a temperature of 1000 °C, it was observed that Sample A shrank by an average of 10 % while the Sample at 1150 °C shrank by an average of 12 %. This shows that at 1000 °C some amount of mineral oxides and volatile clay components may still be remaining

4.9. AVERAGE FIRED SHRINKAGE OF SAMPLE B AT 1000 °C AND 1150 °C

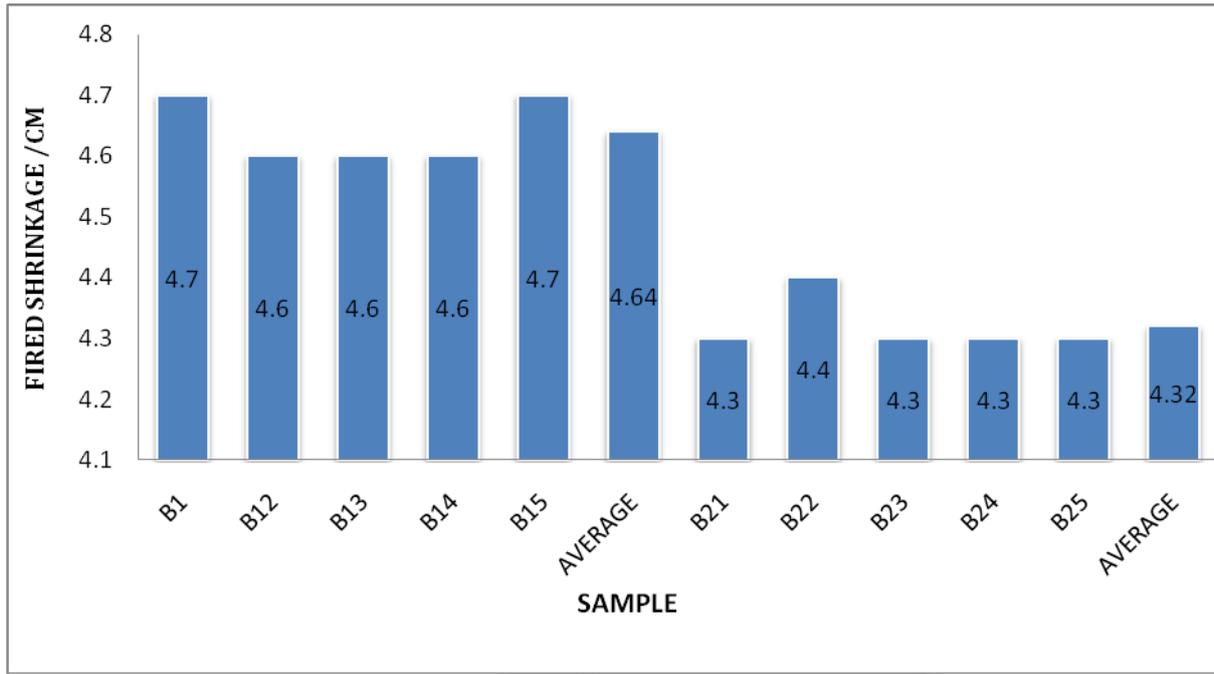


Figure 4.8: A bar graph showing average fired shrinkage (%) of sample B at 1000 °C and 1150 °C

The average fired shrinkage of Sample B at 1000 °C was found to be 10 % and that of Sample B at 1150 °C was also found to be 14 %. The higher percentage of shrinkage of the Sample at 1150 °C also resulted from the burning away of excess sawdust and other volatile clay components.

4.10. AVERAGE FIRED SHRINKAGE OF SAMPLE A AND B AT 1000 °C.

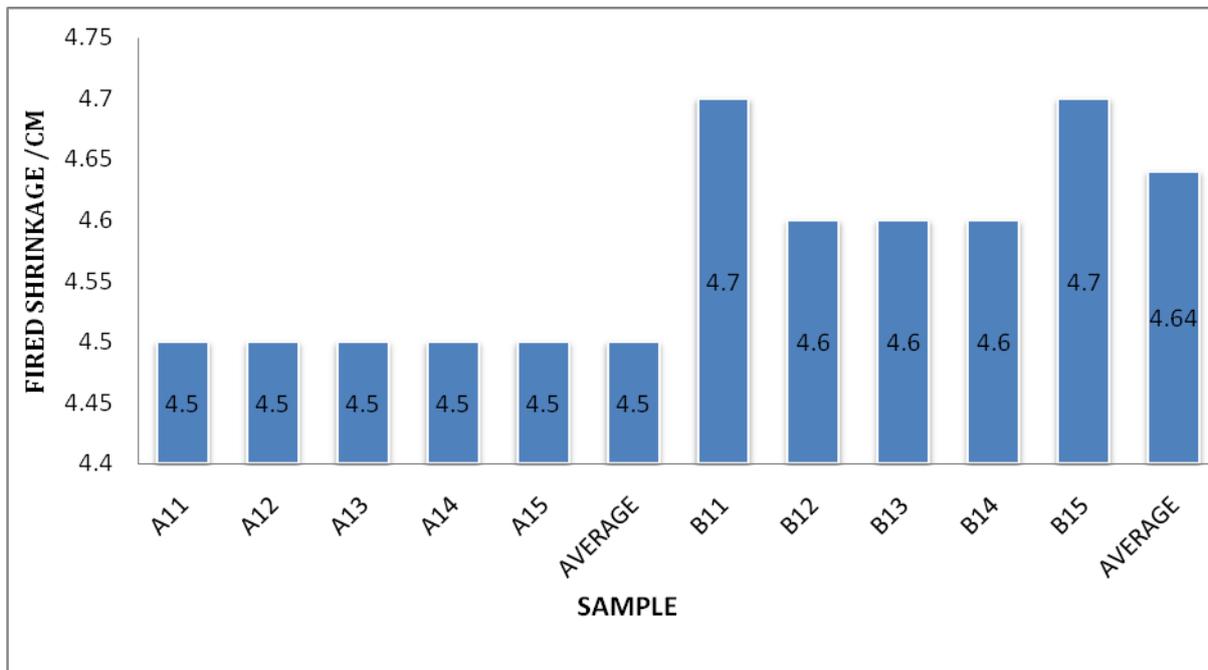


Figure 4.9: A bar graph showing average fired shrinkage (%) of samples A and B at 1000 °C

From the graph above, it can be observed that the average percentage shrinkage for Sample A at 1000 °C was 10.0 % and that of Sample B was also 10.0 %. This could have been a result of the easy and effective drying of the Sample B at the initial stage.

4.11. AVERAGE FIRED SHRINKAGE OF SAMPLE A AND B AT 1150 °C.

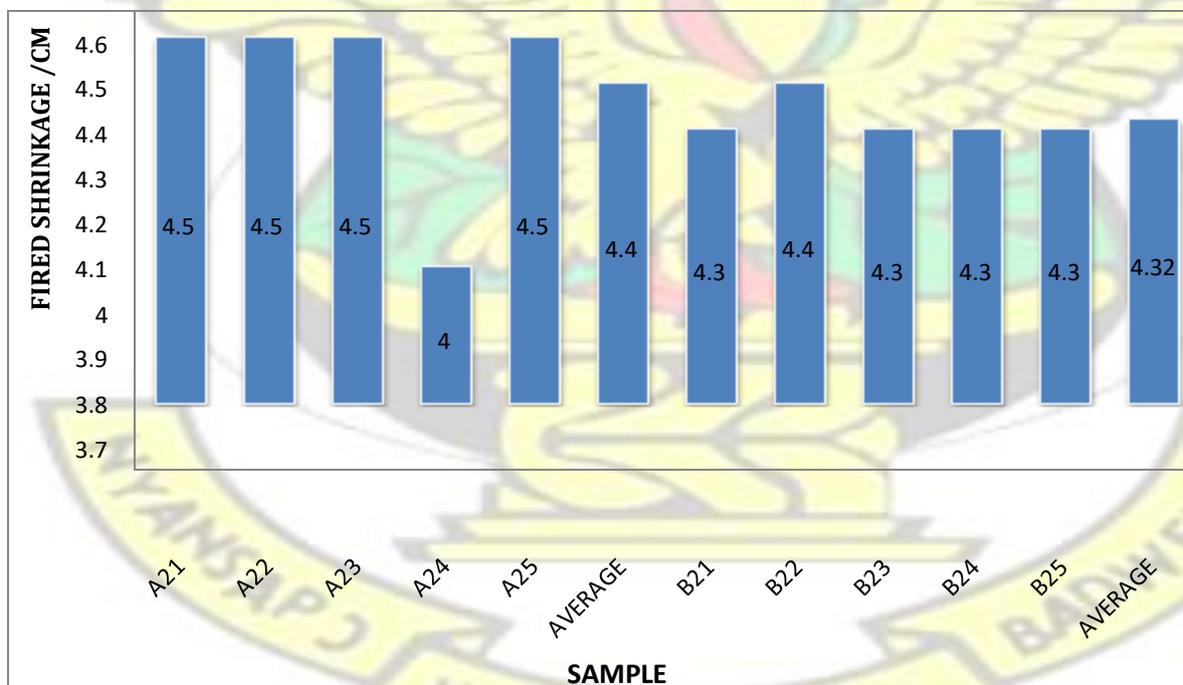


Figure 4.10: A bar graph showing average fired shrinkage (%) of samples A and B at 1150 °C

Average fired shrinkage of Sample A at 1150 °C was found to be 12 % while the average fired shrinkage for Sample B at 1150 °C was also found to be 14 % (as shown in figure4.10). It could

be observed that at this temperature Sample B had the most shrinkage which is quite insignificant. This could have resulted from the burning away of the extra sawdust (impurities) which have stayed on till this temperature.

4.12. AVERAGE SOAKED WEIGHT OF SAMPLE A AND B AT 1000°C

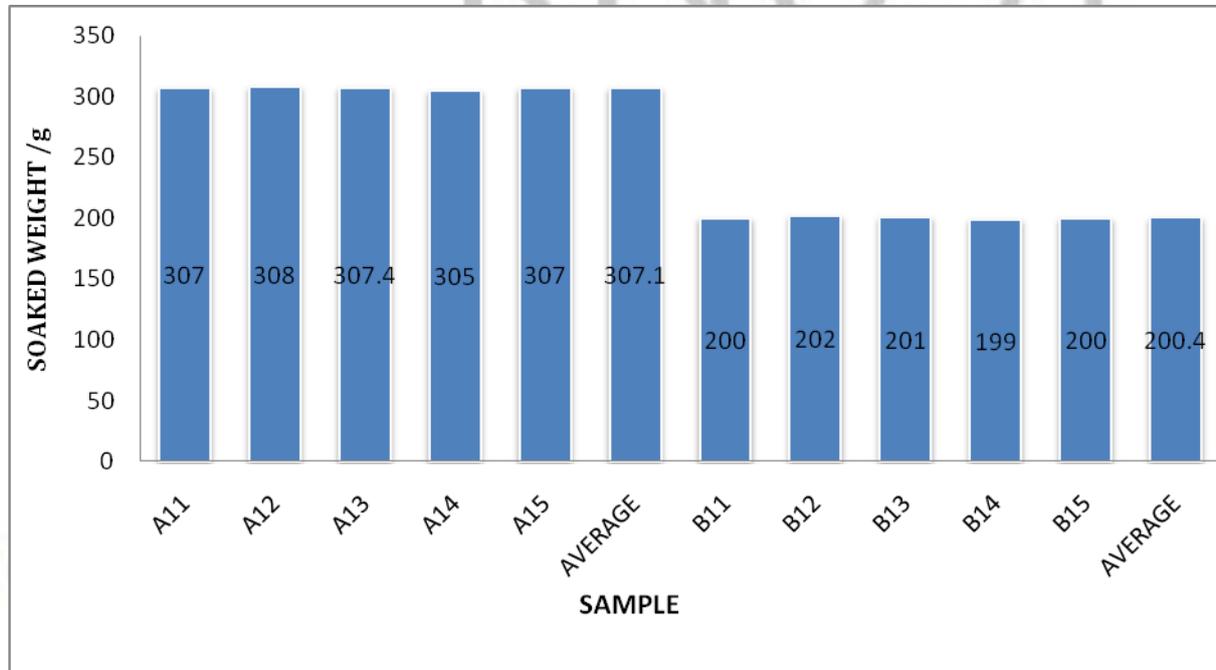


Figure 4.11: A bar graph showing average fired soaked weight of test samples A and B at 1000 °C.

The average soaked weight of test Sample B was found to be 2.00×10^{-1} kg which is higher in terms of water absorption than the average soaked weight of test Sample A which is 3.07×10^{-1} kg. Test Sample B contains sawdust which burns at that higher temperature thus leaving more pores in it, thus making it possible to absorb more than test Sample A which does not contain sawdust.

4.13. AVERAGE SOAKED WEIGHT OF TEST SAMPLES A AND B AT 1150 °C

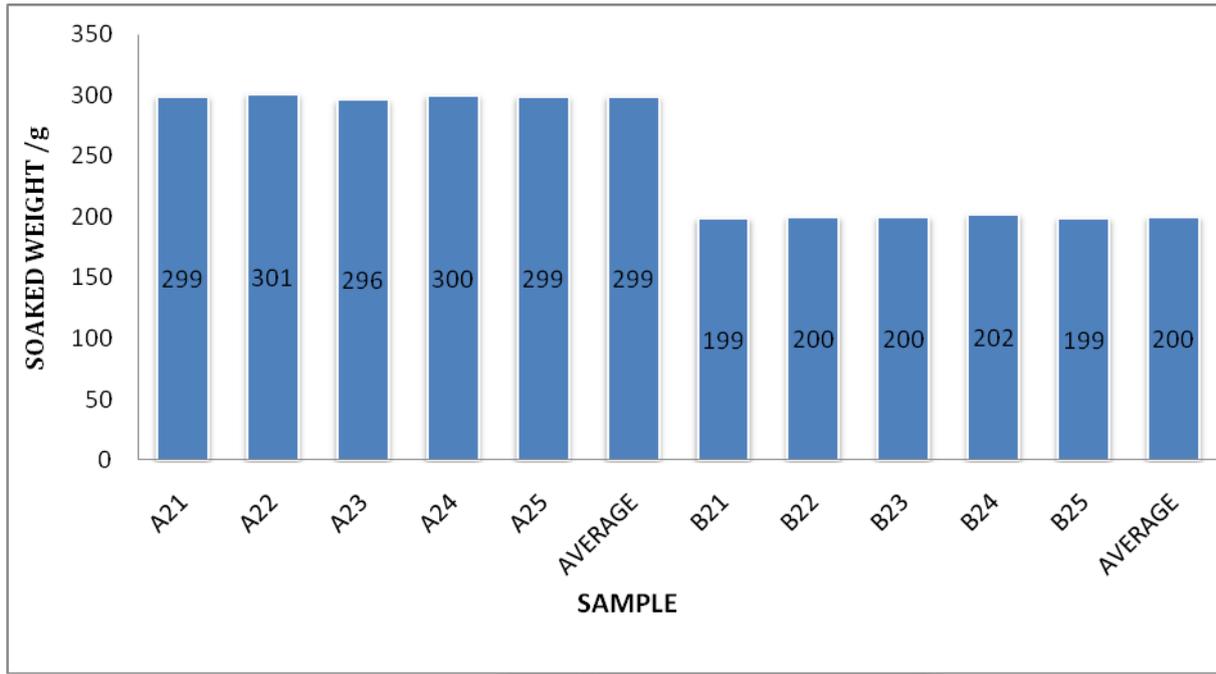


Figure 4.13: A bar graph showing average fired soaked weight of test samples A and B at 1150 °C

Average soaked weight of test Sample B was found to be 1.99×10^{-1} kg which is higher in terms of water absorption than the average soaked weight test Sample A which is 2.99×10^{-1} kg. Test Sample B possesses a higher soaked weight because it contains more pores than test Sample A. This is as a result of average of variation manufacturing materials.

4.14.0 AVERAGE % POROSITIES AT 1000 °C AND 1150 °C OF SAMPLE A

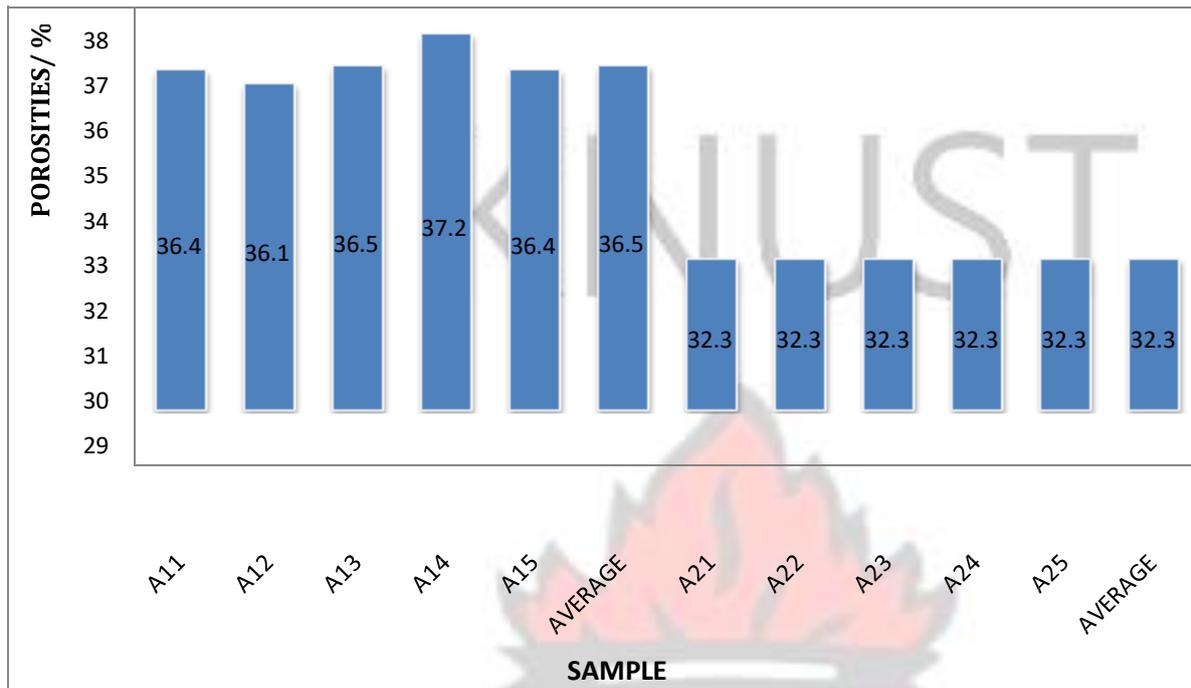


Figure 4.14.0 A bar graph showing average % porosities of sample A at 1000 °C and 1150 °C

Porosity of burnt clay honeycomb is paramount due to the number as well as the sizes of open pores into which water (smoke) can be soaked in. The test Samples A₁ was fired at 1000 °C and test Sample A₂ was fired at 1150 °C, both were soaked in boiling water (1000 °C) and left in the boiling water for twenty-four hours. Bubbles of various dimensions were observed to be emanating from the test samples. This observation signified the presence of air trapped in the open pores of the test sample during the heating process which was gradually forced out and replaced by the water molecule. After measuring their respective weights after being brought out and cooled, it was observed that their weights have increased which indicates the presence of water molecules in the test samples. After the heating and soaking of the test sample, it was observed that the test sample A₁ posses an average apparent porosity value of 36.5 % which is higher than that of A₂ which is also 32.3 %. This observation could be interpreted relatively; the water molecules under pressure for several hours were able to penetrate the smaller

capillary pores of both samples. The absorption values of both test samples were relatively fast although that of A₂ was a bit faster.

The observation in difference in apparent porosity between the two test samples also attests to the fact that the rate of a material depends on the size and number of open pores. High porosity value can be reduced by good compactly of aggregates in the honeycomb.

4.14.1 AVERAGE % POROSITIES AT 1000 °C AND 1150 °C OF SAMPLE B

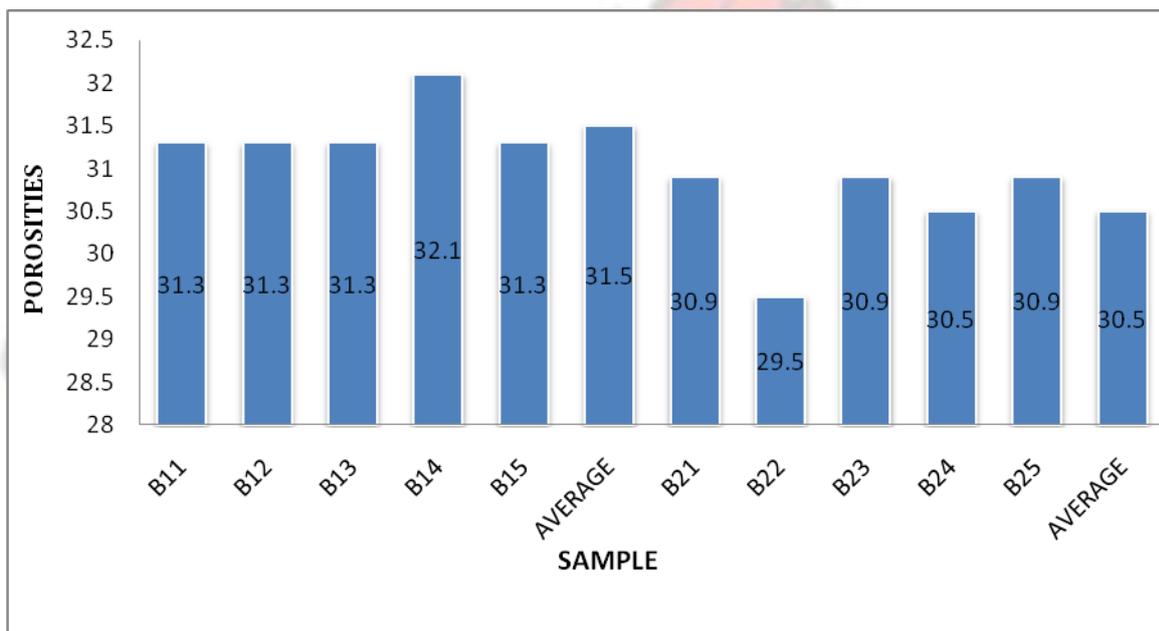


Figure 4.14: A bar graph showing average % porosities of sample B at 1000 °C and 1150 °C

After the absorption test the percentage (%) porosity of sample B₁ was found to be 31.5 % and that of B₂ was 30.5 %. This observation could also be interpreted by the number of open pore found in the test sample.

4.14.2. AVERAGE % POROSITY AT 1150 °C OF SAMPLE A AND B

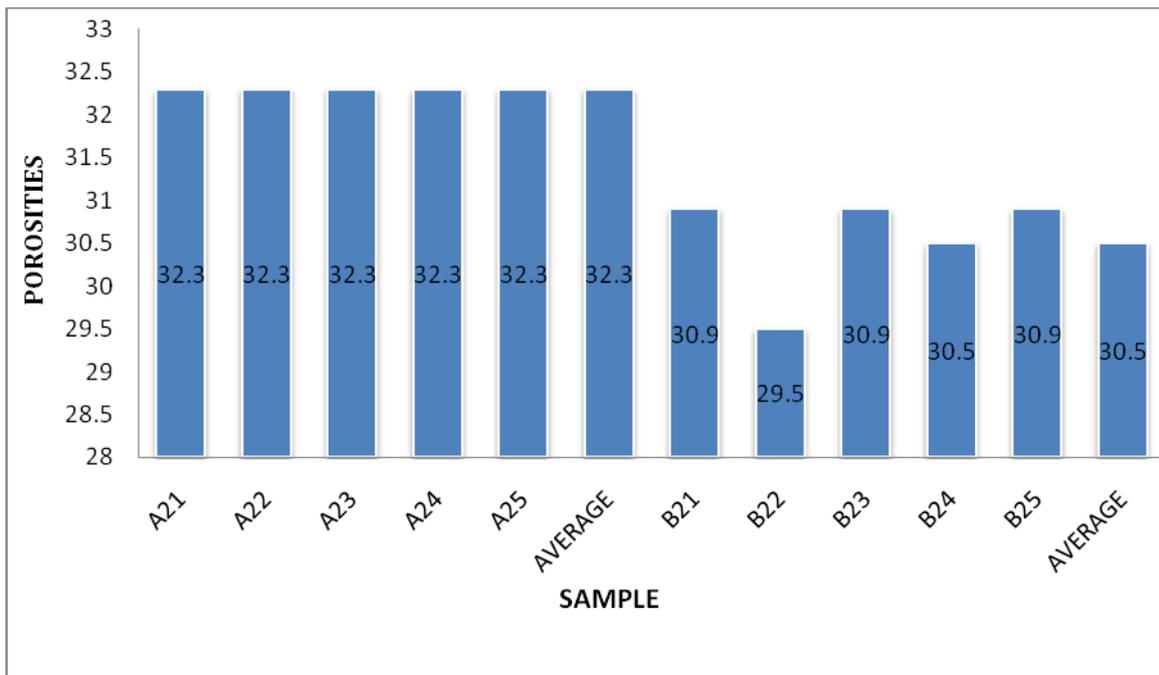


Figure 4.15: A bar graph showing average porosity % of test samples A and B

After the absorption test, test Sample A₂ had an average porosity of 32.3 % while that of test Sample B₂ was found to be 30.5 % signifying that test Sample B₂ at the same temperature as that of A₂ has more open pores thus a higher absorption rate and a reduction in the % apparent porosity.

4.15. AVERAGE COMPRESSIVE STRENGTHS OF SAMPLE A AT 1000°C AND 1150°C

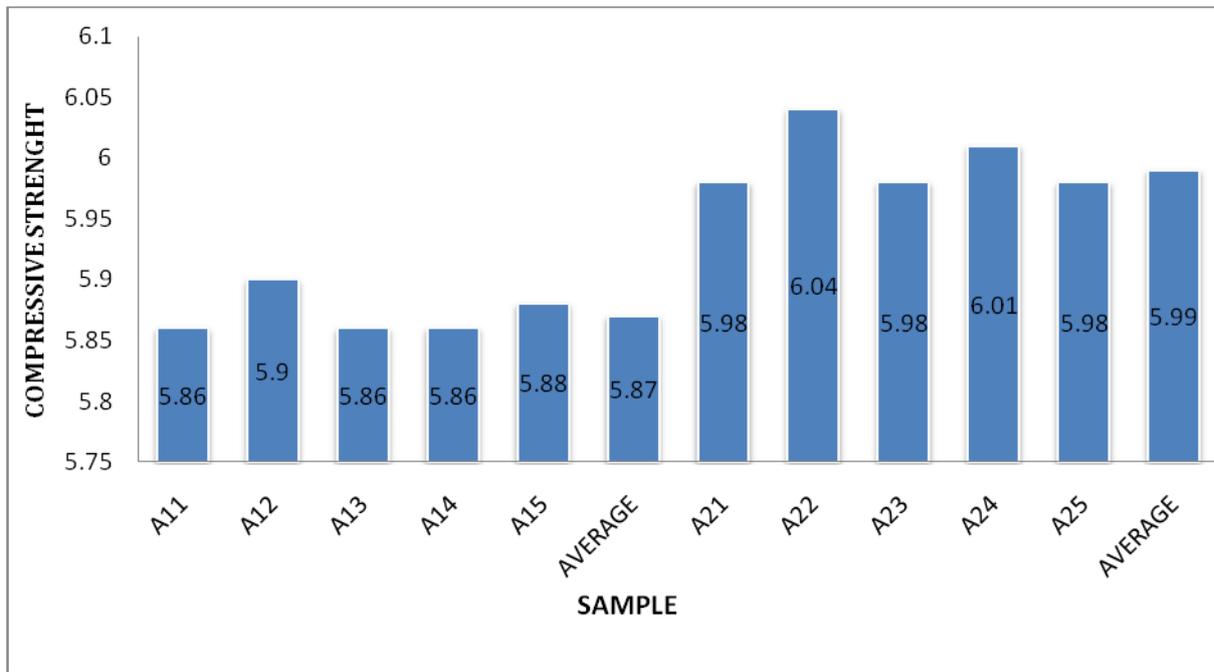


Figure 4.16: A bar graph showing average compressive strengths of fosu clay at 1000 °C and 1150 °C of sample A

After the compression test it was found that the average compressive strength of test Sample A fired at 1000 °C and 1150 °C were (5.87 ± 0.07) KNmm^{-2} and (5.99 ± 0.04) KNmm^{-2} respectively. The interpretation of the higher value obtained for test Sample A at 1150 °C indicates that higher temperature firing has removed all chemically combined water in the clay which made it more compact and hence the relative high resistance to fracture. It could also be that the higher temperature firing has caused some of the silica molecules present in the clay to introduce glass-like phases which in turn increase the strength of the honeycomb. When this happens, dislocation movement could be extremely difficult because of the walled bound particles they possess. The particles are strongly bounded together hence dislocation motion along certain crystallographic direction will be hindered by strong network. At failure, the test samples cracked into fragments. Upon close examination, it was realized that the failure could be associated to internal imperfection resulting in uneven stress distribution.

4.15.1 AVERAGE COMPRESSIVE STRENGTH OF SAMPLE B AT 1000 °C AND 1150 °C

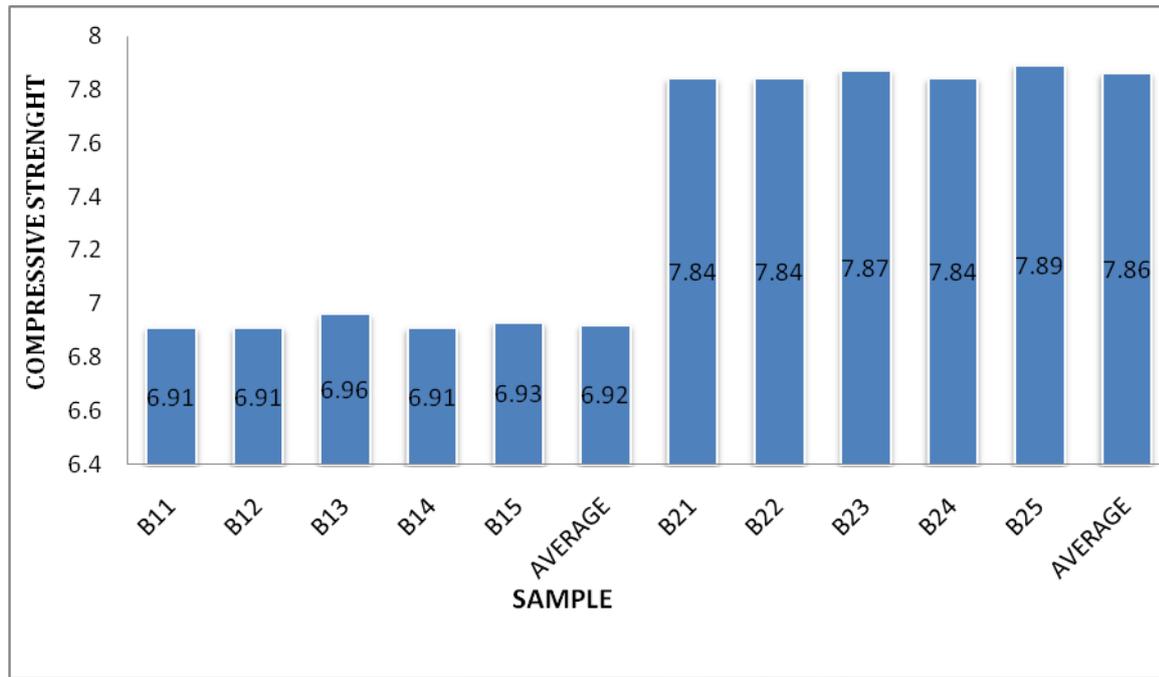


Figure 4.17: A bar graph showing average compressive strengths of fosu clay at 1000 °C and 1150 °C of sample B

The compression of Sample B also indicated the compressive strength of the test Sample B at 1000 °C and 1150 °C were $(6.92 \pm 0.07) \text{ KNmm}^{-2}$ and $(7.86 \pm 0.05) \text{ KNmm}^{-2}$ respectively. The interpretation of the higher value obtained to a test sample at 1150 °C indicates that higher temperature firing has removed all the chemically combined water in the clay which made it more compact and hence the relative high resistance to fracture.

CHAPTER FIVE CONCLUSION AND RECOMMENDATION 5.1. CONCLUSION

In the study of the manufacture of honeycomb in catalytic conversion of automobile exhaust system, using local clay components, (a case study of the clay’s mechanical properties), the following deduction were made: The porosity of Sample A fired at 1000 °C and 1150°C were

36.5 % and 32.3 % respectively. The difference in porosity between the same sample fired at different temperatures was due to the fact that at 1150 °C most of the organic compounds in the sample would have burnt and escaped thus leaving more pore in the sample fired at 1150 °C thus accounting for the smaller value in apparent porosity which indicates that the sample is more porous. Again, Sample A at 1150 °C has a higher compressive strength than the same sample at 1000 °C, the difference in compressive strength was due to the fact that at 1150 °C the sample has been fully sintered thus making it free from excess water and other inorganic substances. This made the sample at 1150 °C very difficult to break compared with the sample fired at 1000 °C which was partially sintered at that temperature. At 1000 °C, Sample A had a fired shrinkage of 10 % and at 1150 °C sample A had an average fired shrinkage of 12 %. At 1000 °C the sample will have been partly sintered but at 1150 °C most organic components would have been given out thus a large reduction in size of the Sample compared with the sample treated to 1000 °C. The porosity of Sample B fired at 1000 °C and 1150 °C were found to be 31.5 % and 30.5 % respectively. The compressive strengths were also $(6.92 + 0.07$ and $7.86 + 0.07) \times 10^{-3}$ KNmm⁻² respectively. The sample also had their fired shrinkages to be 11 % and 14 % for 1000 °C and 1150 °C respectively. The reasons for these results came as a result of the extra heat treatment which was undergone by the sample treated at 1150 °C. Upon further comparison it was realized that Sample A and B treated at 1150 °C were chosen but Sample B was chosen as the best for the manufacture of catalytic honeycomb due to the following reasons:

- Sample B fired 1150 °C had a percentage shrinkage of 14 % of its dried sample which Sample A at 1150 °C had a percentage shrinkage of up to 12 % of its original dry sample.
- The sawdust which were in corporation in the Sample B caused this difference in that as Sample A is all clay and the spaces between particles after firing will not be much but in the case of Sample B the sawdust incorporated would have caused the increase in distance between the clay particles.

- In the case of porosity, the porosities for Sample A and B at 1150 °C were 32.3 % and 30.5 % respectively. This indicates that Sample B at 1150 °C is very porous since a smaller value apparent porosity indicates the low porous the material is.

Here the spaces the sawdust where occupying would serve as extra pores thus the lower apparent porosity.

- The compressive strength was found to be $5.99 \times 10^{-3} \text{ KNmm}^{-2}$ and $7.86 \times 10^{-3} \text{ KNmm}^{-2}$ for Samples A and B respectively. Even though they have been treated to the same temperature, Sample B had a higher compressive strength compared with that of Sample A, thus making Sample B stronger which can withstand the excess heat and resist all manufacturers of shocks produced by the engine.

Comparing these apparent porosity values with that of American Standard and Testing Machines (ASTM) where 1 % to 1.5 % is a second class honeycomb and 1% being a first class honeycomb in cold regions, then in tropical regions like Ghana, the sample with an apparent porosity of 30.5. % will work well.

5.2. RECOMMENDATION

- Below are the recommendations made for future study and use.

It is however recommended that further investigations should be conducted on the clay materials to a certain input parameters such as; the major component of the clay materials and their impact on the refractoriness of the clay materials and also the thermal shock resistance as a result of rapid temperature variations.

Further studies can be conducted to ascertain the economic viability of commercial honeycomb production using Fosu Clay.

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APPENDIX A

TABLE 9

SAMPLE	GREEN LENGTH	DAYLENGTH	% DRY SHRIKAGE
A1	5	4.9	2
A2	5	4.9	2

Average=2

TABLE 10

SAMPLE	GREEN LENGTH	DAY LENTGH	% DRY SHRINKAGE
B1	5	4.7	8.6

B2	5	4.5	10
----	---	-----	----

Average=9.3

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TABLE 11

SAMPLE A	GREEN LENGTH	FIRED LENGTH	% FIRED SHRINKAGE
A1	5	4.5	10
A2	5	4.5	10

TABLE 12

SAMPLE	GREEN LENGTH	FIRED LENGTH	% FIRED SHRINKAGE
A1	5	4.4	12
A2	5	4.4	12

TABLE E 13

SAMPLE	GREEN LENGTH	FIRED LENGTH	% FIRED SHRINKAGE
B1	5	4.6	8
B2	5	4.4	12

Average=10

TABLE 14

SAMPLE	GREEN LENGTH	FIRE LENGTH	% FIRE SHRINKAGE
B1	5	4.3	14
B2	5	4.3	14

TABLE 15

SAMPLE	DRY WEIGHT	DRY SHRINKAGE	FIRE SHRINKAGE	FIRE WEIGHT	SOAKED WEIGHT IN AIR	SOAKED WEIGHT IN WATER
A11	283	5	4.5	267	307	197
A12	285	5	4.5	269	309	198
A13	284	5	4.5	267	307.4	196.6
A14	280	5	4.5	264	305	195
A15	283	5	4.5	267	307	197
Average	283	5	4.5	266.8	307.1	196.7

TABLE 16

SAMPLE	DRY WEIGHT	DRY SHRINKAGE	FIRE SHRINKAGE	FIRE WEIGHT	SOAKED WEIGHT IN AIR	SOAKED WEIGHT IN WATER
A21	283	4.5	4.5	265	299	194
A22	285	4.5	4.5	267	301	196
A23	280	5	4.5	262	296	191
A24	284	4.5	4.0	266	300	195
A25	283	5	4.5	265	299	194
Average	283	4.9	4.4	265	299	194

TABLE 17

SAMPLE	DRY WEIGHT	DRY SHRINKAGE	FIRED SHRINKAGE	FIRED WEIGHT	SOAKED WEIGHT IN AIR	SOAKED WEIGHT IN WATER
B ₁₁	191	4.7	4.7	159	200	69
B ₁₂	193	4.6	4.6	161	202	71
B ₁₃	192.2	4.6	4.6	160	201	70
B ₁₄	191	4.6	4.6	157	199	68
B ₁₅	191	4.7	4.7	159	200	69
Average	191.64	4.64	4.64	159.2	200.4	69.4

TABLE 18

SAMPLE	DRY WEIGHT	DRY SHRINKAGE	FIRED SHRINKAGE	FIRED WEIGHT	SOAKED WEIGHT IN AIR	SOAKED WEIGHT IN WATER
B ₂₁	191	4.6	4.3	156	199	60
B ₂₂	192	4.6	4.4	159	200	61
B ₂₃	192	4.5	4.3	157	200	61
B ₂₄	192	4.5	4.3	157	202	63
B ₂₅	194	4.6	4.3	156	199	61
Average	192	4.6	4.32	157	200	60.6

TABLE 19

SAMPLE	POROSITY (%)
A ₁₁	36.4
A ₁₂	36.1
A ₁₃	36.5
A ₁₄	37.2
A ₁₅	36.4
AVERAGE	36.5

TABLE 20

SAMPLE	POROSITY (%)
A ₂₁	32.3
A ₂₂	32.3

A ₂₃	32.3
A ₂₄	32.3
A ₂₅	32.3
AVERAGE	32.3

TABLE 21

SAMPLE	POROSITY (%)
B ₁₁	31.3
B ₁₂	31.3
B ₁₃	31.3
B ₁₄	32.1
B ₁₅	31.3
AVERAGE	31.5

TABLE 22

SAMPLE	POROSITY (%)
B ₂₁	30.9
B ₂₂	29.5
B ₂₃	30.9
B ₂₄	30.5
B ₂₅	30.9
AVERAGE	30.5

TABLE 23

SAMPLE	COMPRESSIVE STRENGTH
A ₁₁	5.86×10^{-3}
A ₁₂	5.9×10^{-3}
A ₁₃	5.86×10^{-3}
A ₁₄	5.86×10^{-3}
A ₁₅	5.88×10^{-3}
AVERAGE	5.87×10^{-3}

TABLE 24

SAMPLE	COMPRESSIVE STRENGTH
A ₂₁	KNmm ⁻²
A ₂₁	5.98×10^{-3}
A ₂₂	6.04×10^{-3}
A ₂₃	5.98×10^{-3}
A ₂₄	6.01×10^{-3}
A ₂₅	5.98×10^{-3}

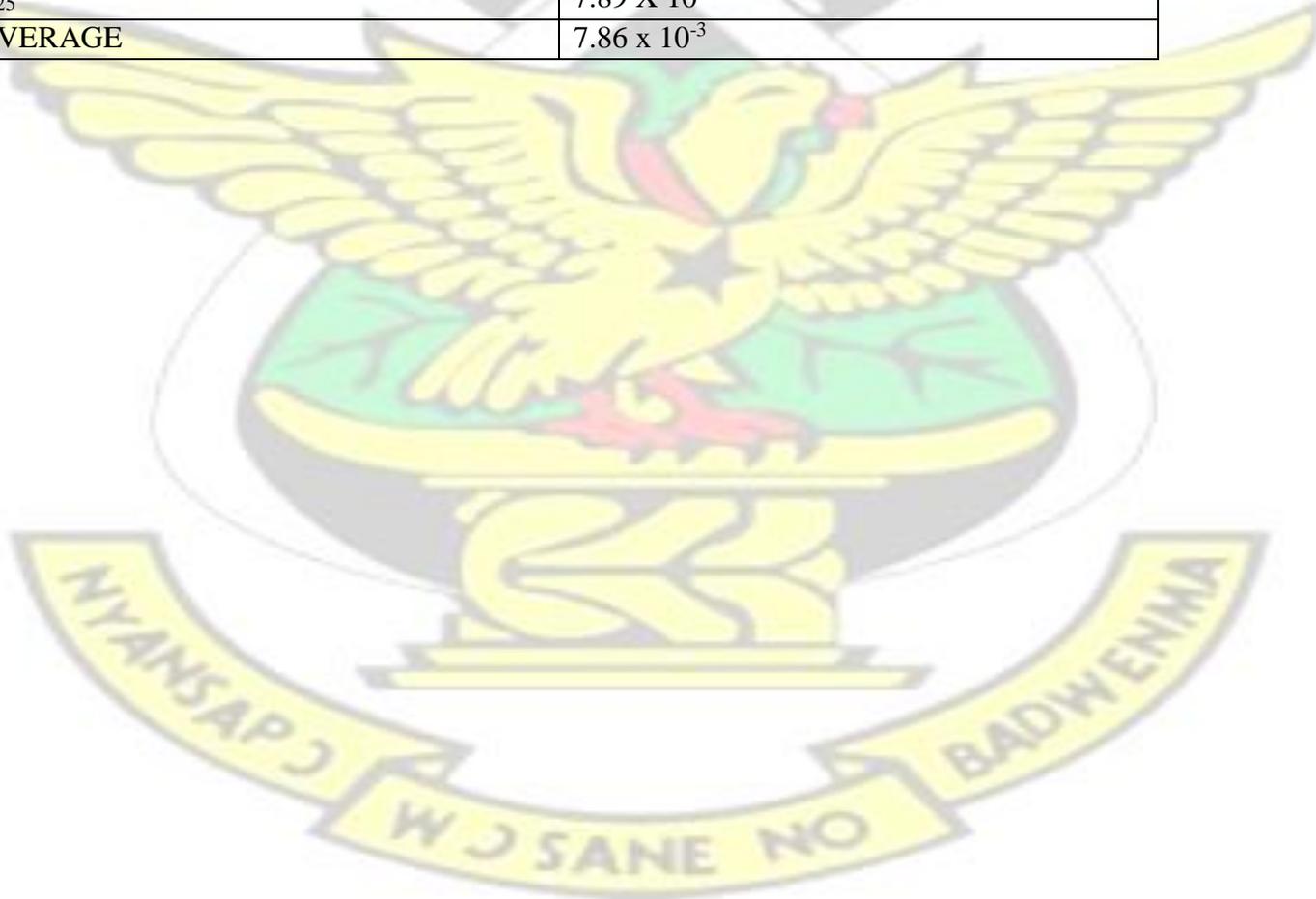
AVERAGE	5.99×10^{-3}
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TABLE 25

SAMPLE	COMPRESSIVE STRENGTH
B ₁	KNmm ⁻²
B ₁₁	6.91×10^{-3}
B ₁₂	6.91×10^{-3}
B ₁₃	6.96×10^{-3}
B ₁₄	6.91×10^{-3}
B ₁₅	6.93×10^{-3}
AVERAGE	6.92×10^{-3}

TABLE 26

SAMPLE	COMPRESSIVE STRENGTH
B ₂₁	7.84×10^{-3}
B ₂₂	7.84×10^{-3}
B ₂₃	7.87×10^{-3}
B ₂₄	7.84×10^{-3}
B ₂₅	7.89×10^{-3}
AVERAGE	7.86×10^{-3}



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APPENDIX B

$$\text{POROSITY} = \frac{W_s - W_d}{W_s - W_w} \times 100\%$$

POROSITY OF A

A₁

A₁₁

$$W_s = 307$$

$$W_d = 267$$

$$W_w = 197$$

$$= \frac{307 - 267}{307 - 197} \times 100\%$$

$$= \frac{40}{110}$$

$$= 1.667\%$$

$$= \frac{40}{110} \times 100\%$$

$$= 36.4\%$$

A₁₂

$$W_s = 309$$

$$W_w = 198$$

$$W_d = 269$$

$$\text{POROSITY} = \frac{W_s - W_d}{W_s - W_w} \times 100\%$$

$$= \frac{309 - 269}{309 - 198} \times 100\%$$

$$= \frac{40}{111}$$

$$= 36.1\%$$

KNUST

A₁₃

$$W_d = 267$$

$$W_w = 196.6$$

$$W_s = 307.4$$

$$= \frac{W_s - W_d}{W_s - W_w} \times 100\%$$

$$= \frac{307.4 - 267}{307.4 - 196.6} \times 100\%$$

$$= \frac{40.4}{110.8}$$

$$= 36.5\%$$

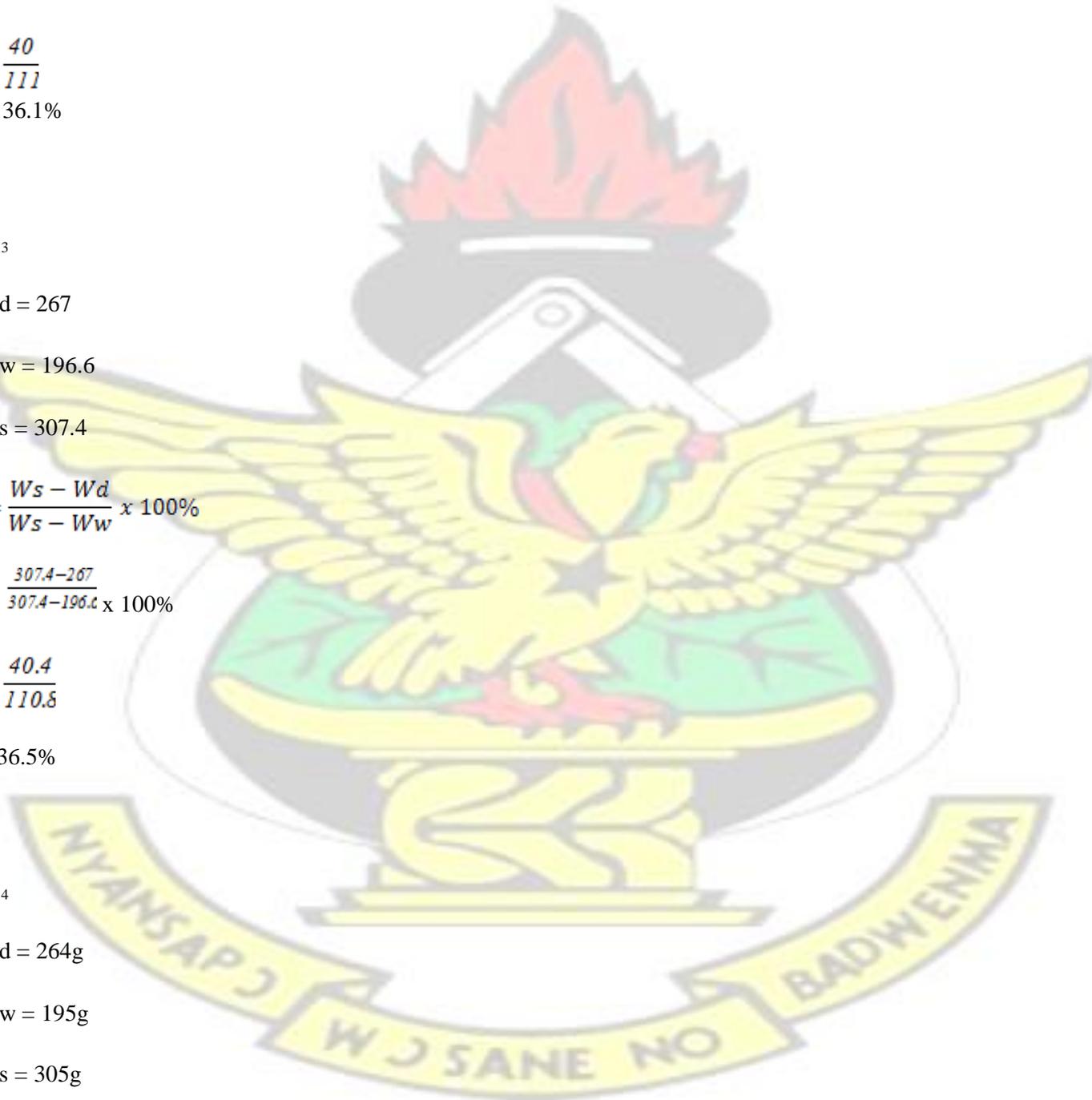
A₁₄

$$W_d = 264g$$

$$W_w = 195g$$

$$W_s = 305g$$

$$\frac{W_s - W_d}{W_s - W_w} \times 100\%$$



$$\frac{41}{116}$$

$$= 37.2\%$$

KNUST

A_{15}

$$W_d = 267\text{g}$$

$$W_w = 197\text{g}$$

$$W_s = 307\text{g}$$

$$\frac{w_s - w_d}{w_s - w_w} \times 100\%$$

$$= \frac{307 - 267}{307 - 197} \times 100\%$$

$$= \frac{40}{116}$$

$$= 36.4\%$$

$$\text{S. D.} = \sqrt{\frac{x-x}{n}}$$

$$\sqrt{\frac{(36.4 - 36.5)^2}{5} + \frac{(36.1 - 36.5)^2}{5} + \frac{(36.5 - 36.5)^2}{5} + \frac{(37.2 - 36.5)^2}{5} + \frac{(36.4 - 36.5)^2}{5}}$$

KNUST

A₂

A₂₁

$$W_s = 299\text{g}$$

$$W_d = 265\text{g}$$

$$W_w = 212\text{g}$$

$$= \frac{W_s - W_d}{W_s - W_w} \times 100\%$$

$$= \frac{299 - 265}{299 - 212} \times 100\%$$

$$= \frac{34}{105}$$

$$= 32.3\%$$

A₂₂

$$W_s = 307\text{g}$$

$$W_d = 267\text{g}$$

$$W_w = 196\text{g}$$

$$= \frac{W_s - W_d}{W_s - W_w} \times 100\%$$

$$= \frac{307 - 267}{307 - 196} \times 100\%$$

$$= \frac{34}{1056}$$

$$= 32.3\%$$

KNUST

A₂₃

$$W_s = 296 \text{ g}$$

$$W_d = 262 \text{ g}$$

$$W_w = 191 \text{ g}$$

$$= \frac{W_s - W_d}{W_s - W_w} \times 100\%$$

$$= \frac{296 - 262}{296 - 191} \times 100\%$$

$$= \frac{34}{105}$$

$$= 32.3\%$$

A₂₄

$$W_s = 300 \text{ g}$$

$$W_d = 266 \text{ g}$$

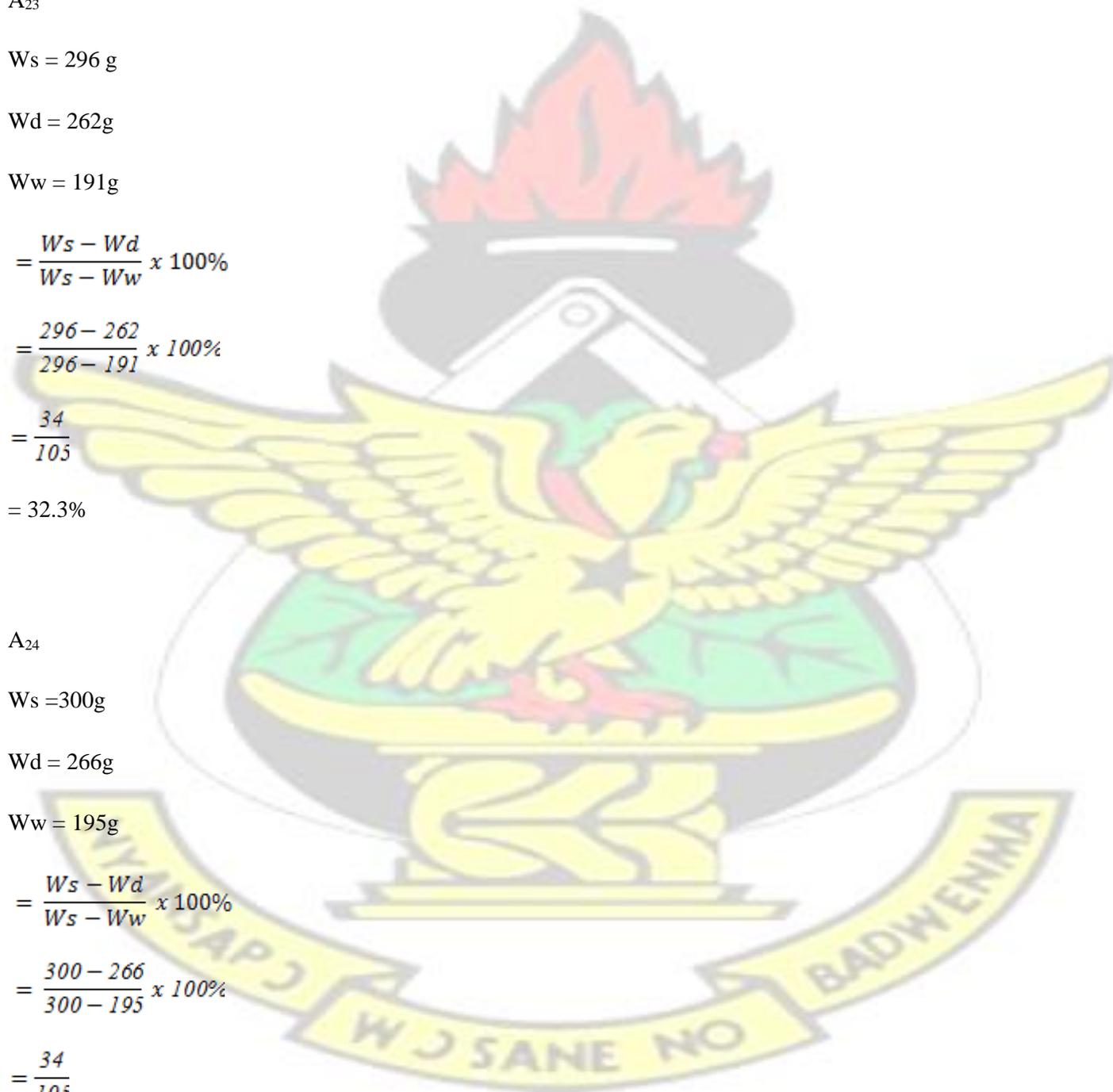
$$W_w = 195 \text{ g}$$

$$= \frac{W_s - W_d}{W_s - W_w} \times 100\%$$

$$= \frac{300 - 266}{300 - 195} \times 100\%$$

$$= \frac{34}{105}$$

$$= 32.3\%$$



KNUST

A₂₅

$$W_s = 299\text{g}$$

$$W_d = 265\text{g}$$

$$W_w = 194\text{g}$$

$$= \frac{W_s - W_d}{W_s - W_w} \times 100\%$$

$$= \frac{299 - 265}{299 - 194} \times 100\%$$

$$= \frac{34}{105}$$

$$= 32.3\%$$

$$\text{S. D.} = \sqrt{\frac{x-x}{n}}$$

$$\sqrt{\frac{(32.3 - 32.3)^2}{5} + \frac{(32.3 - 32.3)^2}{5} + \frac{(32.3 - 32.3)^2}{5} + \frac{(32.3 - 32.3)^2}{5} + \frac{(32.3 - 32.3)^2}{5}}$$



KNUST

POROSITY OF B

B₁

B₁₁

$$W_s = 200\text{g}$$

$$W_w = 69\text{g}$$

$$W_d = 159\text{g}$$

$$\begin{aligned} & \frac{W_s - W_d}{W_s - W_w} \times 100\% \\ &= \frac{200 - 159}{200 - 69} \times 100\% \\ &= \frac{41}{131} \end{aligned}$$

$$= 31.3\%$$

B₁₂

$$W_s = 202\text{g}$$

$$W_w = 71\text{g}$$

$$W_d = 161\text{g}$$

$$\begin{aligned} &= \frac{W_s - W_d}{W_s - W_w} \times 100\% \\ &= \frac{202 - 161}{202 - 71} \times 100\% \end{aligned}$$

$$= 31.3\%$$

KNUST

B₁₃

$$W_s = 201\text{g}$$

$$W_w = 70\text{g}$$

$$W_d = 160\text{g}$$

$$= \frac{W_s - W_d}{W_s - W_w} \times 100\%$$

$$= \frac{201 - 160}{201 - 70} \times 100\%$$

$$= \frac{41}{131}$$

$$= 31.3\%$$

B₁₄

$$W_s = 199\text{g}$$

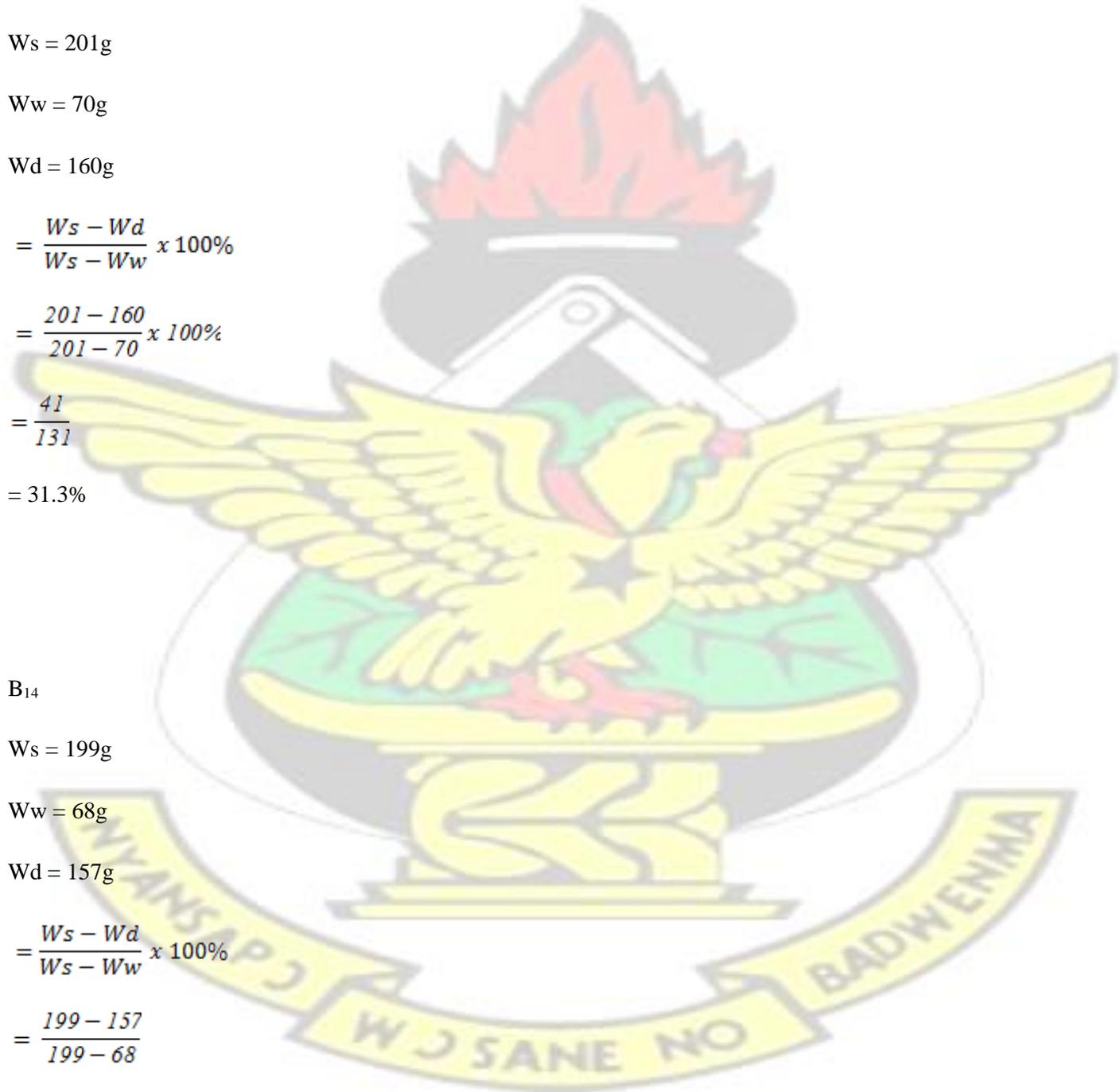
$$W_w = 68\text{g}$$

$$W_d = 157\text{g}$$

$$= \frac{W_s - W_d}{W_s - W_w} \times 100\%$$

$$= \frac{199 - 157}{199 - 68}$$

$$= \frac{42}{131}$$



$$= 32.1\%$$

B₁₅

$$W_s = 200\text{g}$$

$$W_d = 159\text{g}$$

$$W_w = 69\text{g}$$

$$= \frac{W_s - W_d}{W_s - W_w} \times 100\%$$

$$= \frac{200 - 159}{200 - 69} \square 100\%$$

$$= \frac{41}{131}$$

$$= 31.3\%$$

$$\text{S. D.} = \sqrt{\frac{x-x}{n}}$$

$$\sqrt{\frac{(31.3 - 31.5)^2}{5} + \frac{(31.3 - 31.5)^2}{5} + \frac{(31.3 - 31.5)^2}{5} + \frac{(32.1 - 31.5)^2}{5} + \frac{(31.3 - 31.5)^2}{5}}$$

B₂

B₂₁

$$W_s = 199\text{g}$$

$$W_d = 156\text{g}$$

$$W_w = 60\text{g}$$

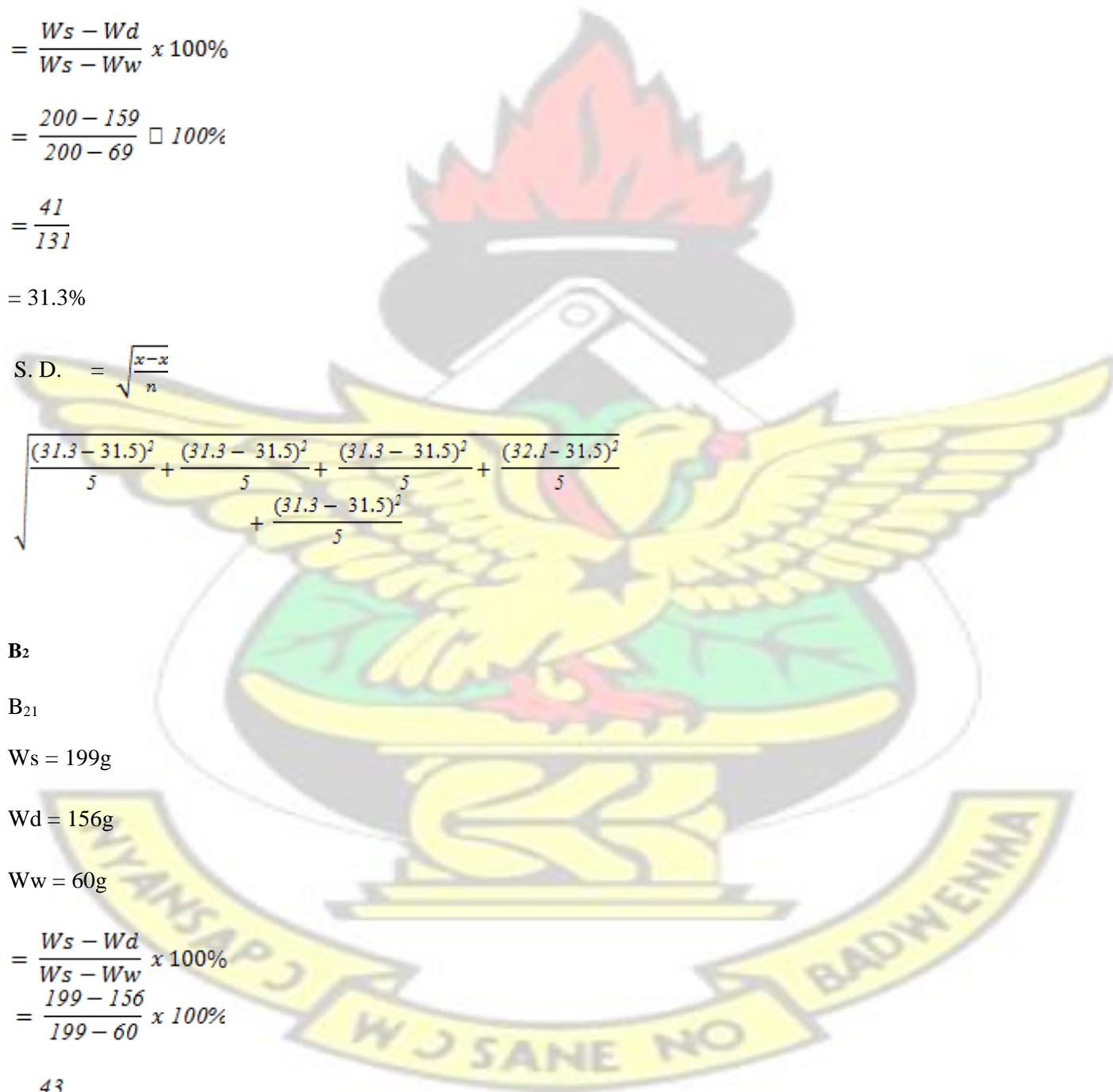
$$= \frac{W_s - W_d}{W_s - W_w} \times 100\%$$

$$= \frac{199 - 156}{199 - 60} \times 100\%$$

$$= \frac{43}{139}$$

$$= 30.9\%$$

KNUST



B₂₂

$$W_s = 200\text{g } W_d$$

$$= 159\text{g}$$

$$W_w = 61\text{g}$$

$$= \frac{W_s - W_d}{W_s - W_w} \times 100\%$$

$$= \frac{200 - 159}{200 - 61} \times 100\%$$

$$= \frac{41}{139}$$

$$= 29.5\%$$

KNUST

B₂₃

$$W_s = 200\text{g } W_d$$

$$= 157\text{g}$$

$$W_w = 61\text{g}$$

$$= \frac{W_s - W_d}{W_s - W_w} \times 100\%$$

$$= \frac{200 - 157}{200 - 61} \times 100\%$$

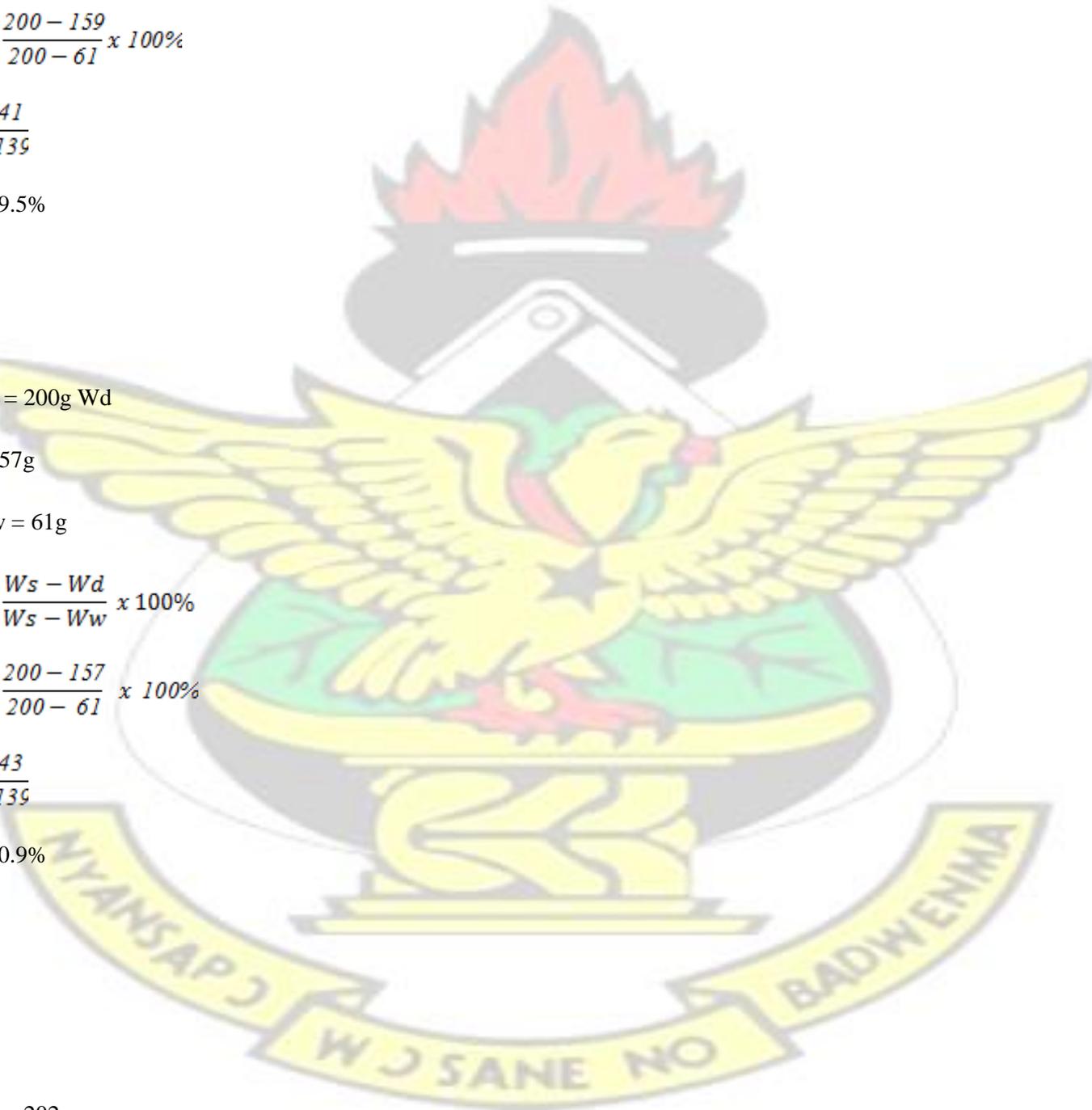
$$= \frac{43}{139}$$

$$= 30.9\%$$

B₂₄

$$W_s = 202\text{g}$$

$$W_d = 157\text{g}$$



$$W_w = 63\text{g}$$

$$= \frac{200 - 157}{202 - 61} \times 100\%$$

$$= \frac{43}{141}$$

$$= 30.5\%$$

KNUST

B₂₅

$$W_s = 199\text{g}$$

$$W_d = 156\text{g}$$

$$W_w = 60\text{g}$$

$$= \frac{199 - 156}{199 - 60} \times 100\%$$

$$= \frac{43}{139}$$

$$= 30.9\%$$

$$\text{S. D.} = \sqrt{\frac{x-x}{n}}$$

$$\sqrt{\frac{(30.9 - 30.5)^2}{5} + \frac{(29.5 - 30.5)^2}{5} + \frac{(30.9 - 30.5)^2}{5} + \frac{(30.5 - 30.5)^2}{5} + \frac{(30.9 - 30.5)^2}{5}}$$

COMPRESSIVE STRENGTH OF SAMPLE A

A₁

A₁₁

Length = 50mm

Width = 50mm

Area = 2500mm²

Failure = 48 × 0.305

Compressive strength = $\frac{\text{load}}{\text{area}}$

$$= \frac{48 \times 0.305}{2500}$$

$$= 5.86 \times 10^{-3} \text{ KNmm}^{-2}$$

KNUST

A₁₂

Length = 50mm

Width = 50mm

Area = 2500

Load = Area x Machine Failure

$$= 48.5 \times 0.305$$

$$= 14.79$$

Compressive strength = $\frac{\text{load}}{\text{area}}$

$$= \frac{14.79}{2500}$$

$$= 5.9 \times 10^{-3}$$

A₁₃

Length = 50mm

Width = 50mm

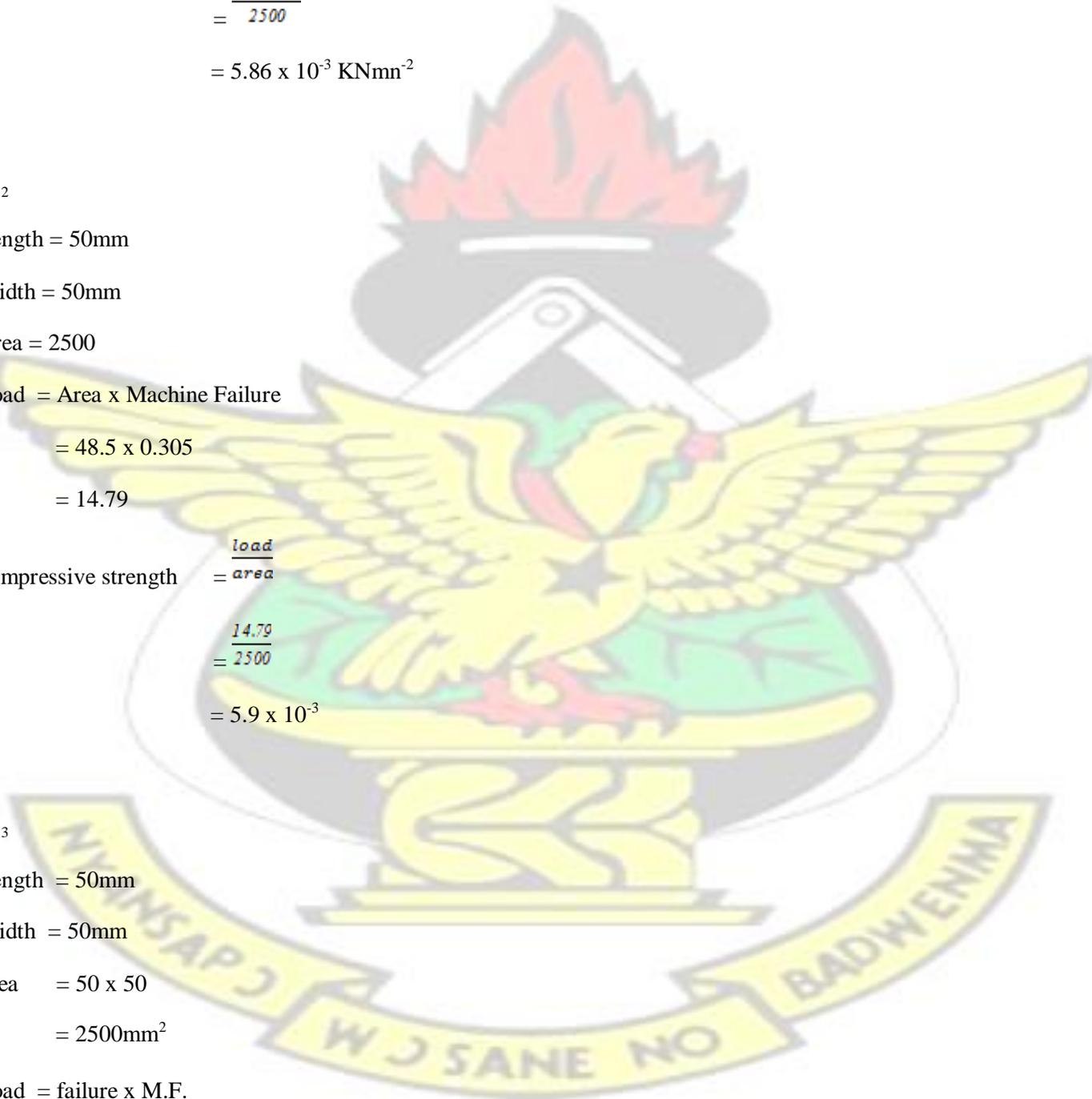
Area = 50 x 50

$$= 2500\text{mm}^2$$

Load = failure x M.F.

$$= 48 \times 0.305$$

$$= 14.64$$



$$\begin{aligned} \text{Compressive strength} &= \frac{48 \times 0.305}{2500} \\ &= 5.86 \times 10^{-3} \text{ KNmm}^{-2} \end{aligned}$$

KNUST

A₁₄

Length = 50mm

Width = 50mm

Area = 2500mm²

Load = failure x M.F.

$$= 48 \times 0.305$$

$$= 14.64$$

$$\text{Compressive strength} = \frac{\text{load}}{\text{area}}$$

$$= \frac{14.64}{2500}$$

$$= 5.86 \times 10^{-3} \text{ KNmm}^{-2}$$

A₁₅

Length = 50mm

Width = 50mm

Area = 50 x 50

$$= 2500\text{mm}^2$$

Load = failure x M.F.

$$\text{Compressive strength} = \frac{48.2 \times 0.305}{2500}$$

$$= 5.88 \times 10^{-3} \text{ KNmm}^{-2}$$

$$\text{S. D.} = \sqrt{\frac{x - \bar{x}}{n}}$$

$$\sqrt{\frac{(5.86 \times 10^{-3} - 5.87 \times 10^{-3})^2}{5} + \frac{(5.9 \times 10^{-3} - 5.87 \times 10^{-3})^2}{5} + \frac{(5.86 \times 10^{-3} - 5.87 \times 10^{-3})^2}{5} + \frac{(5.86 \times 10^{-3} - 5.87 \times 10^{-3})^2}{5} + \frac{(5.88 \times 10^{-3} - 5.87 \times 10^{-3})^2}{5}}$$

KNUST

A₂

A₂₁

Length = 50mm

Width = 50mm

Area = 2500mm²

Load = failure x M.F.

$$\text{Compressive strength} = \frac{49.5 \times 0.305}{2500}$$

$$= \frac{15.09}{2500}$$

$$= 6.04 \times 10^{-3} \text{ KNmm}^{-2}$$

A₂₃

Length = 50mm

Width = 50mm

Area = 2500mm²

Load = failure x M.F.

$$= 49 \times 0.305$$

$$\text{Compressive strength} = \frac{49 \times 0.305}{2500}$$

$$= 5.98 \times 10^{-3} \text{ KNmm}^{-2}$$

A₂₄

Length = 50mm

Width = 50mm

Area = 2500mm²

Load = failure x M.F.

$$= 49.3 \times 0.305$$

$$\text{Compressive strength} = \frac{49.3 \times 0.305}{2500}$$

$$= 6.01 \times 10^{-3} \text{ KNmm}^{-2}$$

A25

Length = 50mm

Width = 50mm

Area = 2500mm²

Load = failure x M.F.

$$= 49 \times 0.305$$

$$\text{Compressive strength} = \frac{49 \times 0.305}{2500}$$

$$= 5.98 \times 10^{-3} \text{ KNmm}^{-2}$$

$$\text{S. D.} = \sqrt{\frac{x-x}{n}}$$

$$\sqrt{\frac{(5.98 \times 10^{-3} - 5.99 \times 10^{-3})^2}{5} + \frac{(6.04 \times 10^{-3} - 5.99 \times 10^{-3})^2}{5} + \frac{(5.98 \times 10^{-3} - 5.99 \times 10^{-3})^2}{5} + \frac{(6.01 \times 10^{-3} - 5.99 \times 10^{-3})^2}{5} + \frac{(5.98 \times 10^{-3} - 5.99 \times 10^{-3})^2}{5}}$$



COMPRESSIVE STRENGTH OF SAMPLE B

B₁

B₁

Length = 48mm

Width = 46mm

Area = 2208mm²

Load = failure x M.F.

$$= \frac{50 \times 0.305}{2208}$$

$$= \frac{15.25}{2208}$$

$$= 6.91 \times 10^{-3} \text{KNmm}^{-2}$$

B₁₂

Length = 48mm

Width = 46mm

Area = 48mm x 46mm

$$= 2208\text{mm}^2$$

$$\text{Compressive strength} = \frac{50 \times 0.305}{2208}$$

$$= 6.9 \times 10^{-3} \text{KNmm}^{-2}$$

B₁₃

Length = 48mm

Width = 46mm

Area = 2208mm²

$$\text{Load} = \frac{50.4 \times 0.305}{2208}$$

$$= \frac{15.37}{2208}$$

$$= 6.96 \times 10^{-3} \text{KNmm}^{-2}$$

KNUST



KNUST

B14

Length = 48mm

Width = 46mm Area =

48mm x 46mm

$$= 2208\text{mm}^2$$

Load = 50 x 0.305

$$\text{Compressive strength} = \frac{50 \times 0.305}{2208}$$

$$= 6.9 \times 10^{-3} \text{KNmm}^{-2}$$

B15

Length = 48mm

Width = 46mm

Area = 2208mm²

Load = failure x M.F.

$$\text{Compressive strength} = \frac{\text{load}}{\text{area}}$$

$$= \frac{50.2 \times 0.305}{2208}$$

$$= \frac{15.31}{2208}$$

$$= 6.93 \times 10^{-3}$$

$$\text{S. D.} = \sqrt{\frac{x-x}{n}}$$

$$\sqrt{\frac{(6.91 \times 10^{-3} - 6.92 \times 10^{-3})^2}{5} + \frac{(6.91 \times 10^{-3} - 6.92 \times 10^{-3})^2}{5} + \frac{(6.96 \times 10^{-3} - 6.92 \times 10^{-3})^2}{5} + \frac{(6.91 \times 10^{-3} - 6.92 \times 10^{-3})^2}{5} + \frac{(6.93 \times 10^{-3} - 6.92 \times 10^{-3})^2}{5}}$$

KNUST

B₂

B₂₁

Length = 46mm

Width = 44mm

Area = 46mm x 44mm

$$= 2024\text{mm}^2$$

LOAD = failure x M.F.

$$\begin{aligned}\text{Compressive strength} &= \frac{52 \times 0.305}{2024} \\ &= 7.84 \times 10^{-3}\text{KNmm}^{-2}\end{aligned}$$

B₂₂

Length = 46mm

Width = 44mm

Area = 2024mm²

Load = failure x M.F.

$$\begin{aligned}\text{Compressive strength} &= \frac{52 \times 0.305}{2024} \\ &= 7.84 \times 10^{-3}\text{KNmm}^{-2}\end{aligned}$$

B₂₃

Length = 46mm

Width = 44mm

Area = 46mm x 44mm

LOAD = failure x M.F.

$$= 2024\text{mm}^2$$

$$\text{Compressive strength} = \frac{52.2 \times 0.305}{2024}$$

$$= 7.87 \times 10^{-3} \text{KNmm}^{-2}$$

B₂₄

Length = 46mm

Width = 44mm

Area = 2024mm²

Load = failure x M.F.

$$\text{Compressive strength} = \frac{\text{load}}{\text{area}}$$

$$= \frac{52 \times 0.305}{2024}$$

$$= 7.84 \times 10^{-3} \text{KNmm}^{-2}$$

B₂₅

Length = 46mm

Width = 44mm

Area = 2024mm²

$$\text{Compressive strength} = \frac{\text{load}}{\text{area}}$$

$$= \frac{52.4 \times 0.305}{2024}$$

$$= 7.89 \times 10^{-3} \text{KNmm}^{-2}$$

$$\text{S. D.} = \sqrt{\frac{x-\bar{x}}{n}}$$

$$\sqrt{\frac{\frac{(7.84 \times 10^{-3} - 7.86 \times 10^{-3})^2}{5} + \frac{(7.84 \times 10^{-3} - 7.86 \times 10^{-3})^2}{5} + \frac{(7.87 \times 10^{-3} - 7.86 \times 10^{-3})^2}{5} + \frac{(7.84 \times 10^{-3} - 7.86 \times 10^{-3})^2}{5}}{4} + \frac{(7.89 \times 10^{-3} - 7.86 \times 10^{-3})^2}{5}}$$

KNUST



APPENDIX C

FIGURE 4.7

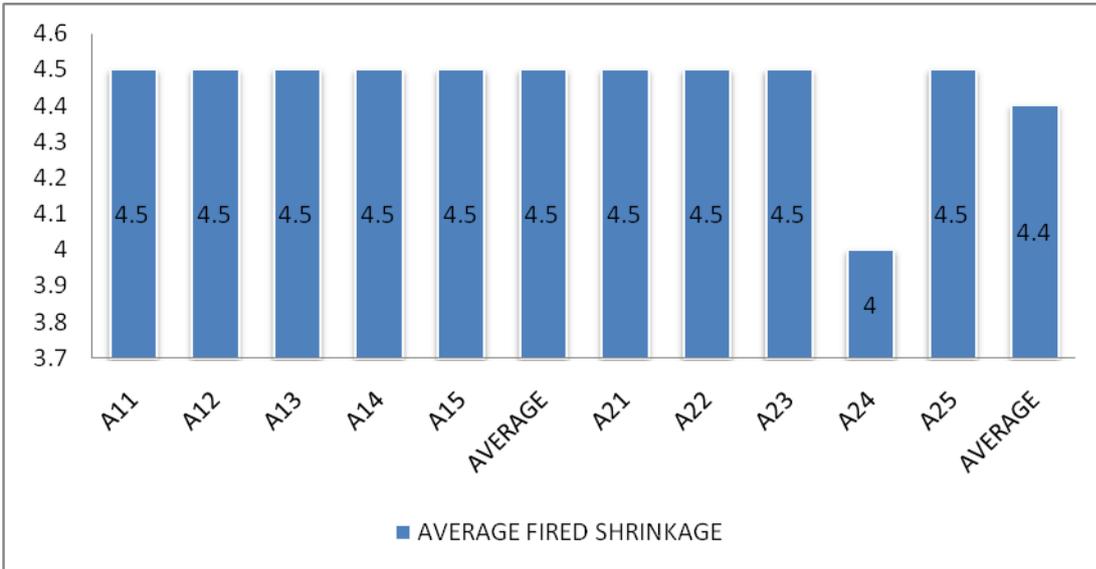


FIGURE 4.8



FIGURE 4.11

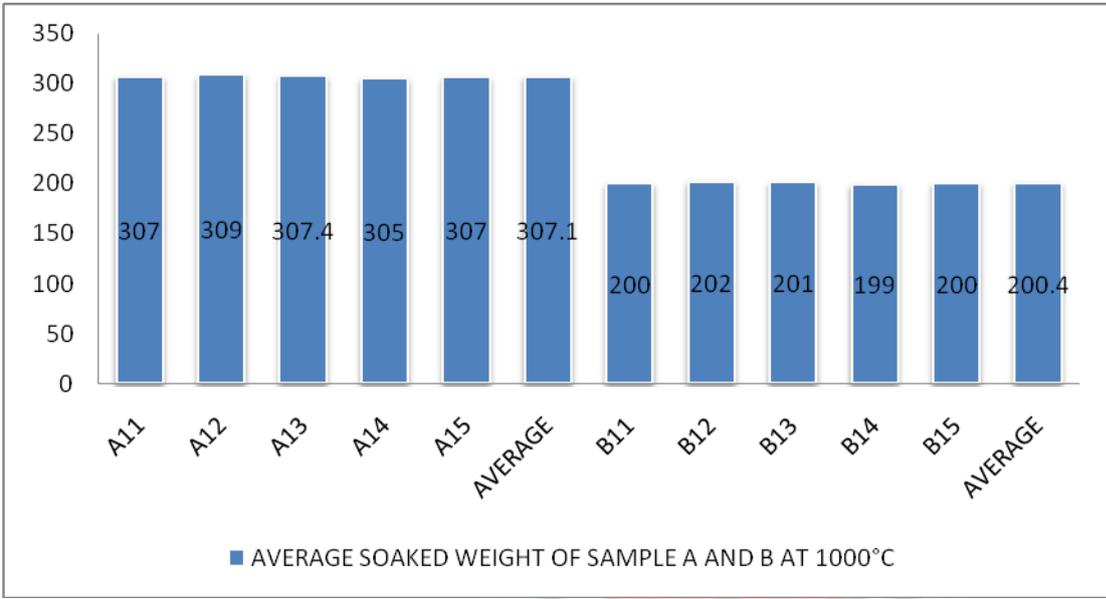


FIGURE 4.12

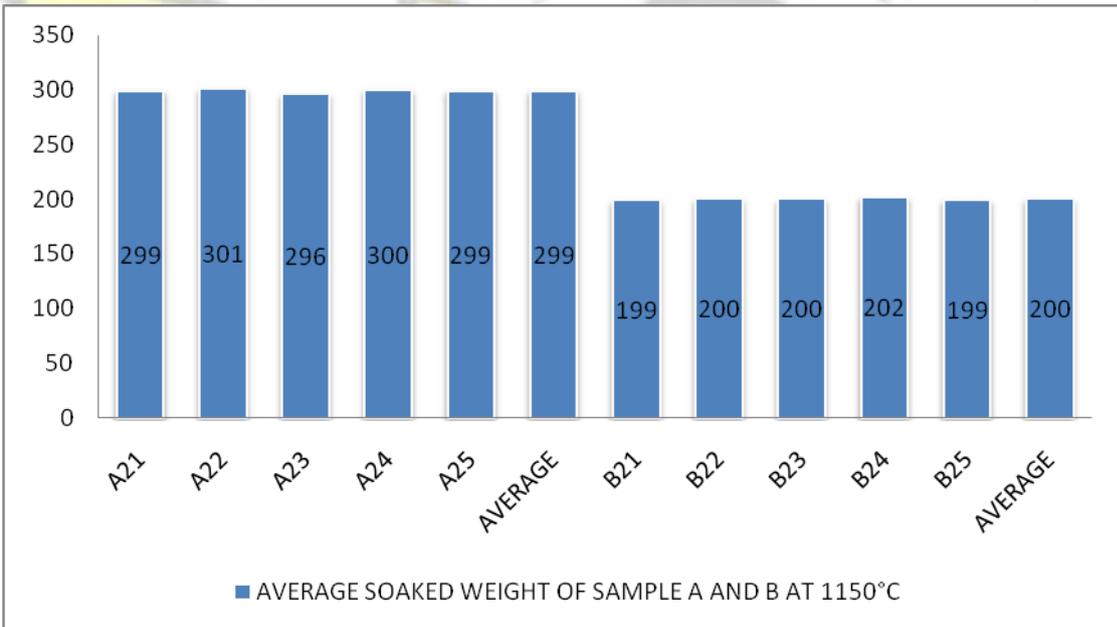


FIGURE 4.9

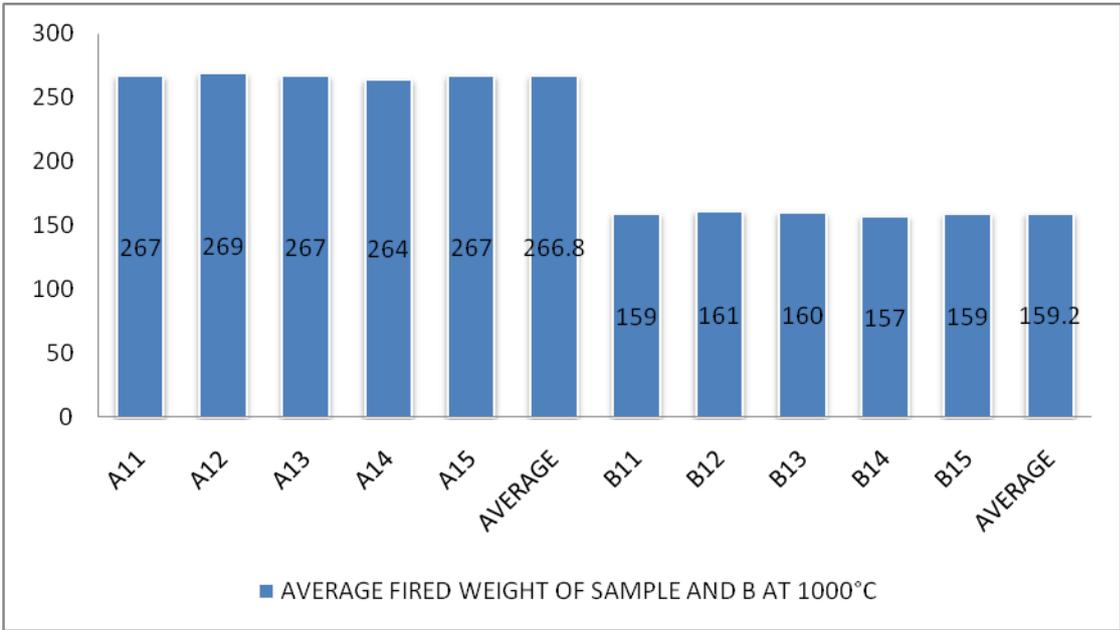


FIGURE 4.10

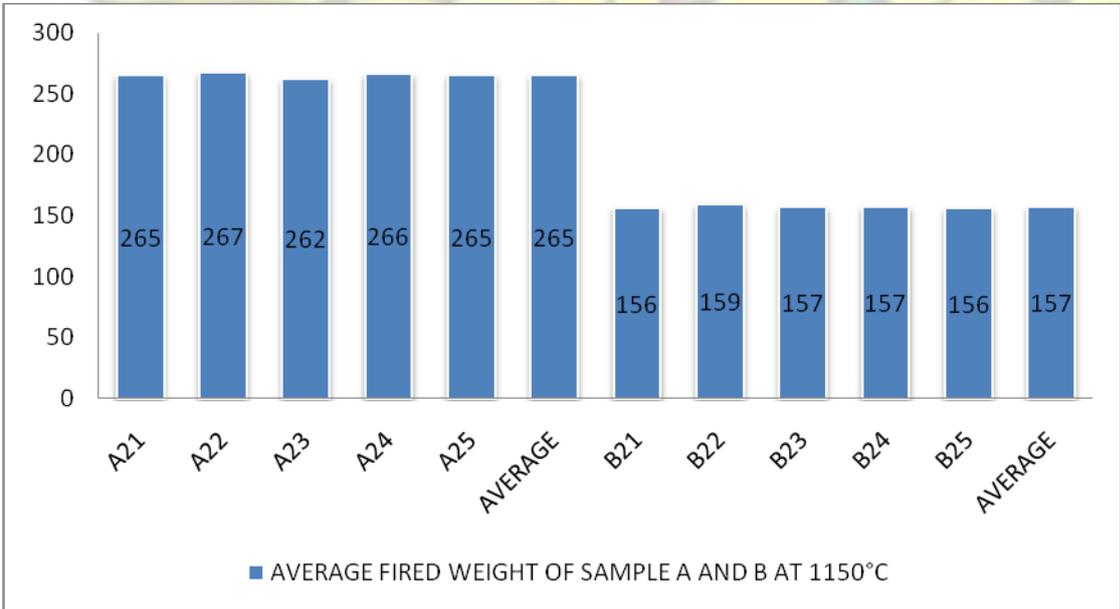


FIGURE 4.16

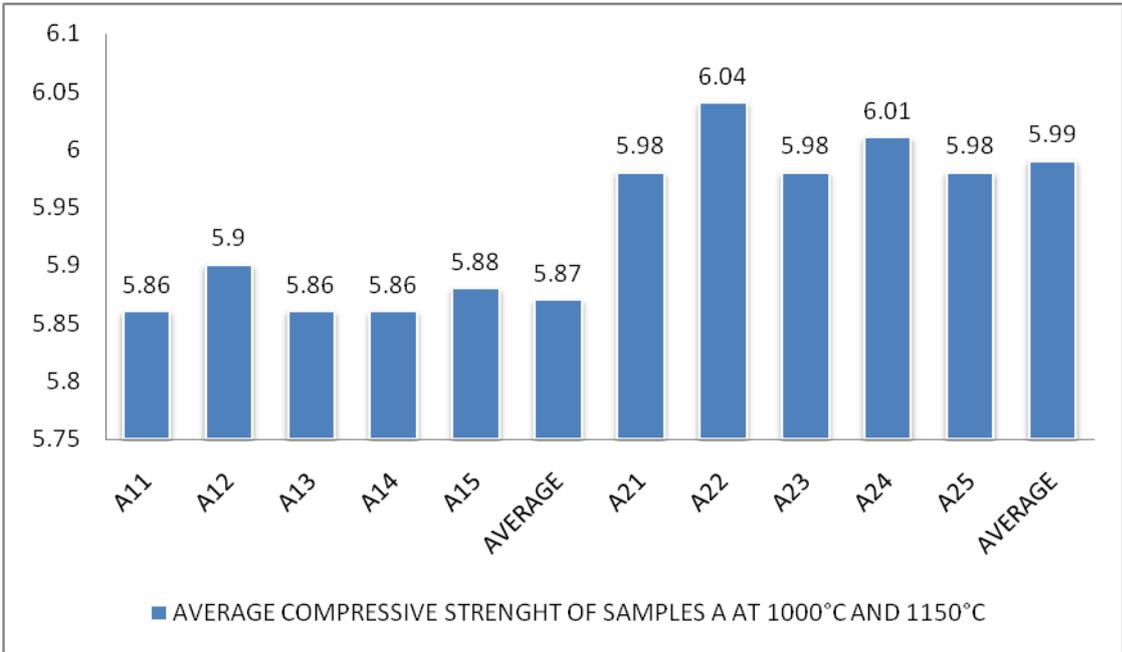


FIGURE 4.17

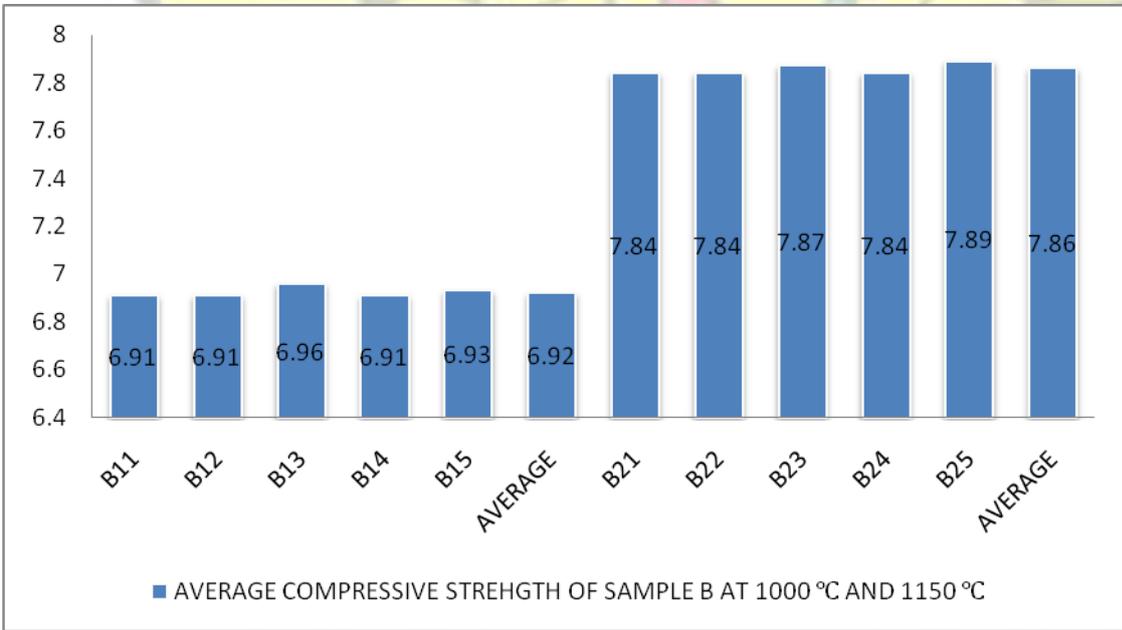


FIGURE 4.13

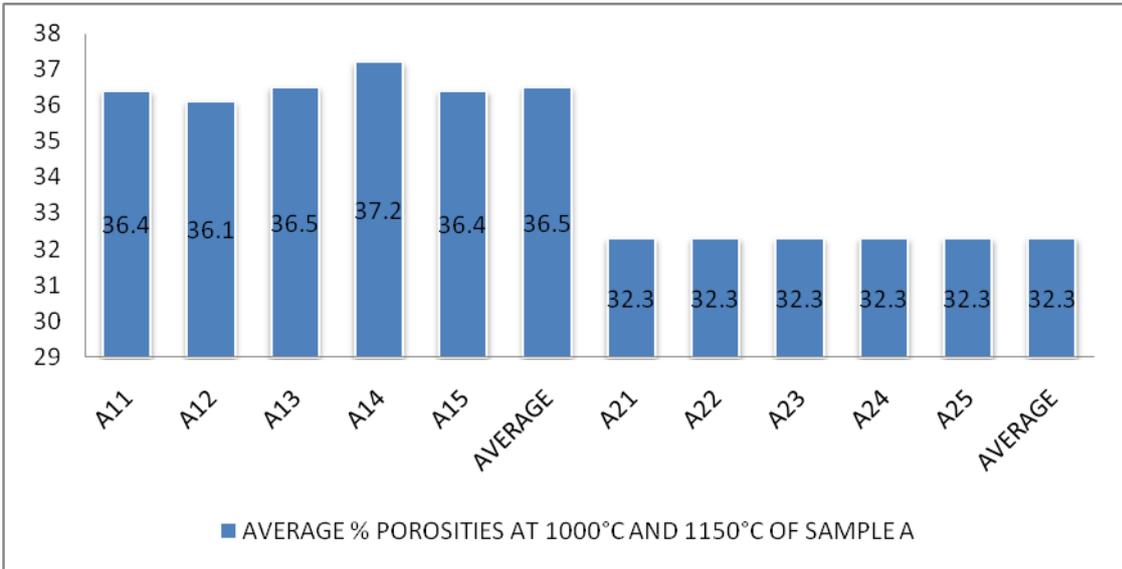


FIGURE 4.14

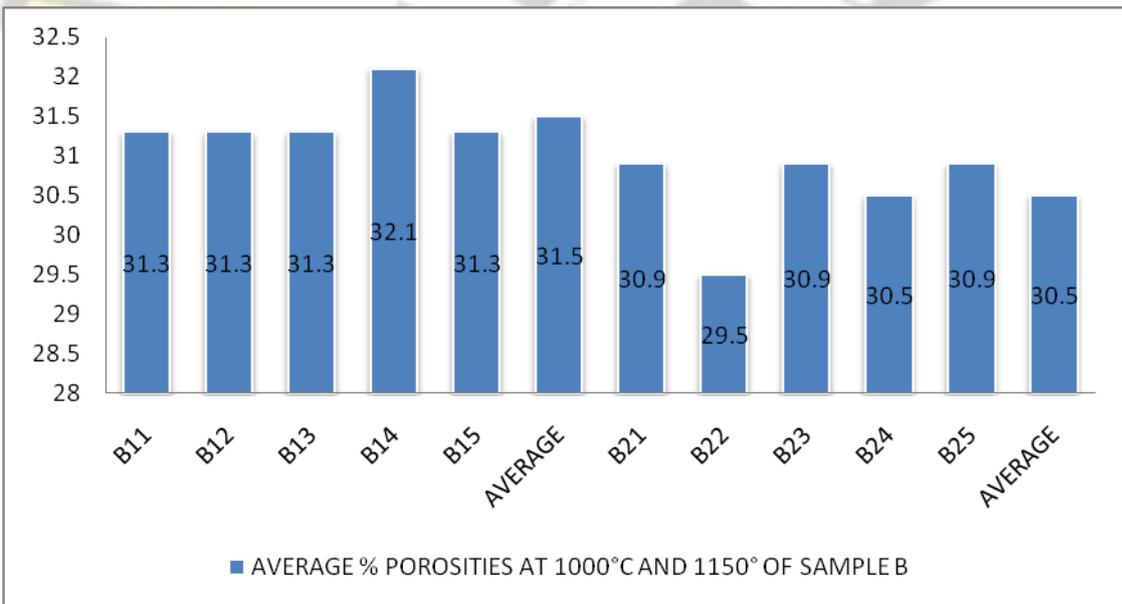


FIGURE 4.9



FIGURE 4.10

