# Physio-Chemical Characterization of the brick clays of Njala in the southern province of Sierra leone

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**ABSTRACT-**The traditional ceramic industry in Sierra Leone has been extremely slow in adopting the automation techniques developed in industrialized countries and did not make appreciable efforts in developing techniques of its own, mainly due to lack of research data and technological expertise. For the traditional ceramic industry to survive and to contribute positively to nation building, high quality and affordable products must be introduced into the market to compete with imported building materials.

This work tried to redress the issue of unavailability of scientific data by extensively investigating the physical and chemical characteristics of the brick bodies produced from selected clays at Njala in the Southern Province of Sierra Leone. This is to justify their suitability for industrial application, especially in low cost building materials production and to develop data bank for further research.

Clay samples were collected from four sites at Njala namely Makonda, Pelewahun and Bonganema inland valley swamps. The physical and chemical compositions of the brick bodies prepared from these clay samples were analyzed using standard laboratory procedures.

The results obtained from both the physical and chemical properties analyzed are within the acceptable range to produce fired clay bricks.

With the exception of Njala clay, which exhibits medium plasticity, the other three clay samples (Makonday, Pelewahun and bonganema have excellent plasticity that justifies their use in ceramic applications, especially in case of complex shape forming and as additives for non-plastic ceramic materials. Water absorption of these clays are comparatively high with low bulk densities at $1000^0$C and permissible linear shrinkage and high crushing strength at firing temperatures above $1000^0$ C.

Typically, clay brick consists of silica (sand) – 50% to 60% by weight, alumina (clay) – 20% to 30% by weight, lime – 2 to 5% by weight and iron oxide – ≤ 7% by weight. The results of the chemical analysis of these clay samples fall within these ranges, hence suitable for fired bricks production. To produce high-quality porcelain, processing of these clays is required to improve on certain physical properties like porosity, density and eventually water absorption. This could be done by addition of one or more of the following materials such as limestone, feldspar, kaolin, sand, talc, wollastonite and pyrophyllite in the right proportion followed by efficient processing technique and optimization of the firing temperature.

**Key Words***:* Ceramic industry, brick clays, fired clay bricks, firing temperature, bulk density, water absorption, shrinkage, crushing strength.

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## INTRODUCTION

The geology of Sierra Leone is dominated by pleistocene and recent alluvium, whose consolidated sediments are mainly clays of estuarine, marine and fluvial origin. Granite and acid gneiss are the major rock types with intermediate igneous and metamorphic rocks of precambrian age. Quartz, alkali feldspar, acid plagioclase, biotite, muscovite, hornblende, haemite, garnet, and serite are the chief minerals with kaolinite as the predominant clay mineral. As a result of this geology, Njala soils are mainly utisols, soils that are usually moist with horizon of clay accumulation and low base supply (Dijkerman et al, 1969). These clays are primary raw materials used in the production of fired bricks production.

The physio-chemical properties of the unfired brick body offers a foundation for the quality of the finished fired brick. Chemical properties such as oxides of aluminium, silicon, iron, potassiun, sodium and physical properties like plasticity, bulk density, porosity, and water absorption, play significant role in determining the mechanical properties, namely strength, of the fired brick. This is attested by certain defects like cracks on the fired brick surface resulting mainly from bubble development within the body matrix during firing.

This study aim at helping not only to improve the mechanical properties of the fired brick but also the durability and beauty of the engineering sturctures, mainly the low-cost buildings presently constructed in Sierra Leone.

## PROBLEM ANALYSIS

The traditional ceramic industry in Sierra Leone has been extremely slow in adopting the automation techniques developed in industrialized countries and did not make appreciable efforts in developing techniques of its own, mainly due to lack of technological expertise. For the traditional ceramic industry to survive and to contribute positively to nation building, high quality and affordable products must be introduced into the market to compete with imported building materials. To achieve this goal, the traditional ceramic industry in Sierra Leone has to learn how to better relate the characteristics and the performance of the raw materials it uses, especially for imported glazes which is posing significant problem of mismatch with the tile bodies prepared from the variable colored clays.

Sierra Leone has high potentials for the setting-up of ceramic industry because of its huge virgin deposits of raw materials. Presently, the country can only boast of few traditional ceramic industries which are still in their embryonic stage, crippling to survive due to inadequate technical expertise. Using the above yardstick, it is easy to see why the ceramic industry has either stagnated or failed. Another case in point is the first ever clay factory in Freetown which failed four years after its establishment in 1976 for want of relevant research data on clay bricks and tile bodies to guide its production.

This work tried to redress the issue of unavailability of scientific data by extensively investigating the physical and chemical characteristics of the tile bodies produced from selected clays at Njala in the Southern Province of Sierra Leone. This is to justify their suitability for industrial application and to develop data bank for further research.

**REVIEW OF LITERATURE**

Bricks have been playing a significant role in building and construction for thousands of years. Despite the reliable workability and accessibility, it is widely known that the production of fired clay brick has always been a rather energy- and resource-intensive process. Many researchers have been conducting a wide range of studies regarding sustainable and innovative bricks, to mitigate the large carbon footprint of brick industry.

The building industry has called upon scientists to develop more sustainable, low cost and lightweight construction materials. Recently, some researchers have reviewed the use of various wastes in brick production to achieve lightweight materials. According to Phonphuak (2013), Kadir and Mohajerani (2010), and Demir (2006) incorporation of waste in raw clay soil will decrease the density of a brick. This is due to the formation of pores inside the brick during firing stage.

The physical and mechanical properties of clay brick can be divided into five parameters which are compressive strength, water absorption, firing shrinkage, dry density and thermal conductivity. Fired clay bricks vary considerably in physical and mechanical properties. They may be said to perform well in various aesthetic appearance such as durability, resistance to rain penetration, compressive strength, fire resistance, sound insulation, low thermal and moisture movement, economy, versatility in application and low maintenance requirements (Lyons, 2007).

The most common result obtained by the scientific community in this field is a decrease in bulk density. During the firing phase, increasing temperature induces a lower bulk density and a higher thermal conductivity due to microstructural modifications (Chiang et al. 2009), water absorption increases positively with the amount of incorporated matter, depending on the nature of the additive, the particle size and the porosity generated (Celik *et al., 2014*). According to Victoria (2013), compressive strength of brick is affected by the porosity, pore size, and type of crystallization.

Clay brick may shrink during drying and firing process. According to Karaman et al. (2006), shrinkage occurs when water between clay particles leaves and particles come closer. A study by Weng et al. (2003) suggested that a good quality of bricks exhibit the shrinkage below 8%. Meanwhile, BIA (2004) has set the desirable limit for firing shrinkage (2.5% to 4%) and drying shrinkage (2% to 4%). To control excessive shrinkage and defects in the structure of the brick, evaporation of the free water surrounding the particles in plastic clay needs to be controlled (CBA, 2002). High temperature and higher amount of waste will lead to high increasing of shrinkage (Weng et al., 2003; Fatih and Umit, 2001).

**EXPERIMENTAL PROCEDURES**

Clay samples were collected from four sites at Njala namely Makonda (Ma), Pelewahun (Pe) and Bonganema (Bo) inland valley swamps. The physical and chemical compositions of the tile bodies prepared from these clay samples were analyzed using standard laboratory procedures.

Preparation of Tile Bodies

Each of the as-mined clay samples collected from the four sites was crushed and ball milled for 12 h followed by drying of the slurries in an oven at 110 °C for 4 h. The dry powders were homogenised and passed through a standard US-sieve No. 12 (<1.68 mm). The slurries were dried and the dry powder passed through US-sieve No.12. 5 mass-% of water was added to the sieved powder, homogeneously mixed to consistence plasticity and aged for 36 h. Test bars of dimensions 5 x 5 x 7 $cm^3$ were pressed using a hydraulic press at a pressure of 36 MPa.

*Firing Technique*

The test bars were dried at room temperature for 48 h followed by moisture oven at 110ºC for 12h. The dried bars were then fired in an electric furnace at 1250ºC at a heating rate of 200ºC/h with a soaking period of 1h. The samples were subjected to natural cooling inside the furnace.

## DETERMINATION OF PHYSICAL/MECHANICAL PROPERTIES

Plasticity, wet-dry shrinkage, firing Shrinkage, water absorption, bulk density were the main physical properties determined from the clays.

*Plasticity*

Plasticity was determined by deformation techniques. 2 kg each of the seven clay samples, in as mined condition, were mixed into workable plasticity. The plastic clay mixtures were rolled into spherical balls of 5cm diameter; five balls for each clay sample. The balls were weighed to fix weight of 113g and each ball was subjected to a deformation test using (name of Machine). The force of deformation $F$ and the height $H$ of the clay ball before deformation and height ($h$) after deformation were measured.

Plasticity Index ($P$) was calculated with the following equation

$$P = F \times (H - h)$$

**Wet-dry shrinkage**

3kg of each of the clay samples were mixed with water to optimum plasticity. Five test pieces of dimension 10mm×500mm×800mm were made from each clay sample by de-airing of the plastic bodies and subsequently cutting the flat de-aired mass with a rectangular copper tile cutter. Two parallel lines exactly 503mm (wet length, $\mathbf{L_w}$) apart joined by a diagonal line were marked across all the test pieces and the pieces were oven dried at 110ºC for 18hours. Measurements were taken for the dry length ($\boldsymbol{L_d}$).

where $\boldsymbol{S_w}$ is the wet-dry shrinkage expressed as vol.-%, $\boldsymbol{L_w}$ is the wet length, and $\boldsymbol{L_d}$ is the dry length.

$$S_w = \frac{L_w - L_d}{L_w} \times 100$$

*DETERMINATION OF FIRING SHRINKAGE*

Following the wet-dry shrinkage test, the oven dried tile pieces for each clay sample were fired at 1000ºC, 1150ºC, and 1250ºC and dry- firing shrinkage ($\boldsymbol{S_f}$) calculated from the measured values obtained as shown below.

$$S_f = \frac{L_d - L_f}{L_d} \times 100(\%)$$

where $L_f$ is the fired length

(a) Determination of Water Absorption, Bulk density and Porosity of the Clay Samples.

The ISO/TC 187, Part 3 standard test for determination of water absorption, bulk density and porosity was used. In these determinations, the Archimedes Immersion Technique was used. Ten tile pieces of dimension (8mm×50mm×70mm) were prepared from each clay sample and were allowed to dry at room temperatures for 48 hours and then dried in a moisture oven at 110ºC for 18 hours. The weight of the dried tile pieces $G_0$ were measured by an electric balance and then fired in an electric kiln at 500ºC, 1000ºC, 1150ºC, and 1250ºC with a socking time of 30mins. The fired tile samples were boiled in water for two hours and allowed to cool for three hours at room temperature. The wet weight, $G_1$ in grams of all the tile samples were measured by electric balance followed by the determination of the weight of water displaced $G_2$ by the tile samples when immersed in a beaker of water.

Water Absorption (WA) Vol.-% was obtained using the equation below

$$WA(\%) = \frac{G_1 - G_0}{G_0} \times 100$$

Bulk density (Bd) g/cm$^3$

$$Bd(g/cm^3) = \frac{G_0}{G_1 - G_2}$$

Apparent Porosity (AP) vol.-%

$$AP(vol.-\%) = \frac{G_1 - G_0}{G_1 - G_2} \times 100$$

*(b) Determination of Crushing Strength of Fired Clay Samples*

The determination of the crushing strength of the fired brick bodies conformed to the ISO/TC 187 (Ceramic Tile), Part 4. Ten fired bricks of dimension (10mm×50mm×70mm), from each clay sample were rubbed free from imperfections with sand paper and fully saturated with water. Three plywood sheets, 3mm thick, were used as seating between the upper and the lower platens of the testing machine and the specimen. The specimens were then tested on flat at loading rate of 200lb/in$^3$/min.

where $Sc$ is the recorded strength, $Sco$ is the compressive strength read from the testing machine, $L$ is the length between the bearer plates, and $A$ is the square end of the tile area.

$$Sco = Sco(0.8 + \frac{0.2}{L/\sqrt{A}})$$

*CHEMICAL ANALYSES OF CLAY SAMPLES*

The clay materials used in the fabrication of the tile bodies were chemically analyzed for $Al_2O_3$, $SiO_2$, $TiO_2$, $Fe_2O_3$, and CaO, MgO, $Na_2O$, and $K_2O$ by XRF using a lithium tetra-borate fusion technique. The American National Bureau of Standards (NBS) 98 was used.

### ANALYTICAL PROCEDURE

The clay samples as received were milled to less than 180-mesh in a tungsten-carbide-line vibromill. One gram of the milled sample and 5g of lithium tetra-borate ($LiB_4O_7.5H_2O$) were weighed (± 0.5mg) into a plastic vial, thoroughly mixed, then fused in a carbon crucible for 30min. at 1000°C. The fusion was poured into a water-cooled platinum dish, thereby quenching the glass and avoiding devitrification. The glass bead was milled for 10 min. in the vibromill; 0.5g of "one shot" phenol formaldehyde powder resin was added and milling continued for further 5 min. The powder was then loaded into a hardened and polished steel mould of 1¼ diameter and pressed at 9000 p.s.i. The pressed pellet was cured in a laboratory oven for 30 min. at 150°C. After cooling, the compact was placed in the spectrograph for examination.

Table 1: Order of Chemical Analysis by XRF

| | $Fe_2O_3$ | $TiO_3$ | $Al_2O_3$ | CaO | $SiO_2$ | MgO | $Na_2O$ | $K_2O$ |
|---|---|---|---|---|---|---|---|---|
| Standard | NBS98 | | | | | | | |
| Operation | Vacuum | | | | | | | |
| Tube volts (kV) | 20 | 20 | 40 | 20 | 40 | 20 | 20 | 20 |
| Current (mA) | 6 | 6 | 20 | 6 | 20 | 6 | 6 | 6 |
| Crystals | LiF | LiF | EDDT | LiF | EDDT | LiF | LiF | LiF |
| Counter | Scintillation 980V | | Gas flow proportional 1630V. 100cm$^3$ P1gas/min. | | | | | |
| 2θ ($K\alpha_1\alpha_2$) | 57.52° | 86.15° | 142.46° | 113.08° | 108° | 54.36° | 96.14° | 96.32° |
| Actual setting | 57.55° | 86.18° | 112.62° | 113.40° | 78.02° | 54.52° | 88.06° | 88.00° |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Discrimination: | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| Attenuation | 23.5 | 17 | 25.5 | 64 | 32 | 64 | 18 | 17.8 |
| Amplitude (V) | 24 | 24 | 32 | 32 | 32 | 32 | 24 | 24 |
| Channel (V) | | | | | | | | |
| | Integrated time constant (I.T.C.) 0.2; differential time constant (D.T.C.),∞ | | | | | | | |
| Fixed count | 256,000 | 32,000 | 64,000 | 256,000 | 64,000 | 256,000 | 256,000 | 256,000 |

**DISCUSSION**

The discussion of the results obtained was based on the four groups of clays treated, i.e. Makonday, Pelewahun, Bonganema and Njala clays.

*Physical Properties of the brick Bodies*

An experimental assessment done on the four clay samples for plasticity indicated Plasticity Indices (PI) ranging 18 to 25% as presented in Table 2. These PI values, especially for Makonday, Pelewahun and Bonganema have high plasticity. Plasticity is the characteristic behaviour of a ceramic material to become permanently deformed after the application of an external force. The plasticity index (PI) defines the plastic field of materials and represents the percentage of moisture that the clays must have to be preserved in a plastic state. A high PI indicates an excess of clay or colloids in the soil.

Plasticity in the processing of clay-based materials is a fundamental property since it defines the technical parameters to convert a ceramic mass into a given shape by application of pressure (Paulo B. Lourenco et al 2010). High plasticity clays have a higher water-retention capacity and a higher plasticity index than low plasticity clays. This means that they are more malleable and can be molded into various shapes. Caused by just the right mixture of water and particle size, plasticity is what transforms dry cracky clay into a workable clay body.

Table 2: Results of plasticity of the four clays investigated

| CLAY SAMPLES | PLASTICITY INDEX (%) | INTERPRETATION |
|---|---|---|
| Makonday (Ma) | 23.50 | High |
| Pelewahun (Pe) | 21.22 | High |
| Bonganema (Bo) | 24.52 | High |

| | | |
|---|---|---|
| Njala (Nj) | 18.65 | Medium |

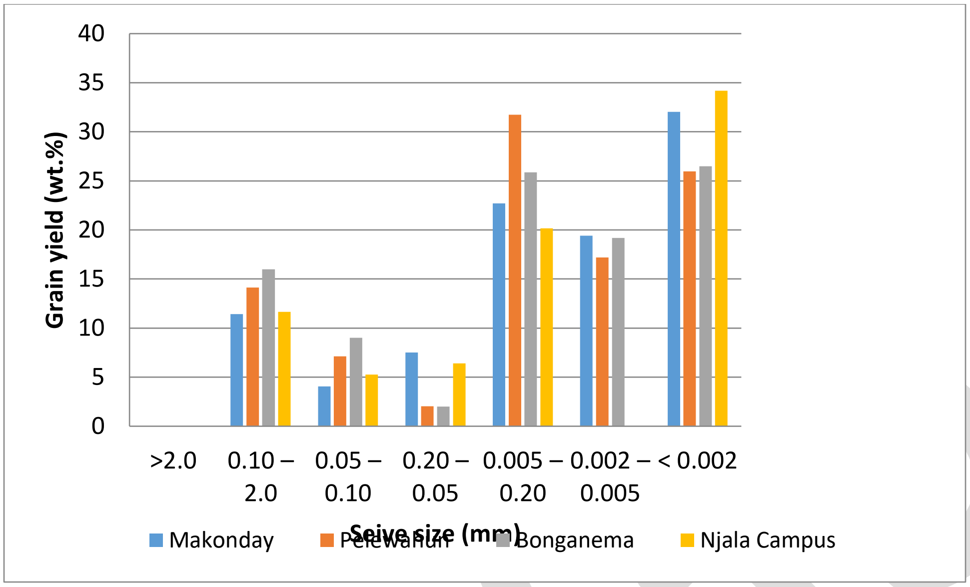


Fig 1: Grain size distribution of clay samples

The grain size distribution of the clay samples analysed for their suitability in fired brick production found the four clay samples to have acceptable grain size distribution of sand, silt and clay ranges for fired bricks production as presented in Figure 2. And Table2

Table 2: Ideal Distribution of Grain Size for Fired Bricks

| S.N | Element | Size | Recommended values |
|---|---|---|---|
| 1 | Sand | 2 mm – 0.063 mm | 20-45% |
| 2 | Silt | 0.063 mm – 0.002 mm | 25-45% |
| 3 | Clay | < 0.002 mm | 20-35% |

The grain size and its distribution of a soil have a decisive influence on its moulding properties and the resultant fired brick quality. Grain size refers to the mean or effective diameter of individual mineral grains or particles. Workability and drying behaviour of the clay body are especially determined by the content of fractions of less than 2µm. Fine grained clays generally have high drying shrinkage rates. However, even within each type of clay the drying parameters varies, depending on the grain size distribution and mineralogical association.

The increase in finer fraction grain size distribution (Makonday and Njlala clays) on fired bricks should also be noted. An increase in grain fraction of less than 2µm (clay fraction) often produces at the same time higher firing shrinkage thereby creating greater chances of warpage and distortion. The properties of clays for brick product, (which are dependent on grain sizes) are significantly affected by the mixing process.

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Table 3: Grain size analysis of clay samples

| Fraction (mm) | Grain yield (wt.%) | | | |
|---|---|---|---|---|
| | Makonday | Pelewahun | Bonganema | Njala Campus |
| >2.0 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.10 – 2.0 | 11.42 | 14.12 | 16.00 | 11.66 |
| 0.05 – 0.10 | 4.05 | 7.11 | 9.01 | 5.26 |
| 0.20 – 0.05 | 7.50 | 2.02 | 2.00 | 6.41 |
| 0.005 – 0.20 | 22.70 | 31.73 | 25.87 | 20.17 |
| 0.002 – 0.005 | 19.42 | 17.18 | 19.18 | 18..89 |
| < 0.002 | 32.02 | 25.96 | 26.48 | 34.19 |

From the physical properties illustrated in Figs.1, it is seen that increased in firing temperature from 1000$^0$C to 1250$^0$C decreased water absorption; the values varied among the three samples analyzed.

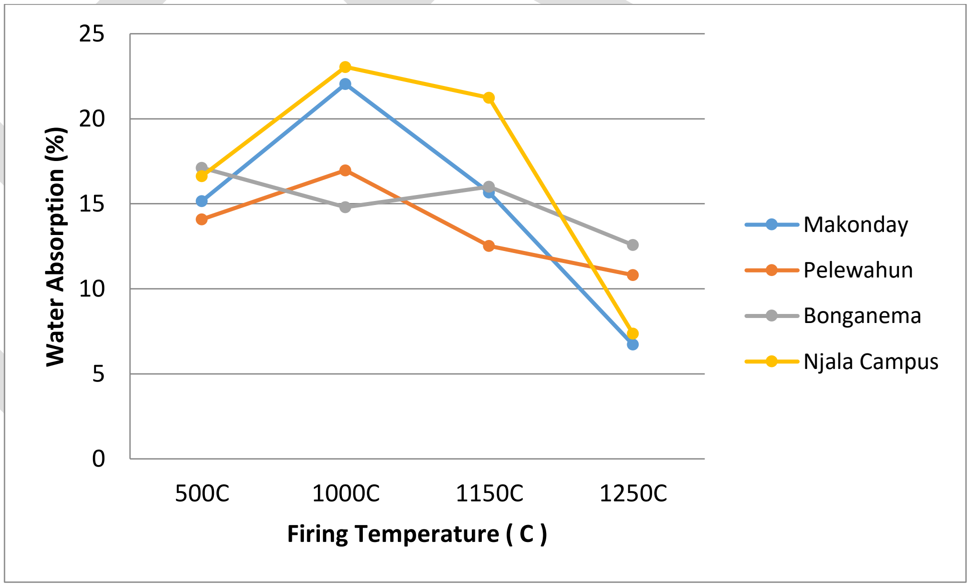



Fig.2: Effect of firing temperature on water absorption of the fired brick samples

From Figure 2, Bonganema, which exhibited the lowest water absorption at 1000$^o$C had the highest water absorption at 1250$^o$C Njala with the highest water absorption at 1000$^o$C and 1150$^o$C showed second to the lowest at 1250$^o$C after Bonganema.

A closed look at the behavior of the bulk density and water absorption curves presented in Figures 2 and 3 showed an inverse relationship between water absorption and bulk density. Njala clay which had the highest water absorption at $1000^0$C showed the lowest bulk density at the same firing temperature while Bonganema clay with the lowest water absorption at $1000^0$ C had the highest bulk density at $1000^0$C.

The packing during the forming stage is an important technological parameter that significantly influences water absorption and dry bulk density (Verônica Scarpini Candido et al, 2014).

The dry bulk density significantly influences the mechanical properties of fired clay products with higher density leading to lower water absorption and higher compressive strength, enhancing overall performance. Increasing sintering temperatures lead to higher bulk density in Aloji fireclay bricks, positively impacting their mechanical properties like compressive strength (CCS) due to denser structure (Amkpa Job Ajala et al 2016)

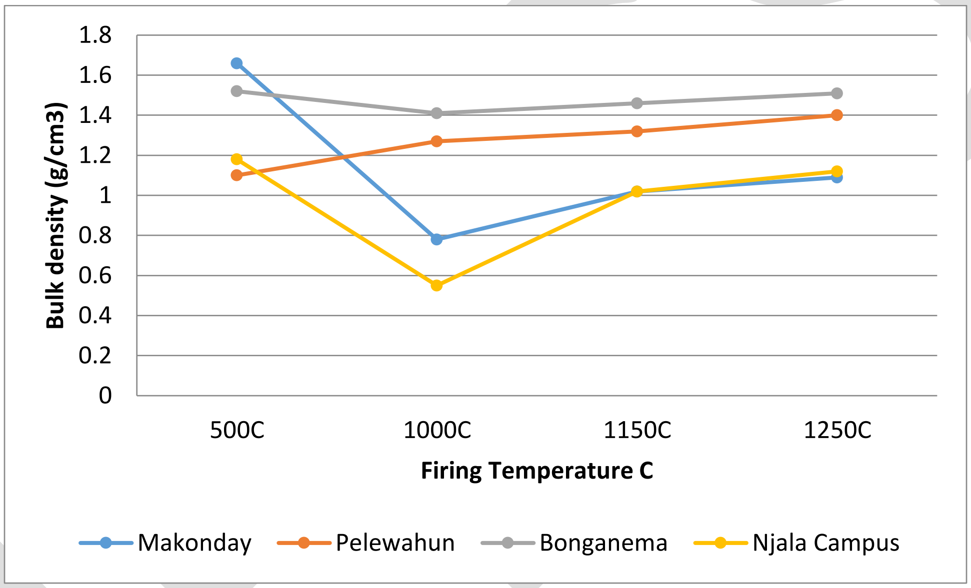



Figure 3: Effect of firing temperature on bulk density

An evaluation of the dry-fired shrinkage of the clay samples at various firing temperature are presented in Figure 4. The results show that dry fired shrinkage increase with firing temperature.

During the firing process, many phases occur namely initial kiln drying, dehydration, burn-off, quartz inversion, vitrification and melting. All these phases influence firing shrinkage and density of brick fired at 700-1100°C.

Complete drying doesn't take place until the piece is in the kiln. This happens when the boiling point of water has been reached (100 degrees C,) leading to the evaporation of moisture. At about 350 degrees C, which is considered the dehydration phase, the chemically combined water of the clay is driven off. This is water that is part of the molecular structure of the clay, not the previously described water that is between the particles of the clay. This drying is completed by about 500 degrees C. At about 900 degrees C is the burning off of organic and inorganic materials, such as carbon and sulphates (Cultrone, et al 2004). All these phases influence the amount of shrinkage.

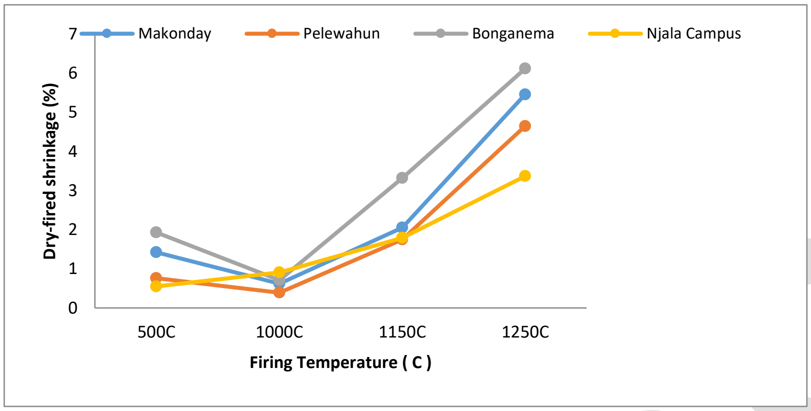



Figure 4: Dry-fired shrinkage of the clay samples

Furthermore, this work evaluated the crushing strength of the clay samples and result presented in Figure 5.

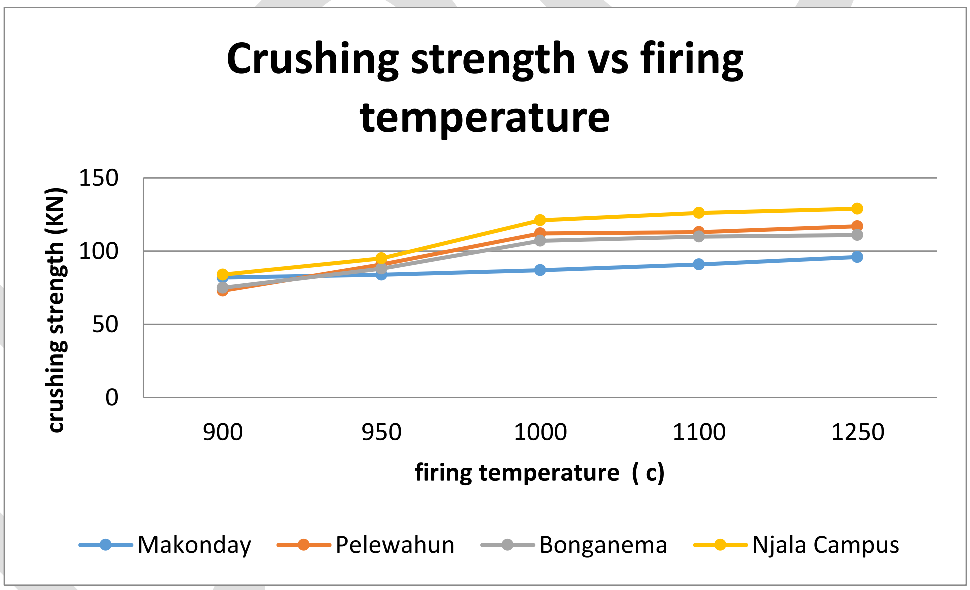



Figure 6: Crushing strength vs firing temperature

A linear relationship was observed between crushing strength of the clays and firing temperatures. Crushing strength of the clays increased with increased firing temperature (Fig.6), but the degree of strength increase varied among the clays investigated. This strength variation could be attributed to the difference in vitrifying property of these clays, which is been influenced by the amount of $SiO_2$ and, to some extent, the fluxing effect of the low amounts of alkaline earth metals present in these clays. With the exception of Makonday clay, the crushing strength of the other samples were within the range of 113 – 117KN, which is an acceptable range for bricks and tiles (DIS ISO 10545 part 4 standard)[169].

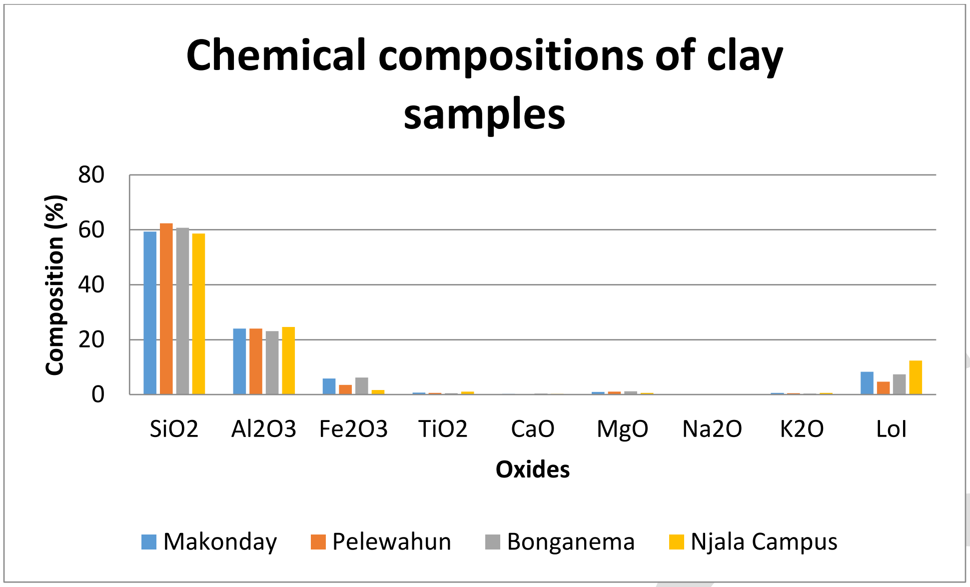
*Chemical Properties of the brick samples*

It is very important to know the chemical properties of clays for the manufacturing of fired bricks and ceramic wares for their effect on the final product. Carbonates lead to the formation of pores when bricks are manufactured at a temperature of 800–1000 °C, alkalis (Na and K salts) absorb moisture from the atmosphere and lead to dampness and efflorescence, quartz mainly acts as a filler and maintains the shape of the bricks and improves the mechanical properties,

The chemical analysis of the three clays studied is given in Table 4 and Figure 6. The samples had high concentration of $SiO_2$ and $Al_2O_3$ ranging between ~58.68 and 62.42%, and ~23 and 24.64% for $SiO_2$ and $Al_2O_3$ respectively, which is a probable justification for the high sintering characteristic of these clays. The $Fe_2O_3$ content ranged between ~2 and 6%, which is a major contribution to the color variance. All the clays have approximately 1% of $TiO_2$ and <1% alkaline and alkaline earth metals. Njala clay has the highest loss on ignition (12.42%) followed by Mokonday, Bonganema and Pelewahun. This high loss on ignition values could be attributed to the organic matter and sulfur contents normally associated with these clays.

*Table 4: Results of chemical analyses of the clay samples*

| Oxides | Clay samples (%) | | | |
|---|---|---|---|---|
| | Makonday | Pelewahun | Bonganema | Njala Campus |
| $SiO_2$ | 59.33 | 62.42 | 60.75 | 58.68 |
| $Al_2O_3$ | 24.06 | 24.04 | 23.14 | 24.64 |
| $Fe_2O_3$ | 5.83 | 3.54 | 6.24 | 1.63 |
| $TiO_2$ | 0.67 | 0.58 | 0.53 | 1.09 |
| CaO | 0.20 | 0.18 | 0.35 | 0.26 |
| MgO | 0.98 | 1.02 | 1.17 | 0.57 |
| $Na_2O$ | 0.13 | 0.11 | 0.17 | 0.13 |
| $K_2O$ | 0.58 | 0.46 | 0.33 | 0.58 |
| LoI | 8.26 | 4.66 | 7.36 | 12.42 |

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### 3.3 CONCLUSIONS

From the results of this study, the following conclusions could be made

1. With the exception of Njala clay, which exhibits medium plasticity, the other three clay samples (Makonday, Pelewahun and bonganema have excellent plasticity that justifies their use in ceramic applications, especially in case of complex shape forming and as additives for non-plastic ceramic materials. Water absorption of these clays are comparatively high with low bulk densities and permissible linear shrinkage.
2. Typically, clay brick consists of silica (sand) – 50% to 60% by weight, alumina (clay) – 20% to 30% by weight, lime – 2 to 5% by weight and iron oxide – ≤ 7% by weight. The results of the chemical analysis of these clay samples fall within these ranges, hence suitable for fired bricks production.
3. On the average the results obtained for both the physical and chemical properties analyzed are within the acceptable range for the production of fired clay bricks. For the production of high quality porcelain, processing of these clays is required to improve on certain physical properties like porosity, density and eventually water absorption. This could be done by addition of one or more of the following materials such as limestone, feldspar, kaolin, sand, talc, wollastonite and pyrophyllite in the right proportion followed by efficient processing technique and optimization of the firing temperature.

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