Development of stable ceramic material for high temperature application in construction: Case study of high temperature resisting bricks

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Abstract

Insulating ceramic boards are sought in various industries, civil engineering workshops and even in homes for numerous uses but its manufacture is quite complex. This research work was aimed at developing a stable ceramic material (high temperature bricks) for high temperature applications in building construction. Insulating ceramic boards were made from clay which was the predominant raw material, sawdust, white Portland cement (WPC) and sand by combining the raw materials in different ratios [A (60% clay + 30% WPC + 10% sand), B (65% clay + 25% WPC +10% sand), C (70% clay + 20% WPC +10% sand), D (75% clay + 15% WPC +10% sand), E (80% clay + 10% WPC +10% sand), F (57.14 % clay + 28.57% WPC + 9.52 % sand + 4.77% sawdust), G (61.90 % clay + 23.81 % WPC + 9.52 % sand + 4.77 % sawdust), H (66.67% clay + 19.05% WPC + 9.52 % sand + 4.77% sawdust), I (71.43% clay +14.29% WPC + 9.52 % sand + 4.77% sawdust), J(76.19% clay + 9.52 WPC + 9.52 % sand + 4.77% sawdust)]. The raw materials were mixed, the green ceramic materials were formed in a mould of 60 × 25 × 2.5 cm, dried at ambient temperature, fired at a temperature range of 900 – 1303 °C and allowed to cold in the kiln. The ceramic boards were then removed and their physical, mechanical and thermal properties determined. Experimental results showed that the apparent porosity values of all the specimens were between 55.42 and 67.28% which are in the international standard range (ISO 5016-1986) of 20 - 80%. The bulk density values of all the specimens were between 1.63 and 1.71 g/cm^3 bringing them closer to the British standard range (BS, 1902 part B 1976) of 1.71- 2.1 g/cm^3. The thermal conductivity values of all the specimens were between 0.31 and 0.94 W/m.k which fall in the ASTM specifications (C177-2023) of 0.01-1.1 W/m.k except for specimen A, B, G, and H which had higher values. The compressive strength of all the specimens were between 2.27 and 6.66 MPa, complying to the ASTM (C64 -2012) which recommends 1.3MPa as the minimum compressive strength value for insulating ceramic boards. None of the specimens absorbed more than 20% water of its own weight in conformity with ASTM (C140-2020). All the specimens had very high specific gravity values not complying with the ASTM (D792 - 2017) range of 2.6 - 2.7. Based on these results, it can be said that specimen I (71.43% clay +14.29% WPC + 9.52 % sand + 4.77% sawdust) is a good substitute for imported insulating ceramic materials used for high temperature application in building construction.

Key words: Local materials, insulating ceramic boards, physical properties, mechanical properties.

1. Introduction

I.1. Problem statement

In Cameroon, thermal insulation materials are often imported with a high cost of transportation and a relatively high purchase cost. In addition, the dry commercially available thermal insulating materials do not fit our local applications as they come in different shapes and sizes. The ceramic materials do not even exist because most times, the ceramic materials we purchase are not stable on their own. To make them stable, we always have to buy other materials and combine with it such as the steel shell which consumes a lot of energy and intends renders the entire material even more expensive. More so, to ensure sustainable economic growth, Cameroon must develop refractory products using indigenous raw materials. This present study is therefore aimed at developing a stable ceramic material for high temperature applications in building construction.

I.2. Objectives

The main objective of this study is to develop stable high temperature bricks (fire resistant, physically and mechanically resistant) thereby helping to reduce the cost and collapse of constructions after fire. More specifically, the study was set out:

- To manufacture stable ceramic materials (high temperature bricks) for high temperature application;
- To determine the physical and mechanical properties of the ceramic materials (high temperature bricks) for high temperature application.
- To determine the thermal properties of the ceramic materials (high temperature bricks) for high temperature application;

I.3. Scope and limits of the study

This study involved the fabrication of insulating ceramic materials (high temperature bricks) and the determination of its properties notably its thermal conductivity, thermal resistance, water absorption, apparent porosity, specific gravity, bulk density and compressive strength. These boards were made with clayey soil as the predominant ingredient. Clayey soil is found in the subsoil which made its mining or extraction difficult. Other important properties like refractoriness and the thermal shock resistance were not determined.

2. Literature Review

2.1. Definition of key terms

Ceramics can be defined as solid compounds that are formed by the application of heat, and sometimes heat and pressure in their manufacture and/or use. Ceramics are also compounds between metallic and nonmetallic elements associated with covalent and ionic bonding. They are most frequently oxides, nitrides, and carbides which include aluminum oxide (or alumina, Al_2O_3), silicon dioxide (or silica, SiO_2), silicon carbide (SiC), silicon nitride (Si_3N_4), and, in addition, what some refer to as the traditional ceramics (those composed of clay minerals (i.e., porcelain)) as well as cement and glass (Eliche-quesada & Pérez-villarejo, 2019). Technically, ceramics are those things made from materials which are permanently changed when heated. Once clay is heated (fired) to between 350^{o} and 800^{o}C, it is converted to ceramic and cannot be reverted back to clay (Boch and Niepce, 2007; Olufunke and Mofolorunsho John, 2021).

Firing or sintering is the process of compacting and forming a solid mass of material by heat and/or pressure without melting it to the point of liquefaction (Eliche-quesada and Pérez-villarejo, 2019). In other words, it is a process of subjecting the green ceramic to elevated temperatures with the purpose of gaining mechanical integrity.

2.2. History of ceramic materials

The word ceramic was primarily used to mean "Potter's Clay," and "burnt stuff." It originated from Greek word “keromikos”, which means ‘burnt stuff’ (Iyasara *et al*., 2015). The first use of fired clay was in making female sculptures. These sculptures represent the first man-made ceramic products in 24000 BC. The firing temperatures were low to medium, and these products are now referred to as earthenware. During 7000–6000 BC, lime mortar was used for construction. The gaps between stones were filled with this material. It was also used to make thick-walled containers. In the period from 7000 to 5000 BC, floors were laid with a plaster-like cementitious material. The interiors of walls were given a coating of this material, and they were later decorated.

The other type of ceramic material that came to be used is gypsum (Plaster of Paris). Today, gypsum is used to make wallboards, moulds, sculptures, and casts. The use of lime mortar was another application of ceramics in old days. This was done by mixing lime with the ash of salty grasses, with water added later. This mixture was used, for example, to fill the spaces between stones in a wall construction.

Historically, ceramics have exhibited extreme brittleness (lack of ductility) and are highly susceptible to fracture. However, newer ceramics are being engineered to have improved resistance to fracture; these materials are used for cookware, cutlery, and even automobile engine parts. Furthermore, ceramic materials are typically insulative to the passage of heat and electricity.

2.3. Classes of ceramic materials

Ceramics are classified in many ways (Figure 2.1). It is due to divergence in composition, properties and applications. Based on their composition, ceramics are: oxides, carbides, nitrides, sulfides, fluorides etc. Based on their specific applications, ceramics are classified as: glasses, clay products, abrasives, cements, refractories and advanced ceramics for special applications. Based on their engineering applications, ceramics are classified into two groups as: traditional and engineering ceramics (Kadhum and Jaffer, 2013).

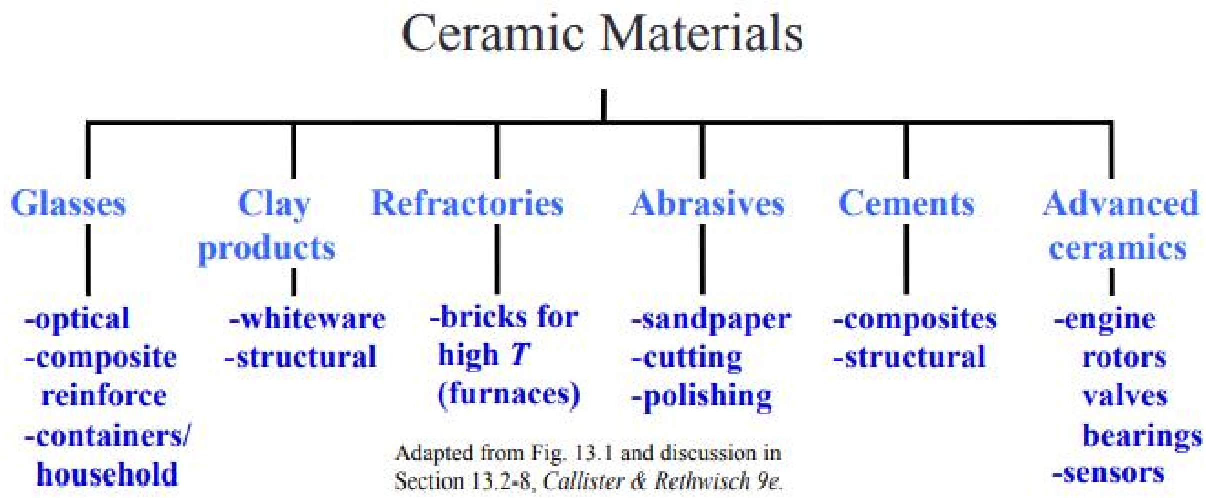


Figure 2.1: Classes of ceramic materials
(Kadhum & Jaffer, 2013)

2.4. Overview of Refractory Ceramic Materials

2.4.1. Properties of refractory ceramic materials

Important properties of refractories are: chemical composition, bulk density, apparent porosity, specific gravity and strength at atmospheric temperatures. These properties are often among those which are used as 'control points' in the manufacturing and quality control process. The chemical composition serves as a basic for classification of refractories and the density, porosity and strength are influenced by many other factors (Iyasara *et al*., 2015). Among these are type and quality of the raw materials, the size and fit of the particles, moisture content at the time of pressing, pressure at mould, temperature, duration of firing and the rate of cooling (Dubreuip and Sobolev, 1999; Kadhum and Jaffer, 2013). Refractory properties can be divided into three main categories: physical, thermal and chemical.

➢ **Size and Dimensional Stability**

The size and shape of the refractories are an important feature in design since they affect the stability of any structure. Dimensional accuracy and size are extremely important to enable proper fitting of the refractory shape and to minimize the thickness and joints in construction.

➢ **Porosity**

Porosity is a measure of the effective open and close pore space in the refractory into which the molten metal, slag, fluxes, vapors etc. can penetrate and thereby contribute to eventual degradation of the structure. The porosity of refractory is expressed as the average percentage of open and closed pore space in the overall refractory volume with an international range of 20-80% (Manukaji, 2013; Obstler, 2012). High porosity materials tend to be highly insulating as a result of high volume of air they trap, because air is a very poor thermal conductor. As a result, low porosity materials are generally used in hotter zones, while the more porous materials are usually used for thermal backup. Such materials, however, do not work with higher temperatures and direct flame impingement, and are likely to shrink when subjected to such conditions. Refractory materials with high porosity are usually not chosen when they will be in contact with molten slag because they cannot be penetrated as easily (Akinfolarin and Awopetu, 2014). Because true porosity takes into consideration the closed and open pores in a refractory, it is difficult to determine.

➢ **Bulk Density**

The bulk density is generally considered in conjunction with apparent porosity (a measure of the open or interconnected pores in a refractory). It is a measure of the weight of a refractory to the volume it occupies. For many refractories, the bulk density provides a general indication of the product quality; it is considered that the refractory with higher bulk density (low porosity) will be better in quality. An increase in bulk density increases the volume stability, the heat capacity, as well as the resistance to abrasion and slag penetration.

➢ **Thermal Conductivity**

Thermal conductivity is defined as the quantity of heat that will flow through a unit area in direction normal to the surface area in a defined time with a known temperature gradient under steady state conditions. It indicates general heat flow characteristics of the refractory and depends upon the chemical and mineralogical compositions as well as the application temperature. High thermal conductivity refractories are required for some applications where good heat transfer is essential such as coke oven walls, regenerators, muffles and water cooled furnace walls. However, refractories with lower thermal conductivity are preferred in industrial applications, as they help in conserving heat energy.

Porosity is a significant factor in heat flow through refractories. The thermal conductivity of a refractory decreases on increasing its porosity. Although it is one of the least important properties as far as service performance is concerned, it evidently determines the thickness of refractory ceramic board work (Walker, 2005)

2.4.2. Types and Characteristics of Raw Materials used in Refractory Manufacture

A wide variety of raw materials are now used in the development, processing and manufacture of ceramic products.

Clay Refractories (Clay, High Alumina); Non Clay Refractories (Basic, Extra-high alumina, Mullite).

2.4.3. Types of Refractories

Refractories are of two types i.e. dense or insulating types. The most high-temperature refractories, such as refractory ceramic boards, are high-density (>120 lb/ft3). They offer excellent resistance in challenging operating environments, such as slags with different chemical compositions, fumes, dust, and gases. Insulating refractories have lower densities (4 to 70 lb/ft3) and provide insulating properties, while offering resistance to corrosion and chemical reactions with the operating environment. Types of Refractories (Fire clay Refractories, Monolithic Refractories, Insulating Refractories)

2.5. Overview of Insulating Ceramic Boards

These are special materials used to optimize the energy use and to prevent its escape into the ambience during high-temperature processes. The function of insulating ceramic boards is to reduce the rate of heat flow (heat loss) through the walls of furnaces. Insulation is effected by providing a layer of material having low heat conductivity, which means heat does not readily pass through them.

2.5.1. Characteristics of Good Insulating Ceramic Boards

The desirable feature of insulating ceramic boards is the low thermal conductivity, which usually results from a high degree of porosity. Structure of air insulating material consists of minute pores filled with air which have in them very low thermal conductivity. The air spaces inside the refractory ceramic board prevent the heat from being conducted but the solid particles of which the ceramic board is made conduct the heat. So, in order to have required insulation property in a refractory ceramic board a balance has to be struck between the proportion of its solid particles and air spaces. The thermal conductivity is lower if the volume of air space is larger. Importantly, the thermal conductivity of a ceramic board does not so much depend on the size of pores as on the uniformity of size and even distribution of these pores. Hence, uniformly small sized pores distributed evenly in the whole body of the insulating ceramic board are preferred. The high porosity of the refractory ceramic board is created during manufacturing by adding a fine organic material to the mix, such as sawdust. During firing, the organic addition burns out, creating internal pores. Extremely lightweight materials have a porosity of 75 to 85% and ultra-lightweight, high-temperature insulating materials have a total porosity greater than 85%. Other ways to accomplish high porosity includes: Using materials which expand and open up on heating; Using volatile compounds like naphthalene; Using aluminum (Al) powder in combination with NaOH solution (called chemical bloating); Using substances which by themselves have open texture e.g. insulating refractory ceramic board grog, vermiculite, ex-foliated mica, raw diatomite etc. Using foaming agents to slip;

2.5.2. Types of Insulating Ceramic Boards

- **With respect to application temperature**
  (Heat resistant insulating materials for application temperatures up to 2000°F: calcium silicate materials; products from siliceous earth, perlite or vermiculite; silica based micro porous heat insulators; alumino-silicate fibers; Refractory insulating materials for application temperatures up to 2500°F: lightweight chamotte and kaolin refractory ceramic boards; lightweight castables; mixed fibers and aluminum oxide fibers; High refractory insulating materials for application temperatures up to 3100°F: lightweight mullite et alumina refractory ceramic boards; lightweight hollow sphere corundum castables and refractory

ceramic boards; special high refractory fibers; Ultra-high refractory insulating materials for application temperatures up to 3600°F: zirconia lightweight refractory ceramic boards and fibers; non-oxide compounds).

- **With respect to their densities:** These are showed in table 2.1.

Table 2.1: Types of insulating boards with respect to their densities

Materials	Porosity	Density
Low Density Insulating Boards (IB-LD)	55 - 65%	1.0 g/cm3 ± 7%
Medium Density Insulating Boards (IB-MD)	45 - 55%	1.2 g/cm3 ± 7%
High Density Insulating Boards (IB-LD)	35 - 45%	1.5 g/cm3 ± 7%

2.6. General Method of Manufacture of Insulating Ceramic Boards

Refractory manufacturing involves four processes: raw material processing, forming, drying, firing and final processing.

2.6.1. Raw Material Processing

To begin the process, raw materials are transported and stored at the manufacturing facility. The raw materials used in the manufacture of ceramics range from relatively impure clay materials mined from natural deposits to ultrahigh purity powders prepared by chemical synthesis. Naturally occurring raw materials used to manufacture ceramics include silica, sand, quartz, flint, silicates, and aluminosilicates (e. g., clays and feldspar). All the raw materials are accurately weighed, so that the quality of the product can be stabilized (Kaushik and Shah, 2016). The main components used are feldspar, silica sand and clay. The feldspar is an alkali flux which lowers the firing temperature and controls density and porosity of the clay body. Silica controls shrinkage and gives rigidity and support to the porcelain body. Kaolin gives soft plastic base, shape and opacity to the fired porcelain (Iyasara *et al*., 2014).

Raw material processing consists of crushing and grinding raw materials, followed if necessary by size classification and raw materials calcining and drying. The processed raw material then may be dry-mixed with other minerals and chemical compounds, packaged, and shipped as product. All of these processes are not required for some refractory products.

2.6.2. Forming

Forming consists of mixing the raw materials and forming them into the desired shapes. This process frequently occurs under wet or moist conditions. Forming is accomplished 3 steps which include: **Stiff-Mud Process, Soft-Mud Process, Dry-Press Process.**

2.7. Kiln firing process of refractories

Pit firing is also one of the oldest known methods for the firing of pottery. Kilns have since replaced pit firing as the most widespread method of firing pottery, although the technique is used by some studio potters. A pit can be considered a rudimentary kiln as the pit sides help to contain the fire and act as insulation. Not all clays are suitable to use in pit firing, and additions of grog 'open up' the clay and make it more resistant to heat shock. Temperatures can reach approximately 700-900 degrees centigrade and so the pottery is porous but sturdy. Pit-fired work is usually not glazed but color can be generated by spreading metal oxides and carbonates around the pieces which volatilize and result in bright colors on the surfaces of fired ceramics. Pots are often burnished. Pit firing involves digging a pit of the appropriate size, laying a bed of sawdust or dried leaves, which will burn slowly, at the bottom of the pit and the pottery placed on top of this. The pots are then covered with combustible materials such as leaves and some kindling, with larger pieces of wood on top. The pile is lit and left to burn and smoulder for several hours.

Saggar firing: A saggar is a container with a lid used to enclose a piece of ceramic ware with combustible materials during firing so that trapped fumes will add color and marking to the surface.

A barrel kiln has a design of a top hat kiln, top-hat kiln designs are built in two sections: an immobile base which includes the firebox, and a removable top section. A barrel kiln has a design of a top hat kiln, and is built in two sections: an immobile base which includes the firebox, and the loading chamber while the removable top section contains the spy-hole and the chimney.

2.8. Effect of firing temperature on refractory production

Refractories are fired between 10 to 40 hours depending on type of kiln and other variables. Fuel for firing may be from natural gas, coal or electric energy. Refractories are fired at high temperature to gain a good strength, durability, density and appearance. At a temperature of about 650ºC, all the water is removed but they are fired at a temperature of 1100ºC because at this temperature there is fusing of sand and lime and the chemical bonds between the materials are strengthen. After firing, the temperature is cooled. Depending on the nature of the clayey materials, refractories can be fired at temperatures higher than 1100ºC but care need to be taken because at higher temperatures the refractory ceramic boards might be melted and the shape distorted. Firing may be divided into the following general stages: Final drying (evaporating free water at a temperature of about 204 ºC), Dehydration (from 149 ºC to 982 ºC), Oxidation (from 538 ºC to 982 ºC), Vitrification and flashing or reduction firing (from 871 ºC to 1100 ºC).

2.9. Ways of improving thermal insulating properties of ceramics

In the field of thermal insulating of building ceramics there are several ways to improve thermal insulating properties (Rzepa *et al*., 2016): Use of additives for porosity increase like: sawdust, cellulose pulp, Styrofoam balls. During the firing process, these components are burned, leaving pores which are centres of very high thermal insulation; Use of the lowest firing temperature for sintering without liquid phase. Liquid phase facilitates sintering process but it also causes flooding of pores which are important to provide thermal insulation of ceramic product; Use of the cavity system in the ceramic products which provide longer heat transfer through ceramic material. This assumption results from fact that ceramics is a material with inferior thermal insulation than the air contained in hollows; Use of the thermal insulating additives in ceramic masses. These additives are characterized by very good thermal insulation properties that is why their addition to masses or products improves this parameter; Partial or total elimination of grouting, the binder made of mortar between masonry components. Binder is a so called thermal bridge, through which heat rapidly flows inside ceramic materials. Vertical grouting is completely eliminated by usage of tongue and groove joints while horizontal grouting can be limited by grinding of surface and applying thin binder.

2.10. Physical property tests for assessment of the quality of refractories

The fundamentals of ceramic manufacturing have not changed over time. However, technological advancements have made contemporary ceramic plants substantially more efficient and have improved the overall quality of the products. Some of test that can be carried out on ceramics after cooling to better assess their quality include;

2.10.1. Compressive strength

This is the amount of load carried by refractory per unit area. Compressive strength is a very important parameter which help to determine the engineering quality of refractories. The minimum compressive strength for refractory materials is about 1.3MPa (Samad *et al*., 2021). The values obtained by Katte et *al.* (2017) were 2.81 and 16.03 MPa on burnt clay brick whereas those obtained by Moundom et *al.* (2022) on mud brick stabilized by palm nut fibres were between 0.32 and 4.5 MPa at 28 days.

2.10.2. Water absorption

Water absorption is an essential factor that describes the durability of the bricks; lower water absorption bricks last long with a low tendency toward environmental damage. The water absorption indicates the densification and its connection to the porosity in the materials. The less the water absorbed by refractory ceramic board the greater its quality. Good quality refractory ceramic board doesn't absorb more than 20% water of its own weight (Panennungi and Rauf, 2005; Velasco *et al*., 2014). Less water penetration insulating ceramic boards are expected as it enhances the durability of the boards and resistance to the natural environment. The water absorption is directly related to the apparent porosity in refractory ceramic board and increases with the increase of pore volume (Akinfolarin and Awopetu, 2014).

2.10.3. Efflorescence test

The presence of alkalis in refractories is harmful and they usually form grey or white layer on the refractory surface by absorbing moisture. If the visible whitish layer is about 10% of the refractory surface then the presence of alkalis is in an acceptable range. If it is about 50% of the surface then it is moderate but if it is over 50% then the refractory is severely affected by alkalis.

2.10.4. Hardness test

A good quality refractory will have to resist against abrasion. In this test a scratch is made on the surface of the refractory. If it does not leave any impression on refractory, then the refractory ceramic board is of good quality. A good quality refractory should not break when dropped from a height of 1 m on a flat surface.

2.10.5. Thermal conductivity

When a system is subjected to a gradient of temperature, a transfer of thermal energy (heat) occurs. These are three major heat transfer mechanisms: (Conduction, Convection, and Radiation).

Heat conduction is caused by microscopic interactions between particles and it takes place in all the phases (solid, liquid, gas). When an object is heated, the particles start to vibrate faster (with higher frequency) and to push or hit their neighbors. The heat energy is thus passed to the neighbors, which also start to vibrate faster and to push other atoms. A sort of domino mechanism is established until the object reaches the thermal equilibrium (Vitiello *et al*., 2021). Heat convection occurs between a surface and a fluid (gas or liquid) and leads to a flow of matter in the fluid. The process can be natural due to a difference in temperature (hot fluids are less dense than cold fluids) or forced by a fan or similar mechanical tools. Thermal radiation is the transfer of energy associated with electromagnetic waves and it becomes significant at high temperatures. It can occur in any transparent medium (solid or fluid) and in the vacuum. Even if the three mechanisms have different characteristics, they often occur simultaneously in the same system. In order for the inside part of the building to be cold for a longer period, the thermal conductivity of the building material must be low as thermal conductivity is define as the rate of heat flow through the material. Refractories have a higher thermal inertia than other constructing materials that is they can conserve temperature when the weather is hot and release heat when the weather is cold. A good refractory is usually a highly porous material with low thermal conductivity with standard values of 0.01-1.1 K (W/m.k) (Samad et al., 2021).

2.10.6. Linear Shrinkage

Refractory clay shrinks substantially on roasting, which results in cracking. Linear shrinkage is the change in linear dimension that has occurred on the refractory ceramic board sample before and after firing. Low shrinkage is preferable for the application of refractory ceramic board in heat treatment furnace (Samad *et al*., 2021). The recommended range of linear shrinkage for refractory ceramic boards is 7% - 9% (Hwaidy *et al*., 2018; Samad *et al*., 2021).

2.10.7. Refractoriness

This is the measure of the fusibility of a material and indicates the temperature at which the material softens. Also, the 'refractoriness' of (refractory) refractory ceramic boards is the temperature at which the refractory bends because it can no longer support its own weight. Pyrometric cones are used in ceramic industries to test the refractoriness of refractory ceramic boards. The refractoriness of a clay sample is directly related to its softening temperature and is expressed as its Pyrometric Cone Equivalent (PCE). Pyrometric cone equivalent is the number which represents the softening temperature of a refractory specimen of standard dimension (38 mm vertical height and 19mm triangular base) and composition. Refractory clays are classified into different grades in respect of their softening temperatures, typified by the number of the standard pyrometric cone which deform under heat treatment (Jo and Philip, 2014). The standard values of refractoriness for refractory ceramic boards should be in the range 500-1700 °C (Ajala and Badarulzaman, 2016).

Other properties a good quality burnt refractory ceramic boards are; bright and uniform color, uniform shape and size, free from cracks, little or no pores as well as produce a metallic sound when struck with each other.

2.10.8. Specific gravity

Specific gravity of an aggregate is defined as the ratio of the mass of solid in a given volume of sample to the mass of an equal volume of water at same temperature. Absolute specific gravity: refers to the volume of solid material excluding voids, and therefore defined as the ratio of the mass of solid to the weight of an equal void free volume of water at stated temperature. The specific gravity test is usually conducted on materials that do not dissolve in or get attacked by water (Jock *et al*., 2013). The specific gravity is the ratio of the density of a solid to the density of water. The apparent specific gravity omits the open-pore volume and relates to the so-called "true" density.

3. Materials and Methods

3.1. Presentation of the zone of study

The current study was carried out, in the rural engineering research unit, Faculty of Agronomy and Agricultural Sciences (FASA) of the University of Dschang. Dschang, the head quarter of the Menoua division in the West region of Cameroon (Figure 3.1) is found on the southern slope of Mount Bamboutos and forms the northern edge of the Mbo plain (Kenfack *et al*., 2011). Dschang, is situated between longitude 10° and 10°5 East of the Prime meridian and between latitude 5°25' and 5°30' North of the Equator. Dschang is bound to the north by the community of Nkong Zem; to the south by that of Fongo-Tongo; to the east by Fokoué and to the south-west by the community of Fontem.

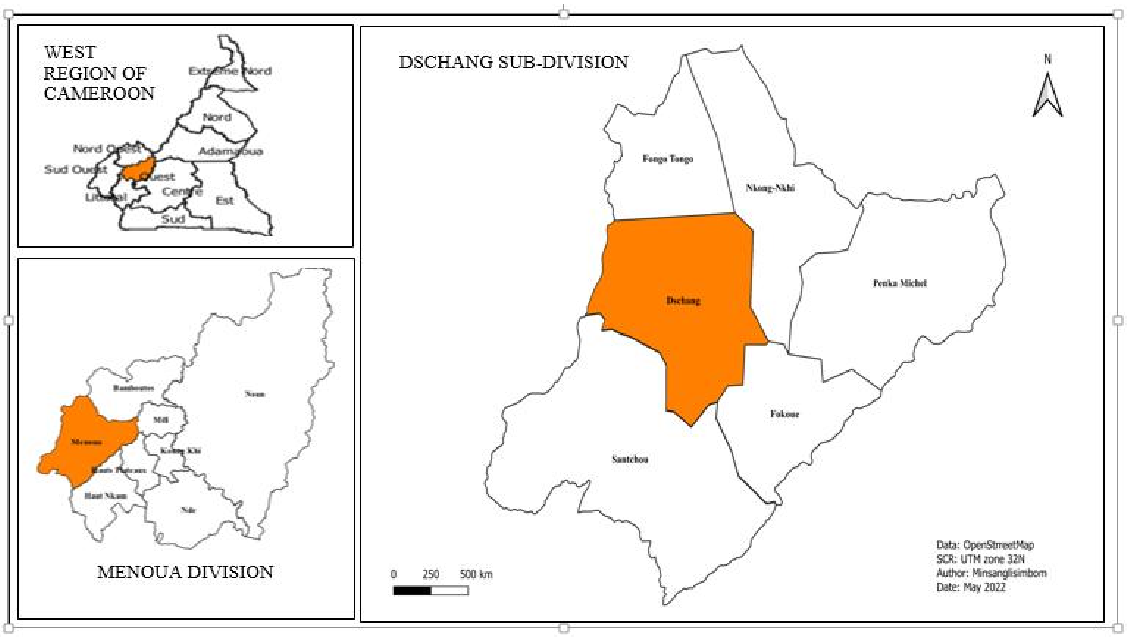


Figure 3.1: Localisation map of Dschang

3.2. Temperature

Dschang is characterised by an equatorial monsoon climate (Tazen *et al*., 2013). The wet season is comfortable, muggy, and overcast and the dry season is warm and mostly cloudy. Over the course of the year, the annual monthly temperature is about 18.83°C. The highest degree of temperatures occur in the month of January while the lowest occur in the months of July and August (Kenfack *et al*., 2020). Temperatures are very constant throughout the year and vary from a monthly minimum of about 18. 4 °C in July to a maximum of about 23.9 °C in February and March (Tazen *et al*., 2013).

3.3. Precipitation

A wet day is one with at least 0.04 inches of liquid or liquid-equivalent precipitation. The chance of wet days in Dschang varies very significantly throughout the year. The wet season lasts about 8 months, from mid-March to mid-November, with a greater than 48% chance of a given day being a wet day. Maximum precipitation occurs in August and September (Tazen *et al*., 2013). The dry season lasts about 4 months 4, from mid-November to mid-March. The month with the fewest wet days in Dschang is January, with an average of 1.3 days with at least 0.04 inches of precipitation. The average annual rainfall in Dschang is about 1790.5 mm with an average daily humidity ranging from 33% to 98%. In some years, even the months of December, January and February which are considered as dry months also experience days of rainfall (Kenfack *et al*., 2020).

3.4. Sunlight radiation

In Dschang, sunshine is more important during the dry season, where it represent 8.5 hours per day, while during the rainy season; it drops to 2.2 hours per day. Dschang experiences a total sunshine of 1,864 hours per year and an average monthly insolation of 155.3 hours. The annual average solar irradiation for Dschang is 5.3 KWh/m^2/day.

3.5. Soils

The relief is mountainous with many plateaus and plains. They are characterised by a succession of hills dominated by a few isolated mountains that can exceed 2000 m in height (Bamboutos Mountains: 2,740 m). The soils of Dschang are very varied in view of the multiplicity of geological substrates which support them. They belong to the red ferrallitic soils formed on more or less reworked basalt and are generally fertile.

3.6. Wind

The average hourly wind speed in Dschang experiences mild seasonal variation over the course of the year. The windier part of the year lasts for 2.3 months, from early July to mid-September, with an average wind speed of more than 1.43 to 1.70 m/s. The windiest month of the year in Dschang is August. The calmer time of the year lasts for 9.7 months, from mid-September to early July. The calmest month of the year in Dschang is May. The wind is most often from the west for 3.3 months, from February to May and for 4.6 months, from May to October, with a peak percentage of 83% in early August. The wind is most often from the south for 2.7 weeks, from May to June, with a peak percentage of 37% in mid-May. The wind is most often from the east for 3.5 months, from mid-October to early February, with a peak percentage of 48% in early January.

3.7. Fabrication of the stable insulating ceramic boards

The stable insulating ceramic boards were produced from clayey earth as the predominant ingredient in combination with white Portland cement and sand in different proportions. The boards were handmade using the artisanal process. The green insulating ceramic boards produced were dried and fired at temperatures over 1000 ˚C. This is because at this temperature there is fusing of sand and lime and the chemical bonds between the materials are strengthen.

3.8.1. Presentation and characterization of raw materials

The raw materials used were clayey earth which was the predominant raw material, white Portland cement, sand and wood sawdust.

- **Clayey earth**

Very large outcrops of these clay deposits exist in the Dschang subdivision of the west region of Cameroon. Clayey earth was used because it contains complex compounds of aluminum (Al_2O_3) and silica (SiO_3) that exist in various proportions with high melting points (figure 3.2 a).. More so, it is cheap and readily available. The clay that was used was gotten from a village in the Dschang subdivision called “Toutsang” (5˚26'7" N and 10˚4'5" E). The clayey earth was wet and the water content was calculated and found out to be 62.5% by weighing a sample of the clay using a precision balance and the mass noted as m_2. The sample was died in an oven at 105 ˚C for 24 hours. The sample was removed from the oven and weighed immediately. The mass was noted as m_1. The water content (w) in the clay was then calculated using equation 3.1.

$$w = \frac{m_2 - m_1}{m_1} \times 100\% \qquad (3.1)$$

Where:

w = water content (%),
m_1 = average mass of the dry samples in gram (g)
m_2 = average mass of the wet samples in gram (g)

By use of the sieve analysis, the percentage of clay as showed in Table 3.1 in the clayey earth, was gotten in the laboratory of Soil Sciences of the University of Dschang. It was found out that the USDA texture of this soil sample was clay.

Table 3.1: Clayey earth characteristics

Property	Value (%)
Sand	6.50
Silt	26
Clay	67.50

- **White Portland cement (WPC)**

Commercially available WPC was gotten from a shop in Douala to act as a binder. WPC was used in this study in exchange for refractory cement because of its low cost and availability. Also, it was used because it contains lime which will act as a mineralizing agent and form a strong bond due to the diffusion of calcium ion on into the silica surface during sintering. According to Samad *et al*. (2021), the chemical analysis of WPC shows that it is composed of CaO (61.65%), SiO_2 (19.43%), Al_2O_3 (10.10%), Fe_2O_3 (3.17%) and other oxides are MgO, SO_3, TiO_2, K_2O, Na_2O. WPC is presented in figure 3.2 b.

- **Sand**

Sand is a granular material composed of finely divided rock and mineral particles. Sand was used because the silica content in it might act as a fluxing agent during sintering thereby increasing the compressive strength of the boards. Sand used in this study was gotten from Santchou (figure 3.2 c). By use of the sieve analysis, as showed in table 3.2, the percentage of sand was gotten in the laboratory of Soil Sciences of the University of Dschang.

It was found out that the USDA texture of this soil sample was sandy clay loam.

Table 3.2: Sand deposit characteristics

Property	Value (%)
Sand	62
Silt	4
Clay	34

- **Sawdust**

Sawdust is used in insulating ceramic board manufacture because the presence of fibers develops the tensile strength of ceramic boards and increase the heat endurance of the boards as reported by Reddy *et al*., 2018. Sawdust among other fibers was used because of its availability and because of the additional indirect social, economic and environmental benefits its usage offers due to its recycling. The sawdust used for this study was gotten from a local sawmill in Dschang and its sizes were just enough to pass through a mosquito net with a mesh size of 1.2 mm (figure 3.2 d).. This size was chosen because according to Ojukwu and Ajemba (2022), pores of larger sizes contribute to increasingly high conductivity whereas small pores remain a good barrier to heat flow.

(a)- Clay **(b)- WPC** **(c)- Sand**

Figure 3.2: Raw materials used in the manufacture of ceramic boards

3.8.2. Raw material preparations

All the raw materials to be used were gotten and assembled in the foundry house of the agricultural department of the University of Dschang. The sand gotten was sun dried for 3 days before usage. The clay gotten was tired in a plastic bag to limit water losses.

(d)- Sawdust

3.8.3. Forming the ceramic material

Forming consisted of mixing the raw materials and moulding them into the desired shape. A mould of 60 × 25 × 2.5 cm was made in the Agricultural Engineering workshop. The raw materials were mixed in ten different combinations as A(60% clay + 30% WPC + 10% sand), B(65% clay + 25% WPC +10% sand), C(70% clay + 20%

WPC +10% sand), D(75% clay + 15% WPC +10% sand), E(80% clay + 10% WPC +10% sand), F(57.14 % clay + 28.57% WPC + 9.52 % sand + 4.77% sawdust), G(61.90 % clay + 23.81 % WPC + 9.52 % sand + 4.77 % sawdust), H(66.67% clay + 19.05% WPC + 9.52 % sand + 4.77% sawdust), I(71.43% clay +14.29% WPC + 9.52 % sand + 4.77% sawdust), J(76.19% clay + 9.52 WPC + 9.52 % sand + 4.77% sawdust) as showed in table 2.3 with water and immediately poured into the mould. In mixing the raw materials, the different percentages of sand and WPC were poured into a bucket. 0.5 l of water was added and mixed thoroughly to obtain a homogenous mixture (Figure 3.3a). 60% of clay was then added (Figure 3.3b) and mixed thoroughly to form a paste. The mould was then filled gradually with the paste, starting with the corners, until completely filled. The paste was then pressed down with the hand. The surface of the paste was smoothened down with a flat piece of iron. Then, the mould was gradually removed forming the green ceramic material. For each combination of raw materials used, a total of 3 ceramic boards were made in order to reduce the effect of errors.

(a) **(b)**

Figure 3.3: Mixing the raw materials

The entire procedure of forming 15 boards was repeated while adding sawdust as a ratio of 5% and new combinations were made as F, G, H, I, and J as showed in table 3.3. This ratio of sawdust was added because according to Benjeddou *et al.* (2018) an addition of more than 6% of sawdust will cause the creation of large pores at certain areas or the creation of elongated pores. These large pores constitute supplementary passages that facilitates the penetration of water which will as a consequence cause an augmentation in the rate of water absorption of the boards.

Table 3.3: Mix proportions of the raw materials for the manufacture of the ceramic boards

Combination	% of Clay	% of WPC	% of Sand	% of Sawdust
A	60	30	10	0
B	65	25	10	0
C	70	20	10	0
D	75	15	10	0
E	80	10	10	0
F	57.14	28.57	9.52	4.77
G	61.90	23.81	9.52	4.77
H	66.67	19.05	9.52	4.77
I	71.43	14.29	9.52	4.77
J	76.19	9.52	9.52	4.77

3.8.4. Drying the green insulating ceramic boards

After forming, the green ceramic boards were dried in the foundry house of the agricultural engineering department, Faculty of Agronomy and Agricultural Sciences of the University of Dschang for about 7 days. Drying is done to eliminate the hygroscopic water and increase green strength of boards. These boards were dried at ambient temperature and under a shade to reduce excessive cracking that could be cause by fluctuations of the sun’s rays.

3.8.5. Firing the green insulating ceramic boards

The green insulating ceramic boards were fired in order to effect the change from clay, a plastic material, into an aplastic ceramic (a thermally stable insulating material). The boards were fired in an already built pit fire kiln (Figure 3.4a). The 62 × 62 cm × 106 cm deep pit fire kiln was made of fire bricks. Air was brought into the kiln by a fan alimented by an electric motor (Figure 3.4b). The very first firing step was the cleaning of the pit fire kiln. The fumes from the kiln were expelled in the exterior through a chimney.

(a)

(b)

Figure 3.4: Pit fire kiln (a) and the air exchange system (b)

Placing the green ceramic boards in the kiln for firing

The fuel used in firing the refractory ceramic boards was a combination of sawdust and firewood because they are burnable and flammable enough to hold heat. A 2 cm layer of sawdust was placed at the bottom of the kiln followed by a few pieces of firewood (Figure 3.5a). Some of the ceramic boards were placed on it and a fire was lighted at this level (Figure 3.5b). More sawdust was poured into the kiln, some of the boards were placed and a few pieces of firewood were again added (Figure 3.5c). Finally, a last layer was made in the same manner and a lot of firewood was placed at the top. The firewood at the top was lighted (Figure 3.5d) and the electric motor was immediately switched on. The electric motor alimented the fan which blew air into the kiln to ensure that the fire has enough oxygen to continue burning and to prevent the buildup of carbon monoxide. The fumes produced were expelled outside the building through a chimney (Figure 3.5e). To acquire a better combustion and more heat, the lid of the kiln was a little bit tilted (Figure 3.5f) to allow more oxygen into the kiln.

No fire accelerant was used because the temperature inside the kiln had to be kept at about 100 ˚C for 90 minutes so as to eliminate any residual moisture that might be left in any of the samples which could cause the expansion of the moisture in the ceramic boards and consequently cause the cracking and even explosion of the boards. Temperatures were read at intervals of 15 minutes using a thermocouple thermometer (Figure 3.5g) and recorded. After 10 hours, the fan was turned off and the boards were left to cool gradually to room temperature inside the kiln. The slow cooling process was ensured in order to prevent possible cracking of the refractory ceramic boards. The entire firing-cooling process took about 48 hours.

(a)

(b)

(c)

(d)

(e)

(f)

(g)

Figure 3.5: Kiln firing process of the refractory ceramic boards

- **The evolution of the firing temperature**

Table 3.4 shows he evolution of the firing temperatures

Table 3.4: The evolution of the firing temperatures

t (min)	T (°C)
0	25,6
15	29,3
30	62,1
45	80,3
60	100,2
75	111,5
90	279,9
105	517,2
120	644,4
135	689,1
150	900,5
165	1061
180	1303
195	1136
210	1107
225	1161
240	1076
255	956,8
270	926,6
285	916,3
300	888,1
315	885,6
330	882,5
345	861,7
360	830,1
375	1125
390	1144
405	1180
420	1122
435	1095
450	1057
465	1052
480	1041
490	1038
510	1017
525	1010
540	929,9
555	886,2
570	864,3
585	851,4
600	844,8

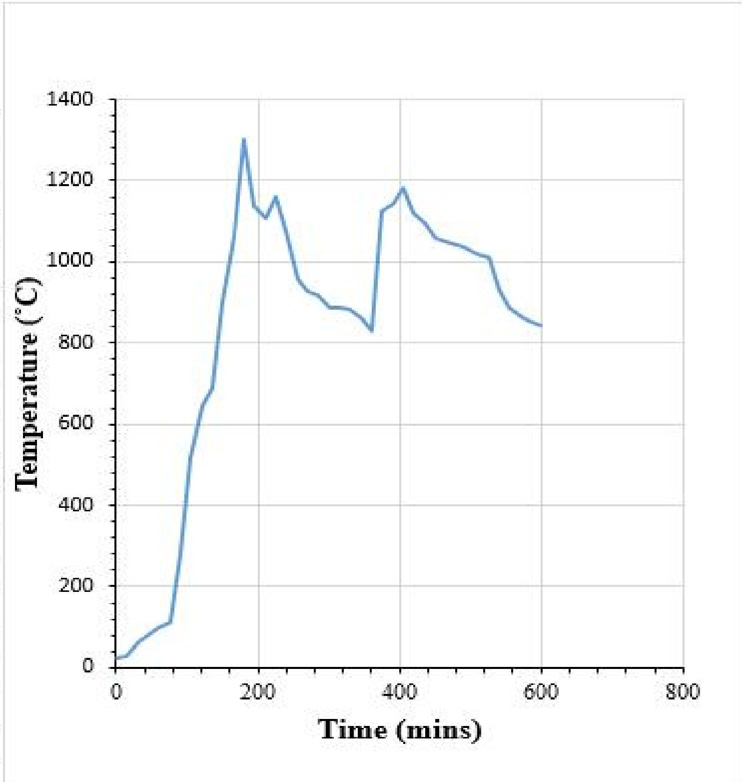


Figure 3.6: Evolution of firing temperatures

- **Offloading the insulating ceramic boards from the kiln**

After 48 hours, the kiln was opened (Figure 3.7) and the refractory ceramic boards were gently removed and dusted.

Figure 3.7: Ceramic boards ready to be offloaded from the kilns

3.9. Determination of the physical and mechanical properties of the insulating ceramic boards produced

3.9.1. Apparent porosity, water absorption, specific gravity and the bulk density tests

The apparent porosity test of the insulating ceramic boards was carried out according to ASTM C20 − 00 (2010). The samples from the kiln were weighed in air to determine their dry weight, D, to the nearest 0.1 g using a precision balance (Figure 3.8a). The test specimens were placed in water (Figure 3.8b) and boiled for 30 minutes to assist in releasing trapped air. The specimens were then cooled to room temperature while still immersed in water for 14 hours and the suspended weight was determined using the Archimedes principle which states that “the upward buoyant force that is exerted on a body immersed in a fluid, whether partially or fully is equal to the weight of the fluid that the body displaces and acts in the upward direction at the center of mass of the displaced fluid”. The weight of the fluid displaced was equal to the buoyant force (Equation 3.2). The suspended weight was gotten by subtracting the buoyant force from the actual weight of the object (Equation 3.3). The volume of the fluid displaced was gotten with the use of a cylinder (Figure 3.8c) and from this volume, the weight of the water displaced was calculate.

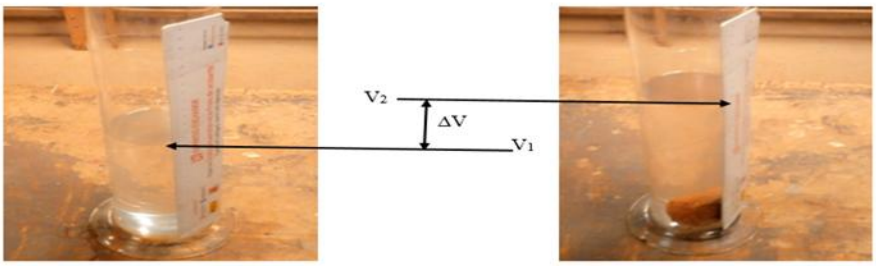
After determining the suspended weight, each specimen was blotted lightly with a moistened cotton cloth to remove all drops of water from the surface and the saturated weight, W, was determined in grams by weighing in air to the nearest 0.1 g.

$$\textbf{Buoyant Force (Fb)} = \rho f \times Vf \times g \qquad (3.2)$$

$$\textbf{Suspended weight, S} = \textbf{True weight – buoyant force} \qquad (3.3)$$

(a)

(b)



(c)

Figure 3.8: (a) Weighing the test specimen (b) specimens immersed in water for boiling (c) determination of the volume of water displaced.

NB: ΔV is the volume of the water displaced

From the measured weights, the volume (Equation 3.4), apparent porosity (Equation 3.5), water absorption (Equation 3.6), the specific gravity (Equation 3.7) and the bulk density (Equation 3.8) were calculated.

$$\textbf{Volume (cm}^3\textbf{) = W - S} \tag{3.4}$$

$$\textbf{Apparent Porosity } (\%) = \frac{\mathbf{W - D}}{\mathbf{V}} \times \mathbf{100} \tag{3.5}$$

$$\textbf{Water Absorption, A } (\%) = \frac{\mathbf{W - D}}{\mathbf{D}} \times \mathbf{100} \tag{3.6}$$

$$\textbf{Apparent specific gravity, T} = \frac{\mathbf{D}}{\mathbf{D - S}} \tag{3.7}$$

$$\textbf{Bulk Density, BD } (\mathbf{g/cm3}) = \frac{\mathbf{D}}{\mathbf{V}} \tag{3.8}$$

Where

ρ_f = density of the fluid
V_f = volume of fluid displaced
g = acceleration due to gravity

This experiment was carried out with all the insulating refractory boards with sawdust additives as well as with the blank insulating refractory boards.

3.9.2. Compressive strength (CS) test of the insulating ceramic boards

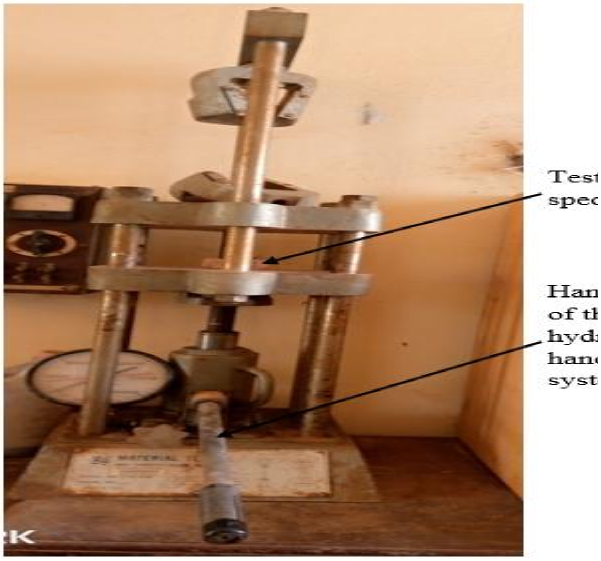
This was determined by the use of the compressive strength test in the renewable energy laboratory of the agricultural department in the University of Dschang using a material tester machine, UTM-30 whose serial number is 121 with a maximum loading capacity of 30 000 lbs. The compressive strength test is a mechanical test measuring the maximum amount of compressive load a material can bear before fracturing. The test pieces were prepared in the form of cubes (Figure 3.9a). A specimen was placed between the lower and the upper platform of the machine (Figure 3.9b) and a force of compression was applied on it by the use of the handle of the hydraulic hand system while observing the specimen keenly. Once a fracture developed on the specimen (Figure 3.9c), the compressive force applied on it was released and the number of pounds was read on the digital indicator (Figure 3.9d). On the machine was indicated 30 000 lbs= 9549 psi. The value that was read on the digital indicator was therefore converted to psi (Equation 3.9) and then to mega pascal (Equation 3.10).

$$CS\ (psi) = \frac{\textit{Value read on the digital indicator x } 9549}{30\ 000} \tag{3.9}$$

$$CS\ (MPa) = \frac{CS\ (psi)\ x\ 6894.759}{1000\ 000} \tag{3.10}$$

This experiment was carried out with all the insulating refractory boards with sawdust additives as well as with the blank insulating refractory boards.

(a)



(b)

(c)

(d)

Figure 3.9: Test specimen (a) Material tester machine (b) apparition of cracks in the compressed test specimen (c) Digital indicator (d)

3.10. Thermal properties of the insulating ceramic boards produced

3.10.1. Thermal Conductivity Test

The thermal conductivity was gotten with the use of Joseph Fourier’s law of thermal conduction. The thermal conductivity was gotten by heating one surface of the insulating ceramic boards with a heating plate (Figure 3.10) and then, measuring the temperature on the two isothermal planes as θ_1 and θ_2 using a thermocouple thermometer.

Figure 3.10: Heating the insulating ceramic board with a heating plate

With the use of Joseph Fourier’s law of thermal conduction (Equation 3.11), the thermal conductivity of the insulating ceramic boards were calculated using equation 3.11.

$$K = \frac{\mathbf{QL}}{\mathbf{A\Delta T}} \tag{3.11}$$

Where,

K is the thermal conductivity in W/m.K
Q is the amount of heat transferred through the material in J/s or Watts
L is the distance between the two isothermal planes in meters
A is the area of the surface in square meters
ΔT is the difference in temperature in kelvin.

In order to solve for K, all the terms in the equation were determined. The distance between the two isothermal planes was measured by use of a measuring tape. The area was calculated using the unit square method. The amount of heat transferred through the material was gotten by converting the electric power produced by the aluminium heating plate to thermal energy.

- **Characteristic of the aluminium heating plate**

The aluminium heating plate had a maximum operating temperature of 100 °C, a voltage of 220 V AC.

- **Calculating the electrical power of the heating plate**

The voltage and current at which the plate was operating was measured directly using a multimeter (Figure 3.11).

(a) **(b)**

Figure 3.11: Measurement of voltage (a) and current (b) values

The power was calculated (Equation 3.12) using the current and voltage values gotten.

$$P = IV \tag{3.12}$$

Where,

P is the electrical power in W
I is the electric current in A
V is the voltage in volts.

- **Converting the power produced by the heat resistant plate to thermal energy**

This was done by the Fourier’s formula (Equation 3.13) of heating.

$$H = I^2Rt \tag{3.13}$$

Where,

H is the thermal energy in J
I is the current A
R is the resistance in Ω
t is the time in seconds.

When all the terms in equation 3.11 were gotten, the thermal conductivity was calculated. The procedure was repeated with all the other insulating ceramic boards and their thermal conductivities were gotten.

3.10.2. Thermal resistance test

Thermal resistance is the reciprocal of thermal conductance (Equation 3.14). The thermal conductance is the amount of energy passing through a material per unit area per unit time when its opposite faces are subjected to a temperature difference of 1 kelvin (Equation 3.15).

$$R = \frac{1}{C} \tag{3.14}$$

$$C = \frac{K}{L} \tag{3.15}$$

Where,

K is the thermal conductivity in W/m.K
L is the distance between the two isothermal planes in meters
R is the thermal resistance (K/W)
C is the thermal conductance (W/m^2K)

4. Results and Discussions

4.1. The insulating ceramic boards produced

➢ **The green ceramic boards produced**

There was a great difference between the blank insulating ceramic boards (Figure 4.1) and those made with an addition of sawdust (Figure 4.2).

(A) 60% clay + 30% WPC + 10% sand

(B) 65% clay + 25% WPC +10% sand

(C) 70% clay + 20% WPC +10% sand

(D) 75% clay + 15% WPC +10% sand

(E) 80% clay + 10% WPC +10% sand

Figure 4.1: Green insulating ceramic boards without sawdust additives

(F) 57.14 % clay + 28.57% WPC + 9.52 % sand + 4.77% sawdust

(G) 61.90 % clay + 23.81 % WPC + 9.52 % sand + 4.77 % sawdust

(H) 66.67% clay + 19.05% WPC + 9.52 % sand + 4.77% sawdust

(I) 71.43% clay +14.29% WPC + 9.52 % sand + 4.77% sawdust

(J) 76.19% clay + 9.52 WPC + 9.52 % sand + 4.77% sawdust

Figure 4.2: Green insulating ceramic boards with sawdust additives

Specimen	A	B	C	D	E	F	G	H	I	J
Number of cracks	12	10	8.7	2.3	1.7	1	0.3	1	0	1

Table 4.1: Number of cracks on the green ceramic materials

The total number of cracks as showed in table 4.1, in the green ceramic boards without sawdust additives were determined and it was noticed that the number of cracks in the boards increased with an increase in the amount of WPC present in them and a reduction in their clay content (Figure 4.2). This equally was observed in the green ceramic boards with sawdust additives (Figure 4.2)

- **Fired insulating ceramic boards**

Figure 4.3 presented the green insulating ceramic boards after firing.

(a)

(b)

Figure 4- 3: Fired insulating ceramic boards (a) blank specimens (b) specimens with sawdust additives

According to figure 4.3, the following observations were made:

There were no further cracks nor breakages in the broken halves of the refractory ceramic boards that were made without any sawdust additives; All the insulating ceramic boards that were made with sawdust additives that were not broken initially were broken at the end of the firing process except one of the boards, I (71.43% clay + 14.29% WPC + 9.52 % sand + 4.77% sawdust); There were no further cracks nor breakages in the broken halves of the insulating ceramic boards made with sawdust additives. The green blank insulating ceramic boards produced had more cracks than those with sawdust additives. This is due to the presence of wood sawdust acting as fibers in the insulating ceramic boards which helps to slow down strength loss in them. This behavior is familiar to the studies of Reddy *et al*. (2018). It can also be deduced that the addition of sawdust in insulating refractory ceramic boards not only strengthens them but improves the thermal shock resistance of the boards. This resistance is offered by the bonding formed by the sawdust in between the clay, WPC and sand matrix which helps in controlling the cracks. These results are consistent with previously reported findings of Duan *et al*. (2016).

4.2 Physical and mechanical properties of the insulating ceramic boards produced

- **Apparent porosity (%)**

The apparent porosity values of all the insulating ceramic boards are showed in table 4.2.

Table 4.2: Apparent porosity of the insulating ceramic boards

Specimen	Apparent porosity (%)
A	55.42
B	60.01
C	60.49
D	61.427
E	62.56
F	62.73
G	63.80
H	64.16
I	66.50
J	67.28

From table 4.2, the apparent porosity values of all the specimens complied with the European standard specification (EN 1094: 2) for insulating ceramic boards, which should possess a porosity higher than 45%. These results are in accordance with international standard range (ISO 5016-1986) of 20 - 80%. The specimens containing sawdust additives had higher apparent porosity values because the wood sawdust which is a pore former was removed when the ceramic material was fired forming as a consequence many pores. Also, for both blank specimens and those with sawdust additives, the apparent porosity increased with an increase in the percentage of clayey earth as a partial replacement of the percentage of WPC. This is because WPC which is binding agent, when combined with sand, act as bonding materials with clayey earth at high temperatures thereby reducing the surface pores of the insulating ceramic boards as reported by Samad *et al*., (2021). This results also corroborates the results of Otero *et al*. (2004).

- **Water absorption (%)**

The water absorption values of all the insulating ceramic boards are shown in table 4.3.

Table 4.3: Water absorption of the insulating ceramic boards

Specimen	Water absorption (%)
A	31.45
B	34.97
C	35.11
D	36.42
E	36.67
F	37.714
G	37.24

H	38.722
I	38.611
J	38.33

According to table 4.3, just like apparent porosity, water absorption increased steadily with a reduction in the percentage of WPC in both blank specimens and those with sawdust additives. The blank specimens equally had lower water absorption values compared to those with sawdust additives. This is because the water absorption of the specimens is closely related to porosity and because wood sawdust leaves plenty of pores when fired out, the pores acts as water reservoirs and as a consequence, lead to an increase in water absorption by the specimens. None of the specimens absorbed more than 20% water of its own weight as recommended by in ASTM (C140-2020) for good quality insulating ceramic boards. This results are also in line with the findings of Velasco *et al*. (2014).

- **Specific Gravity**

The specific gravity values of all the insulating ceramic boards are shown in table 4.4.

Table 4.4: Specific gravity of the insulating ceramic boards

Specimen	Specific Gravity
A	4.638
B	5.180
C	6.031
D	4.866
E	4.069
F	4.476
G	4.225
H	4.419
I	4.251
J	4.836

From table 4.4, the specific gravity values for all the specimens was not close to the required range of 2.6 - 2.7 recommended for good quality insulating ceramic boards as per ASTM (D792 – 2010). These results are consistent with the findings of Jock *et al*. (2013) and Al-nawafleh (2009). This could be because of the presence of abrasive powder (lime) found in WPC used in the manufacture of all the insulating ceramic boards. These results authenticates the findings of Hamza *et al*. (2011).

- **Bulk Density (g/cm^3)**

The bulk densities of all the insulating ceramic boards are shown in Table 4.5.

Table 4.5: Bulk density of the insulating ceramic boards

Specimen	Bulk Density (g/cm^3)
A	1.698
B	1.6804
C	1.6613
D	1.6359
E	1.6288
F	1.936
G	1.7572
H	1.7528
I	1.7227
J	1.7079

According to table 4.5, the bulk density of the blank specimens as well as those with sawdust additives increased with an increase in the percentage of WPC in the specimens. This could be due to the fact that during sintering, the calcium oxide of WPC created a calcium silicate phase by reacting with the active silica present in sand. The reaction of this active silica with WPC is very effective helping to eliminate the spaces between granules and microspores leading to more packing efficiency and better densification during sintering. These results corroborates the findings of Samad *et al*. (2021). Also, the specimens with sawdust additives had lower bulk densities than the blank specimens. This is due to the oxidation of the wood sawdust during the firing process which results in weight loss. However, the bulk density values of all the specimens fell in the British standard range (BS, 1902 part B 1976) of 1.71- 2.1 g/cm3 corroborating the results of Hassan *et al*. (2007), H. Al-Taie et al. (2014) and those of Jock *et al*. (2013).

- **Compressive strength (MPa)**

The compressive strength values of the insulating ceramic boards are shown in table 4.6.

Table 4.6: Average compressive strengths of the insulating ceramic boards

Specimen	Compressive strength (MPa)
A	4.974
B	3.072
C	2.780
D	2.634
E	2.2678
F	6.657
G	6.5107
H	5.048
I	5.41
J	3.731

According to table 4.6, the compressive strengths of all the specimens increased with an increase in the percentage of WPC as a partial replacement of the percentage of clay in the insulating ceramic boards. This is because the action of lime (CaO) from WPC acted as a mineralizing agent during firing and the formation of the strong bond is due to the diffusion of calcium ion unto the silica surface during sintering. The specimens with wood sawdust additives had higher compressive strength values compared to the blank specimens. This could be because the presence of sawdust in the specimens strengthened the bonding with the clay, WPC and sand matrix. These results are consistent with the previously reported findings of Duan et al. (2016). However, ASTM (C64-2012) recommends 1.3 MPa as the minimum value for insulating ceramic materials. These values corroborated the results of Katte et *al.* (2017) and Moundom et *al.* (2022). This implies that, all the specimens have acceptable compressive strength values.

4.3. Thermal properties of the insulating ceramic boards produced

- **Thermal Conductivity (W/m.K)**

Thermal conductivity values of the different insulating ceramic boards are shown in table 4.7.

Table 4.7: Thermal conductivity values of the different insulating ceramic boards

Specimen	Thermal conductivity
A	3.377
B	2.820
C	0.850
D	0.8133
E	0.9367
F	0.8133
G	1.150
H	1.147
I	0.3133
J	0.660

According to table 4.7, all the specimens with sawdust additives produced lower thermal conductivity values than the blank specimens. This is because of the lower porosity of the blank specimens. This shows that thermal conductivity decreases in ceramic materials as its porosity increases with the pores acting as non-heat conducting media. That is, the presence of air in these pores created by the oxidation of the wood sawdust reduced the thermal conductive capacity of the boards thereby increasing their insulating characteristics. This is in line with the findings of Akinfolarin and Awopetu. (2014). Also, thermal conductivity increased in the blank specimens as the percentage of WPC increased. This is because WPC which is a binder tends to bond all the particles in the specimen leaving little or no pores. These results authenticate the findings of Samad *et al*. (2021). However, the thermal conductivity values of all the ceramic boards except specimen A (60% clay, 30% WPC and 10% sand) and B (65% clay, 25% WPC and 10% sand) complied with the ASTM specifications (C177- 2023) for insulating ceramic boards, which should possess thermal conductivity values between 0.01-1.1 W/m.k.

➢ **Thermal resistance (K/W)**

The thermal resistance of the insulating ceramic boards are shown in table 4.8.

Table 4.8 : Thermal Resistance of the insulating ceramic boards

Specimen	Thermal Resistance (K/W)
A	0.7614
B	0.958
C	3.478
D	3.104
E	2.717
F	3.0783
G	2.226
H	2.356
I	8.84
J	4.003

Table 4.8 showed that specimen I, was the specimen with the highest resistance to heat flow and specimen A, was that with the least resistance to heat flow. This results are in line with the fact that thermal resistance is the reciprocal of thermal conductance.

5. Conclusions and Recommendations

Insulating ceramic boards are sought in various industries, civil engineering workshops and even in homes for numerous uses but its manufacture is quite complex. This research work was aimed at developing a stable ceramic material (high temperature bricks) for high temperature applications in building construction. Insulating ceramic boards were made from clay which was the predominant raw material, sawdust, white Portland cement (WPC) and sand by combining the raw materials in different ratios [A (60% clay + 30% WPC + 10% sand), B (65% clay + 25% WPC +10% sand), C (70% clay + 20% WPC +10% sand), D (75% clay + 15% WPC +10% sand), E (80% clay + 10% WPC +10% sand), F (57.14 % clay + 28.57% WPC + 9.52 % sand + 4.77% sawdust), G (61.90 % clay + 23.81 % WPC + 9.52 % sand + 4.77 % sawdust), H (66.67% clay + 19.05% WPC + 9.52 % sand + 4.77% sawdust), I (71.43% clay +14.29% WPC + 9.52 % sand + 4.77% sawdust), J(76.19% clay + 9.52 WPC + 9.52 % sand + 4.77% sawdust)]. The raw materials were mixed, the green ceramic materials were formed in a mould of 60 × 25 × 2.5 cm, dried at ambient temperature, fired at a temperature range of 900 – 1303 °C and allowed to cold in the kiln. The ceramic boards were then removed and their physical, mechanical and thermal properties determined. Experimental results showed that the apparent porosity values of all the specimens were between 55.42 and 67.28% which are in the international standard range (ISO 5016-1986) of 20 - 80%. The bulk density values of all the specimens were between 1.63 and 1.71 g/cm3 bringing them closer to the British standard range (BS, 1902 part B 1976) of 1.71- 2.1 g/cm3. The thermal conductivity values of all the specimens were between 0.31 and 0.94 W/m.k which fall in the ASTM specifications (C177-2023) of 0.01-1.1 W/m.k except for specimen A, B, G, and H which had higher values. The compressive strength of all the specimens were between 2.27 and 6.66 MPa, complying to the ASTM (C64 -2012) which recommends 1.3MPa as the minimum compressive strength value for insulating ceramic boards. None of the specimens absorbed more than 20% water of its own weight in conformity with ASTM (C140-2020). All the specimens had very high specific gravity values not complying with the ASTM (D792 - 2017) range of 2.6 - 2.7. Based on these results, it can be said that specimen I (71.43% clay +14.29% WPC + 9.52 % sand + 4.77% sawdust) is a good substitute for imported insulating ceramic materials used for high temperature application in building construction. With regard to the results obtained and the conclusions that followed, the recommendation of using correct proportions of all ingredients in the fabrication of insulating ceramic materials was made.

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