Title of the project:

Development of Electrical Porcelain Insulator from Local Ceramic Raw Materials and Industrial Waste.

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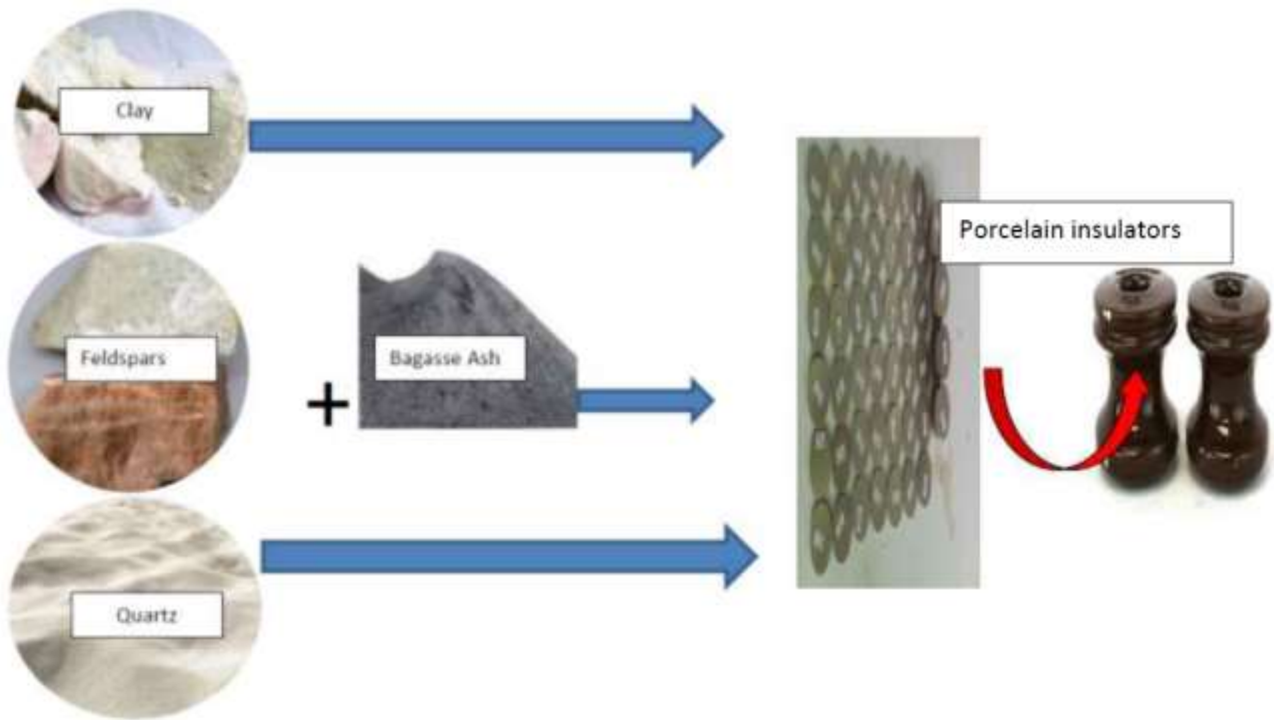

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Dec. 2022
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Approval of Investigators

We hereby declare that the research report entitled “Development of Electrical Porcelain Insulator from Local Ceramic Raw Materials and Industrial Waste.” is our original work; all sources are duly acknowledged and the report is compiled by incorporating the necessary comments and suggestions given by the reviewers.

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Abstract

In this study, two clay materials Bombawuha (BC) and Denkaka (DC), two feldspar materials Arerti (AF) and wolkite (WF) and Chancho sand (CS), as well as sugarcane bagasse ash (SCBA) and sugarcane fly ash (SCFA) wastes collected from Wonji Shewa sugar factory of Ethiopia were investigated to be used as a potential raw materials for producing quality electrical porcelain insulators. A 5kg of each samples of the aforementioned raw materials were collected and processed from deposits located at Bombawuha (6° 05′ 20″ N and 38° 46′ 30″ E), Denkaka (8° 33' 36" N, 39° 10' 29" E), Wolkite (8° 16′ 50″ N and 37° 46′ 40″ E), and Arerti (90º 6' and 90º 5' N and 39º 46' and 39º 26' E), and Chancho (9° 18' 29.1240" N and 38° 45' 11.2320" E), respectively. They were dried, and ground to sieve size of 63μm for clays, feldspars, and sugarcane bagasse ash and 45μm for sand, then the mineralogy, chemical composition, thermal property, plasticity, and particle size distribution of raw materials were characterized by using x-ray diffractometry (XRD), atomic absorption spectrometer (AAS), Thermogravimetry analysis (DTA-TG), Atterberg plasticity test, sieve-hydrometer analysis, respectively. Based on the raw materials chemical compositions different w% of mixed feldspar, bombawuha clay and quartz raw materials as well as SCBA were selected to be used and accordingly six (6) different porcelain insulator body compositions without SCBA (labeled Batch-1, Batch-2, and Batch-3) and with SCBA (labeled: Batch-4, Batch-5, and Batch-6) were formulated. A total of two hundred four (204) (one hundred sixty two (162) a cylindrical shaped for physical and electrical strength test plus forty two (42) rectangular-shaped for mechanical strength test) bodies of the desired formulations were prepared. The batches were fired at firing temperature of 1200°C, 1250°C, and 1300°C and firing time of 1.5hr, 2hr and 2.5hr. Finally, the fired products were investigated for their physical properties (water absorbance, bulk density, and apparent porosity), electrical properties (dielectric strength), mechanical strength (flexural strength/modulus of rupture), phase analysis by XRD and microstructure by SEM-EDS. XPS were also used to complement the XRD data. The aforementioned properties of porcelain insulators were analyzed as a function of firing temperature and time. Only those fired samples which possess good electrical properties were used for mechanical test. The XRD and AAS results revealed that unlike Denkaka clay in Bombowha clay, kaolinite mineral was found to be a major mineral constituent with appreciable silica (46.72 wt%) and alumina (35.32 wt%) content, it has relatively higher level of clay fractions (20.58%); and has middle range plasticity index (PI = 11.2%) which is suitable and encouraging for optimal behavior in pressing and drying. The ratio of Al_2O_3/SiO_2 met the required amount for mullite phase formation during the porcelain body's sintering. This was observed in the DTA curve at 1001.23 ºC. The Arerti (AF) contains mainly albite and the Wolkite feldspar (WF) is predominantly composed of anorthoclase minerals with less alkali contents (Na_2O, K_20) of <6wt %. The sugarcane ashes (SCBA and SCFA) waste contained SiO_2 (65.06+ %) as a major oxide, and followed by Al_2O_3 (10.88+ %), which is comparable to natural feldspar, and it has higher alkaline oxides (K_2O and Na_2O) content and iron oxide as compared to natural feldspars. This implies the sugarcane waste ashes can be used as an alternative to substitute the natural feldspar with proper formulation in which the SCBA is a preferred materials over SCFA as it contained relatively higher proportions of refluxing agent (8.66%). Among the tested porcelain insulator bodies without SCBA, the test body with composition of 40% Clay, 40% feldspar and 20% quartz (Batch-3) and fired at 1250 °C for 2 h exhibited water absorbance of 0.17%, apparent porosity of 0.42%, bulk density of 2.45 g/cm^3, the dielectric strength of 8.22 kV/mm and flexural strength of 43.63 MPa, which satisfies the required properties for quality porcelain insulators. Moreover, the physical-mechanical properties and dielectric strength measured for each porcelain sample with SCBA confirmed batch SCBA10 with the composition of (10% SCBA waste, 50% BC, 30% mixed Feldspar (AF and WF in 50:50%), and 10% CS) fired at 1250°C and at firing time 2.5hr was found to have the dielectric strength of 6.14 kV/mm, dielectric strength of 42.53 MPa and water absorption of 0.35%, which satisfies the obligatory properties for quality porcelain insulators. In conclusion, the experimental result of this study confirmed that standard quality porcelain electrical insulators could be produced using locally available raw materials (Clay, Feldspar, and quartz) and the partial replacement of Feldspar by sugarcane bagasse ash (SCBA) waste in Ethiopia at optimized condition.

Keywords: *Porcelain insulator, Feldspar, bagasse ash, Quartz, Bombowha clay, sintering temperature.*

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Abbreviations and Acronyms

AAS...Atomic Absorption spectrometer

AF... Arerti feldspar

ASTM..................................... American Standard for Testing Materials

BC... Bombowua clay

CS... Chancho sand

DC.. Denkaka clay

DTA....................................... Differential Thermal Analysis

ICDD...................................... International Center for Diffraction Data

LL... Liquid Limit

LOI... Loss on ignition

MOR....................................... Modulus of rupture

PI... Plastic Index

PL.. Plastic Limit

SCBA...................................... Sugarcane bagasse ash

SCFA .... Sugarcane bagasse ash

SEM.. Scanning Electron Microscopy

TA... Thermal Analysis

TGA.. Thermogravimetry Analysis

WF.. Wolkite Feldspar

XRD.. X-ray Diffraction

1. Introduction

1.1.Background and Justification

Developments of the modern world depend significantly upon a continuous electric power supply. Currently the consumption of electric energy has been significantly increasing specially in developing countries due to the rapid evolution of industries and change in human life style. For instance, in Ethiopia the energy sector has been growing in the past two decades and reached currently electric power of 2360 MW, this would be expected to reach 10,000 MW in the next 10 years, however the country believed to have a potential of 45 GW from hydro-power, 5 GW from geothermal, 10 GW from wind power and other energy sources like solar and coal (Mondal et al., 2018). Now a day in Ethiopia the access of electricity reaches about 55%, in addition to the local supply it is already connected to Sudan, Djibouti and the Border towns of Kenya, but the local annual demand growth reached up to 25-30% and its already signed to export to Tanzania, Egypt, Rwanda, Burundi, South Sudan and Yemen (EEP, 2015). But, with growing demand, utilities must provide secure and reliable power delivery while maximizing the performance of the power distribution system from both technical and economic standpoints. Interruptions or failures within the power systems may damage valuable high-voltage equipment and lead to considerable loss of revenue, mainly for industrial consumers. For this reason, an insulator is used in the transmutation and distribution system of electric power to deliver the electric energy to the intended customer safely. This implies that there is an over increasing demand of extra high voltage, large capacity and long-distance transmission and distribution placed on the country, so it needs a great attention for the country electric power transmission and distribution technology.

In electric power transmission and distribution system, there must be an insulator material between the overhead conductors and supported towers or poles to prevent the flow of current from conductors to the earth through grounded supporting towers (Moyo and Park, 2014). In this distribution network, insulator materials have two major functions; fastening mechanically and insulating electrically the component of electrical network (Liebermann and Schulle, 2002). In general, the quality of electric insulators determines the efficiency of transmission and distribution of electric power. Hence, quality electrical insulators are among the critical materials of electric power transmission systems. In Ethiopia, there is a great challenge placed on the distribution and transmission system, among those challenges; the quality, cost and availability of overhead insulator materials is the prominent one.

Ethiopia electric power corporation utilized both locally manufactured and imported insulator materials, but the local manufacturer mainly relay on imported goods such as ball clay to produce porcelain insulator for the domestic demand of overhead insulator. This is due to low quality of the local product and insufficient availability of the raw materials (Merga et al., 2019). However, it is obvious that such kind of state of affairs adversely affects the country foreign exchange reserve, and affects the sustainability of the ceramic manufacturing industries. It is also being an obstacle for the big dream of short and long term rapid developing strategy of the country. Therefore, the development of quality overhead insulators from locally available raw materials and industrial wastes get due attention to extend sustainable development of the country.

Recently three kind of overhead insulator materials have been applied in electric power transmission and distribution system namely porcelain, composite and glass insulators. Among those insulator materials utilized porcelain insulator is the most commonly and wildly used material (Islam et al., 2004; Ovri and Onuoha, 2015). It possesses several outstanding properties simultaneously such as; high mechanical strength, exceedingly resistance to high temperature, electricity, and harsh environment, and corrosive resistance which could not be realized by other type of insulators (Meng et al., 2012; 2014; 2016; Cajetan et al., 2015). They are not sensitive to minor differences in composition, fabrication, techniques, and firing temperature (Demchuk et al., 2009; Islam et al., 2004), and have a very long lifetime (Mehta et al., 2018). Moreover, the raw materials used for its production are also naturally available compared to other type of insulators which needs industrially processed materials (Moyo and Park, 2014). These properties of Porcelain insulators are the reasons for their continued use over the decades, despite the emergence of new insulator materials like plastics and composites (Olupot et al., 2010).

Electrical porcelain insulators are the most complex multi-phase ceramic materials basically produced from naturally available plastic materials (clay), flexing agent (feldspar) and filler materials (quartz) under thermal condition. Each of these raw materials plays specific roles in influencing the properties and performance of the final products (P. Olupot, 2006). Clay provides plasticity and is a source of alumina, which, together with quartz and alkaline fluxing elements, forms mullite and glassy phase during the firing process. Both phases contribute to the improvement of the mechanical and dielectric strength of a porcelain insulator. Feldspar promotes vitrification and densification of the porcelain sample at the end of the firing process. Quartz maintains a porcelain structure and regulates the ratio between SiO2 and Al2O3 to form mullite (3Al2O3•2SiO2). Therefore, the composition of the raw materials and the firing temperature influence the physical-chemical properties of the resulting ceramics due to series of transformation which occur upon firing within the sintered body (Bergmann, 2004). The final sintered porcelain insulator is expected to contain sufficent mullite phase ($Al_6Si_2O_{13}$), and undissolved quartz (SiO_2) crystal embedded in glassy phase that attribute to the microstructure of ceramic body (Meng et al., 2012; Yaya et al., 2017; Ngayakamo and Park, 2018).

The final product to be applied in electric power distribution and transition system, it required to possess an excellent technological property such as physical properties (i.e. water absorbance, porosity and density) and mechanical and electrical strength, even in humid and corrosive environments (Meng et al., 2016). Technological properties of triaxial porcelain insulator depend on concentration of each phase developed during firing, which intern depend on the result of firing condition and chemical composition of raw materials (Ngayakamo and Park, 2018). It means that it depends on the choice of raw materials applied, proper formulation of the selected raw materials and firing condition (temperature, dwelling time, cooling time, heating rate, and etc.). On the other hand, the properties of raw materials are the result of the geological condition of the original deposit, that may vary from place to place, so it need an intensive investigation of their ceramic natures like mineralogy, chemical composition, physical properties and firing characteristic in order to manage the properties of the final product (Yaya et al., 2017). Moreover, sustainable development of Porcelain electrical insulators required reduction of the production costs, especially energy and raw materials costs. This may be achieved by adopting fast firing cycles and using fluxes, feldspars (Njoya et al., 2017) and uses of locally available raw materials (Merga et al, 2019).

In Ethiopia, in spite of enormous availability of natural and industrial ceramic raw materials, quality porcelain insulator couldn’t be produced from local materials only. In the country potential ceramic raw materials are found in different part of the country. For instant, clay found in Bombowha and kombolch zone of Oromia region (Fentaw and Mengistu, 1998) as well as clay found in Belesa (Hosanna) and Ansho area of southern region, of Ethiopia (Lijalem, 2016; Andualem, 2018) have shown a characteristic potential properties required for porcelain insulator fabrication when compared to clays utilized for porcelain production in literature Olupot et al., (2013); Moyo and Park, (2014); Yaya et al., (2017). Additionally, according to the office of Tigrai region mine and energy, about 9 x10.7 m3 of kaolin found in the region which yet not exploited and can be applied in ceramic industry (Lijalem, 2016). Feldspar and quartz deposit are found in Arero worda Guji zone of Oromia region (Andualem, 2018). However, preliminary study indicated Arero feldspar that has been used by Tabor ceramic has low flux or alkaline oxide content ($K_2O + Na_2O < 7$wt.%) compared to the chemical composition requirement of feldspar in porcelain production described in literature Moyo and Park, (2014). This may lead to either raising consumption of energy or extensive usage of feldspar in order to get sufficient glassy phase in porcelain body. But such kind of practices is not appropriate as it depletes natural resources and increase product cost due to high energy consumption. Therefore, finding alternative high grade feldspar deposit in the country or partially substitute feldspar by economic materials like sugarcane bagasse ash or other industrial wastes of sufficient and reliable amount that contain high silica and sufficient amount of flux or alkaline oxide to yield the required glassy phase at economic firing temperature is important.

On the other hand, currently the whole world is suffering from two types of problems, i.e., the disappearance of virgin resources (material and energy) and the production of excess wastes. For example, associated to a rapid growth of sugar industries in Ethiopia, vast quantities of solid wastes are added to our environment. One of the solid wastes remains as the final waste in the sugar production chain is sugar cane bagasse ash (SCBA), produced in the process of generating electricity from bagasse. A tone of burnt sugarcane bagasse may generate 25–40 kg of bagasse ash. The estimated quantity of bagasse ash produced from Ethiopia's sugar industries may reach up to two million tons per annum. These materials are usually dumped on open grounds and have detrimental effects on the environment. Thus, incorporating the SCBA in the ceramic industry has several advantages: saving natural raw materials, lowering energy consumption during subsequent processing, and lowering environmental pollution (Junkes et al., 2012). Moreover, recycling of this waste material has great contribution to the fulfillment of Ethiopia green economic strategy by minimizing the environmental burden of anthropogenic activities.

Previous studies identified the use of some waste as a potential supplement of feldspar that might improve the quality of the insulator and lower the firing temperature leading to cost cuts, such as soda-lime glasses (Matteucci et al., 2002), blast furnace slag (Kausik Dana & Das, 2004b), metallurgical slags (K. Dana & Das, 2003), rice straw ash (RSA), rice husk ash(RHA) (Prasad et al., 2001), silica fume (SF) (Prasad et al., 2002), fly ash (FA) (Kausik Dana & Das, 2004a). Moreover, the study confirmed SCBA has a similar chemical composition to common natural aluminosilicate porcelain raw materials to be used as an alternative source of feldspar for porcelain insulator production (Teixeira et al., 2014). Therefore, this study aims to intensively investigate the ceramic potential of locally available natural raw materials in geologically conducive mineral bearing areas and waste materials (clay, sand, feldspar, and sugarcane bagasse ash waste) to produce quality porcelain electrical insulators which fit the required standard and used the selected porcelain bodies for prototype production.

1.2.Objective of the study

General objective

The research project has a general objective of investigating the potential of locally available clay, sand, and feldspar and the effect of partial substitution of feldspar by SCBA to produce quality porcelain electrical insulators.

Specific Objectives Includes:

- Characterize the mineralogy, chemical composition, thermal properties, plasticity, and particle size distribution of clay, feldspar, quartz as well as sugarcane bagasse ash and fly ash wastes.
- Produce electrical porcelain insulator from locally available raw materials (clay, feldspar and quartz) and by partially replacing feldspar with sugarcane ash by optimization of batch composition, and firing conditions.
- Characterize the quality of produced insulators by determining physical properties (i.e porosity, water absorbance and bulk density), phase change by XRD, electrical properties

(dielectric strength), mechanical strength (flexural strength), and the microstructure, of the product.

1.3.Significance of the study

With successful implementation of the project results:

- The energy costs, overall production cost, dependency on foreign currency (by import substitution), and natural resource depletion will be reduced which in turn help us to meet sustainability in the country development.
- Even though, the primary beneficiaries of this study are the Ethiopian electric power corporation (EEPC), Tabor ceramic share company, sugar industries and other ceramics industries found in Ethiopia; new job opportunities will also be created as individuals or group of peoples are expected to be involved in the value chain of ceramic production. Which is in the mining, transportation, processing, and supply of raw materials and products to the end users
- Efficient industrial waste management that led to reduction of wasted resources that goes to nearby water bodies and landfills will be achieved;
- Promote the country's natural resource proper utilization trends.
- Generated fundamental knowledge on the potential of indigenous ceramic raw materials and efficient use of wasted resources as alternative ceramic materials were obtained which are used as reliable secondary data sources for further investigation.

2. Literature review

2.1. Overview of Electrical insulators

Electrical insulators are materials which inhibit the current flowing in electric system; it is important for preventing damage and reliability of electrical system and equipment; and also, a basis for protecting individuals from electric shocks and assures safety of personnel while carrying out electrical works ((Islam et al., 2004; Moyo & Park, 2014; Ezenwabude & Madueme, 2015; Cajetan et al., 2015; Yaya et al., 2017). It is undeniable that current development and civilization of human life is the result of electric power, and for generation, transmission and distribution this power to the intended user overhead insulators materials have been playing as back bone role (Ajakor et al., 2015). Now a day electric power industry tends to develop extra high voltage, large capacity and long-distance transmission (Kitouni, 2014), beside the demand of quality electrical insulators increase extensively.

According to the materials composition insulators that have been applied in electric power transmission and distribution systems could be classified in to three main types namely porcelain insulator, composite insulator and glass insulators (Moyo & Park, 2014; Meng et al., 2016). Each of these materials has a number of advantages and disadvantage, for instance, glass insulators are considered to have very high resistivity and strength comparing to porcelain and composite polymer insulators. However, the problem associated with glass insulators is the leakage of current if the air dust is deposited to the wet glass surface. Polymer or composite polymer insulators have light weight comparing to ceramic equivalents. The problem associated with polymer insulators is the tendency to exhibit electrical failure if there is any unwanted gap between core and weather sheds (Moyo and Park, 2014). Whereas, porcelain insulator is the most commonly used insulator materials utilized in electric power transmission and distribution system as it it possess several outstanding properties simultaneously such as high mechanical strength, high electrical stability and corrosive resistance even in humid and harsh environment which could not be realizes by other type of insulators (Meng et al., 2012; 2016; Cajetan et al., 2015; Ovri and Onuoha, 2015). Moreover, the advantage of porcelain insulator over others would also be raw materials used for its production are naturally available compared to other type of insulators which needs industrially processed materials (Moyo and Park, 2014).

2.2. Electrical Porcelain insulator

Electrical porcelain insulators are the most complex multi-phase ceramic materials used as overhead insulator for both low- and high-tension insulation (Yaya et al., 2017). It is basically made by heating a mixture of three major natural raw minerals (quartz, feldspar and kaolin clay/ also called china clay) in a kiln to a temperature between 1,200 °C and 1,400 °C (Cajetan et al., 2015). For the electrical insulation application, the most required properties of the porcelain electrical insulator are high mechanical strength and high dielectric strength to withstand high voltage. Moreover, low porosity and water absorption are among other essential properties of electrical porcelain. The toughness, strength, and clarity of porcelain arise mainly from the formation of glass and the mineral mullite within the fired body at these high temperatures (Oladiji et al., 2010). However, the proportions of the raw materials influence both the phase compositions of the fired body, and their mechanical and physical properties (Akwilapo and Wiik, 2004; Ngayakamo & Eugene Park, 2019).

2.3.Ceramic raw materials

The basic raw materials used for electric porcelains production are widely available in earth as primary rock and as segmented form. Which are plastic materials such as kaolin, ball clay and other clayish materials; while flex materials include albite, orthoclase, Anorthite type of feldspar and quartz, alumina as filler in which all are characterized by small particle sizes (Manfredini and Hanuskova, 2012; Jamo, 2015). The role played by each raw material in a porcelain system is different; kaolin reacts with feldspar and develops mullite crystals after firing. This improves on flexural strength due to interlocking of mullite needles. Feldspar begins to forms molten glass at about 980 to 1100°C, depending on its chemical composition, assisting the sintering process and enabling virtually zero water absorption (Cam and Senapati, 1998). Quartz promotes thermal and dimensional stability thus preventing warping. However, the principle factors that influence the uses of these raw materials needs to be optimized to produce quality porcelain insulator and it is the concern of scholar in the area.

Clay

The term clay refers to a naturally occurring material composed of primarily finely grained minerals with grain size less than 2 micron, which become plastic at appropriate water contents and will harden when dried or fired (Al-Ani and Sarapaa, 2008). Pure clays do not occur naturally, they contain organic matter and other minerals that do not impart plasticity (Ouahabi et al., 2014). Clay minerals form an important group of the phyllosilicates, usually formed as a result of chemical weathering of other silicate minerals at the earth's surface. The clay minerals are mostly crystalline, means that atoms composing them are arranged in definite geometric patterns and distinguished by layered structures composed of polymeric sheets of SiO_4 tetrahedral linked to sheets of $(Al, Mg, Fe)(O,OH)_6$ octahedral (Guggenheim et al., 1995; Al-Ani and Sarapaa 2008; (Mejia, 2013). Common clay minerals are Kaolinite, Smectite (montmorillonite), Illite, Chlorite, and Vermiculite (Manfredini and Hanuskova, 2012). This minerals experience different properties even though each of them comprised of octahedral and tetrahedral sheets as their basic building blocks. The arrangement and composition of the octahedral and tetrahedral sheets account for most of the difference in their physical and chemical properties (Al Ani and sarapaa, 2008).

Generally, the utility of a clay mineral in specific applications are due to their physical and chemical properties, which are mainly dependent on two factors: (a) their crystal structure, which can be either a 1:1 structure (one tetrahedral sheet bound to another octahedral sheet) or a 2:1 structure (one octahedral sheet between two tetrahedral sheet) and (b) their chemical composition. Additional factors are essential in determining a clay's properties and applications: the non-clay mineral composition, organic material content, the type and amount of exchangeable ions and soluble salts, and the texture (Moraes et al., 2017). In ceramic industry the plastic nature of clay acts as a binder for other body ingredients in the green state which confirms plasticity of the body for easy molding/ shaping (Lee and Iqbal, 2001), and when it fired at elevated temperature transform to crystalline mullite phase (Lee and Iqbal, 2000). But such nature of clay associate with the type of clay minerals present and the level of non-clay mineral in it (Yaya et al., 2017).

Feldspar

Feldspar are the most common and abundant rock forming aluminosilicate minerals in the earth crust which contain varying proportion of potassium, sodium and calcium oxides (Manfredini and Hanuskova, 2012; Ajakor et al., 2015). Feldspar have the same basic structure as quartz except that one in every four Si is replaced by Al therefor instead of Si_4O_8

(quartz), feldspar contain $AlSi_3O_8$. As Al has a 3^+ charge whereas Si has a 4^+ charge, the resulting charge difference is balanced by K or Na for alkaline feldspar or by Ca for calcium feldspar and yield potash feldspar/ Orthoclase or Sanidine (K_2O. $Al2O_3$. $0.6SiO_2$), soda feldspar / Albite (Na_2O Al_2O_3. $0.6SiO_2$), and lime feldspar /Anorthite (CaO Al_2O_3. $0.2SiO_2$), respectively (Aliyu et al., 2016). They are the common feldspars and affect the quality of feldspar for different application and hence they are the major commercial interest for ceramic industry (Lee and Iqbal, 2000). In ceramic industry feldspar is a low temperature melting minerals due to its alkali content and form enough liquid is glassy phase at low firing temperature. The resulting liquid fills the gap or void space in the microstructure and leads to densification of the body (*Lee et al., 2008*), as well as its relict nucleate with primary mullite originated from clay and grow to secondary mullite that is more harder and stronger phase in triaxial porcelain (*Meng et al, 2016; Iqbal, 2008*). Nowadays, mixed feldspars are considered suitable fluxing agents for porcelain manufacture. Firstly, as they develop a very dense glassy phase that embeds the new forming crystals and a part of the residual crystals present in the microstructure that enhances the densification process. Secondly, the mixed feldspar minimizes the effect of changes in mineralogical mining (Mathur et al., 2015).

Sand/Quartz

Sand is the most common stable forms of silicon dioxide (SiO_2) at room temperature and found in nature in a crystallized form. Sand contains between 95 to 100% of quartz by mass (Boch and Niepce, 2001). Quartz constitutes one of the most readily available geological materials used in industries, it consist of very highly optimal percentage of silicon oxide (SiO_2) which occurring alone in pure state. It is estimated that about 12% of the Earth's crust is made of quartz and its primary source is sandstone. In porcelain production silica helps to balance the viscosity of the glassy phases and the basic matrix of the glassy phase in the finished product and its properties is the principle factor influencing flexural strength of the porcelain insulators (Manfredini and Hanuskova, 2012; Silberberg, 2013). Quartz particle size in the range of 10-32 μm found to increase flexural strength and has a superior effect on flexural strength compared to firing temperature and quartz content (Stathis et al., 2004; Kobayashi et al., 1992).

2.4. Important Properties of Raw Materials for Porcelain Insulator Production

2.4.1. Plasticity of clay minerals

Plasticity was defied as a property which permits a material to be deformed under stress without rupturing and to retain the shape produced after the stress is removed (*Valaskove 2015*). The plasticity of clay depends on the clay-water system, in which clay that shows maximum plasticity has optimum water content. Whereas, a decrease in plasticity is observed at higher or lower water contents due to the rapid change in the system's extensibility (W. Lawrence, 2006). As a rule, optimal plasticity can be considered as the minimum plasticity required for the moulding process to be performed satisfactorily, without any subsequent deformations or problems involving low mechanical strength in the green or dry pieces arising (W. Lawrence, 2006). In general, increasing plasticity is due to: the presence of clay minerals in which the layers are weakly bound (such as montmorillonite), the reducing size of particle and the presence of organic substance (e.g. ball clay) (Andrade et al., 2011; Manfredini and Hanuskova, 2012).

Clay minerals with weak interlayer force and very fine particle size like montmorillonite, halloysite, and ball clays absorb high amount of water in interlayer and easily swell and belong to the upper range of plasticity, this kind of clay minerals has a potential hazard of cracking during fabrication (*Akwilapo and Wiik, 2003*). This is because during drying stage it loss the water content present in interlayer as result produces high level of shrinkage. Additionally such kind of clay minerals can take a week to dry a green body. Kaolinite and illite minerals due to having strong intermolecular attraction force between the layers they exhibit moderate to low plasticity and can dry in a short time and results little shrinkage. As result kaolinite and illite are favorable for porcelain insulator fabrications (*Valaskove, 2015*).

2.4.2. Ability to form mullite phase

Mullite ($3Al_2O_3.2SiO_2$) is an aluminosilicate refractory material with various attractive properties, such as low thermal expansion, a high melting point, high thermal stability, low dielectric constant, high thermal shock resistance and chemical stability. It is the only stable crystalline phase in Al_2O_3-SiO_2 systems under normal atmospheric pressure at room temperature through elevated temperature (Sanchez-Soto et al., 2018; Hossain et al., 2018).

Due to these properties, the mullite phase is the major target in the production of porcelain insulators and it is a characteristic constituent of all ceramic products (Islam, 2004). Generally, kaolinite improves mullite formation (Manfredini and Hanuskova, 2012, Das and Dana, 2003). Because of the high level of alumina or low ratio of the level of SiO2: Al2O3 In general, the high level of alumina or low ratio of SiO_2:Al_2O_3 in a Kaolinite and illite favor the formation of mullite. Whereas due to low alumina content in montmorillonite less favours the formation of mullite (Merga et al., 2019). As result using Kaolinite and illite mineral containing clay for ceramic industry is favorable.

Previous studies revealed the importance of the extent of mixing of various compositions of micro-regions (including pure clay agglomerates and feldspar-enriched regions) in the unfired ware during the production of porcelain. On heating, these regions react to form different types of mullite. Mullite crystals derived from the pure clay (kaolin) agglomerate relicts are cuboidal and are referred to as primary mullite (2:1 type-mullite) since they form at the lowest temperature. Elongated needle-shaped mullite crystallizing from the feldspar-rich melt is termed secondary mullite (2:1 type-mullite) as it forms later in the firing process. The third form of mullite termed tertiary mullite has been detected in porcelains containing alumina as filler (Lee & Iqbal, 2001).

2.4.3. Contents of fluxing agent

The chemical and structural behavior of feldspar materials are the result of its weathering stage of the original deposit (*Olupot*, *2006*). A feldspar that found at early stage of geological transformation consist higher alkaline (K_2O + Na_2O) content with low level of Al_2O_3 due to its unweather nature of rock, but feldspar deposit found in more advance stage of geological condition to transform to kaolinite clay which contain relatively low level of alkaline as result of weathering and its fluxing behavior reduced. However, a feldspar that can be applied for porcelain insulator fabrication required to contain an alkaline oxide (K_2O + Na_2O) a minimum of 12 wt.% in order to obtain sufficient liquid or glassy phase required in the microstructure of porcelain body at economic firing temperature (*Moyo and Park, 2014*).

2.4.4. *The level of impurities in the raw materials*

Clay and feldspar also contain small amounts of oxides, such as Na2O, CaO, MgO, TiO_2, and Fe_2O_3, which may influence the body's crystallization behaviour and vitrification temperature and glass viscosity (Iqbal & Lee, 2000). The impurities reduced the compactness of ceramic, and overall porosity is as high as 15%, which causes a significant reduction in material strength and deterioration of its dielectric property (Gao et al., 2015; Kyasager & Prasanna, 2016).

Iron (III) oxide may exist in clay, feldspar and quartz in various level depend on the geological nature of the deposit, however its minor amount in ceramic materials produce significant effect on the microstructure of porcelain body. During firing stage on production process it produces appearance of color due to its chromophore properties, which the color intensity depend on its level in materials (*Manfredini and Hanuskova, 2012*). Moreover at elevated firing temperature Fe_2O_3 transformed to Fe_3O_4 as result it release enclosed oxygen (*Akwilapon and Wiik, 2003*)

$$3Fe_2O_3 \longrightarrow Fe_3O_4 + 1/2O_2$$

The release of oxygen gases enclosed in the pore (called bloating) may lead to a formation of pore in the microstructure as result it significantly reduce the physical (such as bulk density) and mechanical properties of the ceramic body. Therefore, a material with low content of iron oxide preferred during triaxial insulator fabrication (*Olupot, 2006*). For electrical insulation should have a high electrical resistivity that minimizes the energy conducted. In addition to electrical resistivity, the Porcelain insulator should exhibit the smallest possible dielectric constant (or relative permittivity) and loss tangent value. In this regard, the presence of iron oxide in aluminous porcelains increased the dielectric constant. The presence of Fe_2O_3 above 3wt% concentration increased the loss tangent, which rises with temperature and frequency (Piva et al., 2013). Moreover, iron oxides are susceptible to oxidation-reduction reactions which lead to colour changes, Fe_3O_4 in combination with silica starts glass formation at temperatures of 1455°C. If it gets reduced to FeO, then glass formation can start at a much lower temperature of 1180 °C. Fe_2O_3 and FeO are red and black, respectively, and confer these colours on clay products (W. G. Lawrence & West, 1982).

The calcium compounds found in clays decompose on heating to form CaO, which acts as a flux. This then results in glass formation and lowers vitrification temperature. It increases the fired strength and reduces the absorption of the product. Cao may also combines with iron minerals and bleaches the red colour to buff. If not fired to sufficiently high temperatures, CaO may remain as free lime, which reacts with water after firing to form $Ca(OH)_2$, which causes significant expansion and may develop sufficient pressure to disrupt the fired product (lime popping) (W. G. Lawrence & West, 1982). In addition to this, certain minerals like dolomite modify the reactivity of clay material and specifically lead to the formation of aluminosilicate of calcium, which inhabits mullite formation and enables consolidation at low temperature with the appearance of the porous product (Manfredini & Hanuskova, 2012). So, there presence have a negative effect on the final product.

2.4.5. Particle size of raw materials

Particle size of raw materials must be controlled to achieve quality porcelain insulator. The milling process is generally used to control the raw materials particle size, which can improve the resulting properties of the green and sintered material. Smaller particle sizes for the quartz and feldspar improve the homogeneity of the vitreous phase and produce a more homogeneous structure for the sintered material (Andreev & Zakharov, 2009a). Particle size of raw materials specifically, quartz particle size has a pronounced effect on flexural strength of porcelain insulator compared to feldspar of the same size [10]. Flexural strength is known to increases with quartz particle size in the range of 10-32 μm, which is attributed to pre-stressing effect and microstructure evolution (Stathis et al., 2004; Kobayashi et al., 1992). Importantly, fine quartz particles dissolve at a faster rate during sintering before the coarse particles (Turkmen et al., 2015). This changes the morphology of the pore from large, irregular and interconnected in samples with coarse quartz particle size to small, regular and isolated in samples with fine quartz particle size. Large-interconnected pores are known to act as crack transmitters other than terminators, hence reducing flexural strength. On the other hand larger quartz grains (> 20 μm) to dissolve completely requires higher temperature and reported to be a temperature higher than 1350°C which led to a porcelain body that consists almost entirely of mullite and glass with little quartz (Dana and Das, 2004). Generally, reducing the grain sizes of the quartz and feldspar increases the amount of vitreous phase and increases the final shrinkage (reduces the porosity), and also reduce the expansion coefficient and smooths out the volume changes on the β to α quartz polymorphic transition (Andreev & Zakharov, 2009b).

2.5. The potential of Ethiopian ceramic raw materials for Porcelain Insulators production

The availability of raw material used to produce electrical porcelain insulators is the primary factor for the final production cost. For instance, in Nigeria, It has been estimated that more than 20% of the total outlay for a typical transmission and/or distribution system of electric energy is spent on insulation alone and prominent among them is porcelain. Nigeria imports almost a hundred percent of the total insulation it uses, of which porcelain occupies a central position, notably from the Asian countries (Ajakor & Ogwata, 2015). Similarly, the local manufacturer in Ethiopia applies foreign raw material (ball clay) to produce the electrical porcelain insulator, which are imported raw material for the domestic demand of overhead insulators (Merga A. 2018). But it is evident that such kind of state of affairs adversely affects the country for exchange reserve and is inconsistent with the driving force for local substitution of imported goods (Ajakor & Ogwata, 2015) to save the foreign currency and finally to reduce production cost.

On the other hand various study reported the presence of a lot of clay deposit found in the country which has a capacity to be used for the production of different ceramic materials. For instance clay found in Bombowha (BC) or Denkaka (DC), of Oromya region, Ethiopia is currently used in the ceramic industries to produce porcelain insulator and tiles (Fenatw and Mengistu, 1998; Lijalem, 2016), Andualem, 2018). Specifically, Bombowha clay (BC) contain similar properties with respect to chemical, physical, and mineralogical properties with other clays applied for porcelain production sited in literature (*Moyo and Park, 2014; Yaya et al., 2017).* Moreover, Hosanna and Ansho clay which are deposited in SPNNRS, Ethiopia contain considerable amount of major oxide (Al_2O_3 and SiO_2) with high degree of kaolinite minerals and moderate plasticity (Andualem, 2018), this can be an advantage for electrical porcelain and other white ware production. Among local clays summarized in Table 1, Bombowha clay has relatively low SiO_2/Al_2O_3 ratio 1.28, which is much closer to pure kaolinite clay 1.14. Its higher amount of Al_2O_3 is an advantage for metakaolinite and mullite phase formation during processing. Moreover, Bombowha clay contain less percentage of Fe_2O_3 (0.84) compared to Hosanna and Ansho clay, which makes Bombowha clay more preferable for porcelain insulator than other clay sources.

Table 1 chemical composition of some local clay materials in comparison with clay materials that have been applied for insulator fabrication in other African countries.

Clays	Oxides in (%)										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	TiO_2	H_2O	LOI	Source
Bombowha	45.60	35.52	0.84	0.01	0.08	0.01	1.24	0.04	0.01	4.32	13.34	(*Fentaw and Mengistu, 1998; Lijalem, 2016; Andualem, 2018*).
Hosanna	48.68	33.22	1.88	0.08	0.16	0.01	1.18	0.05	0.27	1.21	12.72	
Ansho	54.70	34.00	2.10	0.00	0.00	0.20	0.20	-	0.60	-	12.90	
Assin-fosu	49.79	35.17	0.76	0.20	1.14	2.14	0.60	0.03	0.14	-	9.6	(*Yaya et al., 2017*)
pugu	53.00	19.10	0.24	0.09	0.01	2.04	12.90	-	-	-	12.62	(*Moyo and Park, 2014*)
Mutaka	68.10	18.70	0.08	0.38	0.18	0.36	9.55	0.09	0.01	-	6.10	*Olupot et al., 2013*)

Where: Bombowha, Hosanna and Ansho are clay materials found in Ethiopian, Assin-fosu are found in Ghana, Pugu used in Tanzania, and Mutaka in Uganda.

2.6.Alternative materials for Porcelain Insulators production

Clay, Feldspar and quartz are generally the most useful raw materials and used in large quantities in the manufacturing of porcelain insulator (clay- based products). However, sustainable uses of the raw materials and minimizing the scarcity of quality raw materials in a location close to the industry demand alternative materials such as waste materials for partial and complete replacement of the natural materials.

In recent times, industrial activities generate vast amounts of solid wastes, which cause considerable environmental and economic problems. For this reason, management of industrial solid waste in ecological and economical manner has become a matter of high global interest. In this regard, solid waste management strategies are currently focused mainly on reuse instead of elimination or storage of waste. Therefore, the ceramic industry, specifically the porcelain electrical insulator industry, is a well-established field for the reuse of solid wastes. This approach has environmental and economic advantages because of the solid waste is incorporated into ceramic formulations in place of non-renewable natural raw materials (Schettino et al., 2016). So far, there are research reports on the replacement of silica/quartz by waste materials such as rice husk ash, sillimanite sand, fly ash, silca fume, and etc in the manufacturing of ceramics (Jamo, 2015). This led to the production of porcelain with better mechanical strength and reduced production costs.

Previous studies also identified numerous silicate-based wastes as a potential supplement of feldspar that might improve the physical and/or microstructural properties of the insulator and lower the firing temperature leading to minimization of production cost and resource depletion. Such as soda-lime glasses (Matteucci et al., 2002), blast furnace slag (Kausik Dana & Das, 2004b; E. Karamanova et al.2011; Doaa et al., 2015), metallurgical slags (K. Dana & Das, 2003), rice straw ash and rice husk ash (Prasad et al., 2001), silica fume (Prasad et al., 2002), and fly ash (S.K. Das et al., 2013). Moreover, the study of Teixeira et al (2008) evaluated the uses of SCBA as a substitute for quartz to produce red ceramic, and Faria et al. (2013) and Souza et al. (2011) reported the possibility of producing ceramics for construction by the incorporation of SCBA up to 20% as a substituent for natural clay. Feldspar is a commonly used fluxing mineral in standard porcelain bodies (Carty & Senapati, 2005).

2.7.Sugarcane bagasse ash (SCBA) in the production of porcelain insulators

Sugarcane is a commonly grown tropical and subtropical crop and is the main sugar crop worldwide. The global sugar crop average is approximately 31.3 million hectares, among which sugar cane accounts for approximately 70% (Xu et al., 2018). Brazil is the world's largest producer of sugarcane, followed by India, China, Thailand and Ethiopia. However, this increasing number of sugar production gave rise to a problem related to dumping huge quantities of solid waste byproducts such as SCBA into the environment. The Brazilian sugarcane industry alone generates around 4 million tons per year of SCBA. The estimated quantity of bagasse ash produced from Ethiopia's sugar industries may reach up to 2 million tons per annum (Mosisa et al., 2019). It is produced in the process of reusing the sugarcane bagasse in the same industry as fuel in boilers for energy co-generation. A tone of burnt sugarcane bagasse may generate 25–40 kg of bagasse ash (Faria and Holanda 2013). These materials are usually dumped on open grounds and have detrimental environmental and human health effects. For instance, inhalation of dust from the disposing of bagasse ash can cause chronic respiratory disease. Moreover, improper land disposal of Bagasse ash in a dry season is vulnerable to wind and increases the quantity of dust in the ambient air (Frias et al., 2011). Thus, incorporating the material like SCBA in the ceramic industry has several advantages: saving natural raw materials, lowering energy consumption during subsequent processing, and contribute in the mitigation of environmental pollution (Junkes et al., 2012).

Previous research findings associated to SCBA showed that it is composed of primarily silica (SiO2) and minor components such as Aluminum, Iron, Calcium, and Potassium oxides (fluxing agent), which is a composition similar to common natural aluminosilicate raw materials (Teixeira et al., 2014; Tonnayopas, 2013; Souza et al., 2011; Hariharan et al., 2018). This means that the reuse of SCBA waste as a possible raw material for porcelain insulators is an important technological solution. Moreover, the observed higher level of Potassium oxides (fluxing agent) in SCBA than the natural raw materials such as feldspar in the studies indicated it can be also used as potential supplement to the natural feldspar to enhance its alkali oxides contents for porcelain insulator production at minimized firing temperature. So far SCBA has been used as a clay substitute in red ceramic production (Faria et al., 2013); as an additive in ceramic materials for the construction industry (Souza et al., 2011); as a potential quartz replacement in red ceramic production (Teixeira et al., 2008). However, the amount of ash to be added is defined by the raw material quality and SCBA composition which is intern varies depending on the place where the sugarcane is produced. Hariharan et al. (2014) also reported the partial substitution of feldspar by SCBA on the porcelain insulator composition results in a reduction in water absorption and porosity and an increase in its bulk density and dielectric strength of the final product.

2.8. Porcelain insulator production process

2.8.1. Production process of Porcelain insulator

The production process of porcelain insulators has many steps (as indicated in Figure 1). It has a fairly long process cycle ranging from 15 days to 21 days. Adding to this long process cycle, porcelain insulators have to pass through almost 35 process steps. Each process steps have its importance and contribute to the quality and performance of the insulators. It transforms raw, earthy materials like clay, quartz, and feldspar into electrical equipment used in the electrical power system. It is then becoming the backbone of electrical power transmission and distribution systems as insulators. (Ash & Chandrasekhar, 2017).

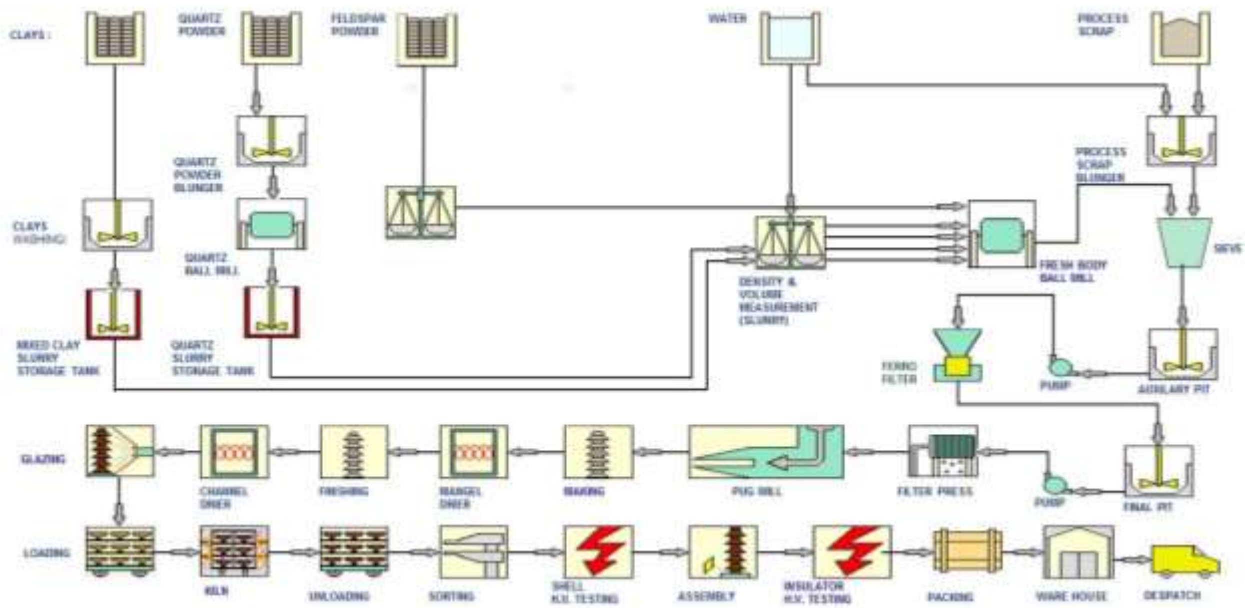


Figure 1 Production process of porcelain insulators (as adopted from Ash & Chandrasekhar, 2017)

Major production process of porcelain insulators involves several stages indicated as follows:

*Preliminary Crushing/grinding***:** The as-mined raw materials such as feldspars and quartz, are reduced to the desired size by successively grinding through one or more jaw crushers and then to a ring mill for final sizing. Oversize particles are screened after ring milling and returned through the process in a closed-loop system. Most clay materials are not beneficiated at the plant site before blending or milling. Still, in some cases, especially where continuous ball milling is subsequently used, the clay portion of the body may be pre-blended in high-speed blungers to ensure dispersion or “slaking” of the clay particles before final blending or milling.

Milling: Once the raw materials are prepared in the correct proportion, it is charged into a ball where crushing by the centrifugal action of the rotating mill and the balls take place. The mill is cylindrical and is made of stainless steel. Both the internal lining and the balls are made of ceramic-making materials to avoid product contamination. The particle size is the controlling parameter for proper milling. Sample from the mill is taken, and particle size is measured using a hydrometer method based on the principle that coarse particles settle faster under gravity.

Blunging: If the milling is acceptable, the mixture from the mill is emptied by the pipeline into the first blunger. The blunger is a large circular tank containing the exact amount of water required by the batch and is equipped with power-driven paddles to agitate the various ingredients of the batch. Agitation is continued until the specific gravity of the slip has reached a required point indicating complete suspension of all the dry ingredients in the water, in other words, until the raw materials are disintegrated and suspended in the water. The function of the blungers is simply mixing and uniforming the body composition.

Sieving and magnetic separation: The sieves separate coarse particles from the slip/ raw porcelain, which is then dried and re-milled later. On the bottom of the vibrating sieves lie permanent magnets that separate iron and other magnetic materials that will otherwise produce spots and coloring problems upon firing.

Filter Pressing: here the excess water is removed, leaving the clay in round cakes containing approximately 25 percent water, thoroughly plastic and ready for processing.

Proportioning: The porcelain body was formulated by varying the composition of the plastic (clay) and the non-plastic (feldspar and silica) materials.

Shaping-forming/Moulding: forming the plastic clay body into the finished insulator shape before the firing to vitrification. The shaping method used depends on the type of raw material and, mainly, upon water content and type of insulator required. Among the methods used to accomplish this are dust or Semi-dry Pressing, Plastic Forming and Casting.

Drying and Bisque firing: the wet porcelain coming from the shape-forming operation typically has moisture contents ranging from 5 to 20 wt%. This water is removed in dryers at temperatures ranging from 40 to 150 °C over one to two days. The drying process is carried out in a series of chambers (intermittent dryers) or tunnels (continues dryers) in which the temperature and humidity of the air are regulated to control the shrinkage which takes place during drying. This was followed by Bisque firing. A Kiln was used for firing.

Glazing: The samples were removed from the Kiln after cooling. Then the glaze was applied

Firing: The samples were returned to the Kiln for firing. The burning of the porcelains is a critical stage in the production process. Firing temperature and atmosphere will determine the ceramic properties, such as strength, porosity, size, and final product colour. Different types of kilns are used for firing porcelain insulators. Tunnel and continuous kilns are more recent innovations, and their use is increasing in porcelain insulator manufacturing. The cooling of the porcelain insulators normally requires 2 to 3 days in a continuous kiln and no more than two days in a tunnel kiln (Rahaman, 2017). However, the rate of cooling will affect the colour and strength of the ceramic. The changes in the structure of triaxial bodies during firing are not completely understood due to their complexity. The table below is an approximate summary of what probably occurs during the firing of a triaxial body.

Table 2 Life history of triaxial body (adopted from Norton, 1974)

Temperature (ºC)	Reactions
Up to 100	Loss of moisture
100-200	Removal of absorbed water
450	Dehydroxylation
500	Oxidation of organic matter
573	Quartz inversion to high form. Little overall volume damage
980	Spinel forms from clay. Start of shrinkage
1000	Primary mullite forms
1050-1100	Glass forms from feldspar, mullite grows, shrinkage continues
1200	More glass, mullite grows, pores closing, some quartz solution
1250	Glass 60%, mullite 19%, quartz19%, pores at minimum

Testing: The final product quality test was conducted.

2.8.2. *Chemistry of porcelain insulator production process*

In porcelain insulator production process the basic reaction steps involved in the removal of non-chemically bound species, such as water and organics, and evolution of different phase can be outlined as follows:

- In the temperature range of 420 -660 ^{o}C, metakaolinite phase formed form kaolinite clay by dihydroxylation of structural hydroxyl groups in the form of water from octahedral coordinated of aluminum sheet in kaolinite minerals (*Lee and Iqbal, 2008; Meng et al, 2016*).

$$\underset{\text{Kaolinite}}{Al_2(OH)_4Si_2O_5.2H_2O} \longrightarrow \underset{\text{metakaolinite}}{Al_2O_3.2SiO_2} + H_2O$$

Due to endothermic nature of the decomposition process this produce an endothermic curve on DTA analysis (*Yaya et al., 2017).* Moreover, by X-ray diffractometer, metakaolinite has an amorphous crystalline nature that produces a wide range of hump reflection under XRD investigation (*Iqbal, 2008*).

- In the temperature range of 950 – 1100^{0}C metakaolinite transformed in to crystalline mullite and amorphous silica phase (*Lee and Iqbal, 2000*).

$$\underset{\text{Metakaolinite}}{Al_2O_3.2SiO_2} \longrightarrow \underset{\text{mullite}}{3Al_2O.2SiO_2} + \underset{\text{amorphous silica}}{SiO_2}$$

Mullite phase is a crystal alumino-silicate compound that primarily originated from clay relict called primary mullite (commoly observed in porcelain microstructure as an aggregate of tiny crystals (<0.5µm) in the clay relicts). In addition to mullite, at this firing temperature feldspar also start to melt and form glassy phase (*Meng et al., 2016*). And as the firing temperature increased above 1100^{0}C the feldspar melts increased and leads to the formation of high amount of glassy phase and starts to nucleate with primary mullite and form secondary mullite and it appears as a long needle (>1µm) shaped crystals (Iqbal & Lee, 2000; *Olupot, et al., 2013*). Bodies with a high percentage of quartz also may contain cristobalite at a temperature above 1200 ^{0}C.

$3Al_2O.2SiO_2$ (mullite) + $6SiO_2$ (silica) → $3Al_2O_3$. H_2O (mullite) + $4SiO_2$ (cristobalite)

- Between 1250 – 1300 0C, feldspar dissolves the silica present in kaolin and that present in the mixture to form feldspar glass.

In general, the typical final microstructures of fired porcelain bodies consist of 10%-25% mullite, with a composition ranging from 2Al2O3.SiO2 to 3Al2O3.2SiO2, 5-25% α-quartz (SiO2), and 0-8% pores dispersed in 65-80% potassium aluminosilicate glass (Iqbal & Lee, 2000),.

2.8.3. Effect of microstructure attribute over the technological properties of porcelain insulator

The properties tested for the porcelain insulators such as physico-mechanical and dielectric properties is depend on the type, amount and size of each phases developed during the firing processes, which depends on the concentration and microstructural attributes influenced by temperature and the chemical composition of the raw materials (Ngayakamo & Park, 2018). Major determinant phases produced during porcelain production are mullite (Al6Si2O3) and unresolved quartz (SiO2) crystal embedded in a continuous glassy phase originated from feldspar and other low melting impurities in the raw materials (Kitouni, 2014). The glassy phase derived from feldspar and quartz component in the porcelain composition has a dominant influence on physical, electrical and mechanical properties of fired ceramics. The glassy phase or liquid derived fills the gaps and voids in the microstructure which leading to densification of the body (*Iqbal*, *2008*) as result the ceramic body become denser and its water absorbance and apparent porosity will decrease. However an excess quantity of glassy phase leads to the formation of blotting phenomena which has a negative effect on the properties of ceramic body.

2.8.3.1. Physical Properties

The physical properties (bulk density, apparent porosity and water absorbance) of porcelain electrical insulator depend on the microstructure and the phase distribution developed during the firing process. Which in turn depend on the chemical composition of the raw materials, the preparation method and the time and temperature of firing (Akwilapo & Wiik, 2003). The glassy phase derived from feldspar and the quartz component in the porcelain composition has a dominant influence on the physical properties of fired ceramics. The glassy phase or liquid derived fills the gaps and void in the microstructure, which leads to densification of the body; thus, the ceramic body becomes denser, and its water absorbance and apparent porosity will decrease (Iqbal, 2008). However, an excess quantity of glassy phase leads to blotting phenomena at high firing temperatures that form small pore or void space, leading to increasing porosity and lower final product quality (P. Olupot, 2006).

2.8.3.2. Electrical properties of porcelain insulator

The most important electrical characteristics of a solid material are the case with which it transmits an electric current. In most solid materials the current arises from the flow of electrons, which is termed electronic conduction. In addition a net motion of charged ions (hole) is possible that produce a current which is ionic conduction. The electrical property in the microstructure of porcelain insulator body is affected by the phases which are developed on sintering (at higher temperature). Among those phases mullite and quartz are important for proper electrical insulation and the glassy phase rilicted from feldspar contain K^+ and Na^+ ions which act as charge carrier. Mullite phases, particularly the needle-like shape, proved to perform well in electrical insulation property. On the other hand, the existence of excessive glassy phase promotes free movement of ions hence poor electrical insulation properties of a porcelain body with less viscosity and (Islam et al., 2004; Moyo & Park, 2014). Moreover, a high amount of quartz leads to a high amount of the glassy phase, which is detrimental to the development of high dielectric strength (Islam et al., 2004).

2.8.3.3. Mechanical properties of porcelain insulators

The mechanical properties of porcelains are largely dependent on their microstructure developed during ceramic processing. This is associated to the concentration, size and arrangement of each individual phases developed during firing stage (Manfredini & Hanuskova, 2012). Their effects on the mechanical properties have been elucidated under the mullite hypothesis, the matrix reinforcement and the dispersion strengthening hypotheses (*Olupot, et al., 2013; Cart and Senapati, 1998*).

The Mullite hypothesis suggested the mechanical strength of the porcelain material was solely dependent on the felt-like interlocking of fine mullite needles. Specifically, the higher the mullte content favored the interloping of the mullite needle. The mullite ($3Al_2O_3 \cdot 2SiO_2$) is characterized by good mechanical, electrical and chemical properties. It is resistant to thermal shocks as well. Hence, it has been argued that the strength grows with the increase of this phase content. The smaller needles can interlock more efficiently than the larger ones. As a result, the temperature of firing and generating the suitable amount of correctly sized needle-shaped crystals of mullite is crucial to achieving higher strength. Therefore according to the mullite hypothesis a ceramic body with higher secondary mullite yields greater strength than scaly crystals of primary mullite.

The dispersion-strengthening hypothesis on other hand states that dispersed particles in the vitreous phase of a porcelain body such as quartz and mullite crystal in the glassy phase limit the size of flow of liquids resulting in increasing strength (*Olupot, 2006*). This hypothesis deals with the homogeneity of phase throughout the body achieved by sufficient mixing in the production process.

Some of the evidence supporting the above hypotheses (Islam et al., 2004) concludes that the best mechanical and dielectric properties can be achieved by high mullite and quartz content with the low amount of the glassy phase in the absence of microcracks. Another evidence shows that under optimized conditions of firing and particle size of quartz (10-30μm), quartz has a beneficial effect on the strength of porcelain, in conformity with the matrix reinforcement and dispersion strengthen hypothesis (P. Olupot et al., 2014).

On the other hand, larger grain size of quartz in the porcelain body has significant effect due to the thermal expansion coefficient mismatch between the quartz crystal and the glassy matrix up on cooling. This thermal coefficient mismatch leads to the formation of micro-crack (*Gralik et al., 2014*). And yet various study carried out to decrease this effect of quartz by partial substitution or completely replacing in by alumina because of alumina has no phase change up on cooling and has relatively similar thermal expansion coefficient (8 x 10^{-6} K^{-1}) that avoid the formation of micro-crack (*Gralik et al., 2014*). But it is not good in relation to the linear shrinkage and its high cost.

The matrix reinforcement hypothesis states that the difference in thermal expansion coefficients between the matrix (glassy phase) and dispersed particles (such as quartz) or crystalline phases formed during firing (such as mullite and cristobalite) produces strong compressive stresses on the glassy phase. The larger these stresses are, the higher is the strength of the porcelain body. The phenomenon is known as the pre-stressing effect. This theory is related to the function of the quartz phase in the porcelain body. The stress generation and associated cracking due to the presence of quartz particles tend to be severe because of the rapid displacive phase transformation of quartz during cooling. However, such problem of quartz can be solved under optimum uniform grain size which result beneficial effect on the mechanical strength of porcelain in conformity with the pre- stressing theory (*Bregava and Bergmann, 2003*).

3. Materials and methods

3.1.Sample collection and preparation

The raw materials samples collected as a potential source of porcelain electrical insulator production includes Bombawuha clay (BC), Denkaka clay (DC), Chancho sand (CS), Arero feldspar (AF), Wolkite feldspar (WF), and Ararti feldspar (AF), and processed at De-yuan ceramic factory found in the Dukem industrial park, Ethiopia. They were originally mined from a deposit located at Bombawuha (6° 05′ 20″ N and 38° 46′ 30″ E), Denkaka (8° 33' 36" N, 39° 10' 29" E), Chancho (9° 18' 29.1240" N and 38° 45' 11.2320" E), Arero (4° 45′ 00″ N and 38° 49′ 00″ E), Wolkite (8° 16′ 50″ N and 37° 46′ 40″ E), and Ararti (90º 6' and 90º 5' N and 39º 46' and 39º 26' E), respectively. As well as sugarcane bagasse ash (SCBA) and sugarcane fly ash (SCFA) waste from Wonji-Shoa sugar factory located in the Oromia region, Ethiopia. They were crushed to reduce the particle size of lump materials followed by soaking in water for three days separately to remove some deleterious materials and decanting the water after three days. The residue were then sundried and milled using a planetary ball mill (P100, RETSCH) and for clays, feldspar, SCBA, and SCFA passed through 63 μm opening Sieve, while quartz passed through 45 μm sieve to homogenize and make ready for characterization (*Yaya et al., 2017, Ezenwabude and Madueme, 2015; Oladiji et al., 2010).*

3.2.Characterization of raw material and waste samples

All raw materials and waste material samples were characterized with respect to their chemical compositions and mineralogy; and thermal property, particle size distribution, and plasticity were characterized for the two clays (BC and DC).

3.2.1. Chemical composition analysis

The chemical composition analysis of raw material (clay, feldspar, and quartz) and waste material (SCBA and SCFA) was done by atomic absorption spectrometer (AAS) (spectry AA-20 plus model). Loss on ignition (LOI) was measured by the mass difference of sample heated at 105 °C and 1000 °C for 2 h (Jara et al., 2020; Regassa et al., 2014), at geological survey of Ethiopia laboratory. Apart from the AAS, the $LiBO_2$ Fusion, HF attack, Gravimetric, Colorimetric were carried out for all samples to perform the complete silica analysis at the Geological Survey of Ethiopia.

3.2.2. *Mineralogy analysis*

The mineralogy of all samples and phase analysis of the fried product was carried out using the XRD machine (Shimadzu XRD-7000 X-ray diffractometer) using Cu-Kα radiation (λ= 1.5418Å), the operating voltage of 40 kV, a current of 30 mA, over the diffraction angle (2θ) range between 10° and 80°. The mineralogy of feldspar, quartz, and sugarcane bagasse ash and sugarcane fly ash was scanned at a normal state, while clays (BC and DC) was both at a normal state and after calcined to 600 °C for 2 h (*Morkel et al., 2006*). The diffraction data pattern of samples was then analyzed by search match against the international center for diffraction data (ICDD) database using the software expert high score (Iqbal, 2008; *Yaya et al., 2017; Mahmoudi et al., 2017*).

3.2.3. *Thermal analysis*

The thermal property of Bombawuha clay (BC) and Denkaka clay (DC) were conducted using differential thermogravimetric analysis (TGA) coupled with Differential Thermal Analysis (DTA) (Shimadzu DTG-60H, Japan) following the procedure reported by (Mahmoudi et al., 2017). An oven-dried normal clay samples (BC and DC) was used and analyzed using differential thermogravimetry operating under inert atmosphere conditions. The samples were heated from room temperature to 1200°C in a Platinum/alumina cup with a heating rate of 10 °C/min, and an empty Platinum/alumina cup was used as control.

3.2.4. *Plasticity test*

The plasticity parameter of Atterberg limits ((liquid limit (LL), plastic limit (PL), and plastic index (PI), PI= LL-PL) of the clays (BC and DC) was measured by using the Casagrande method following (ASTM D4318, 2005; *Mahmoudi et al., 2017*).

Liquid limit (LL) values were determined for a portion of clay finer than the No.40 sieve. 200 gm of clay samples was prepared and mixed thoroughly with distilled water into a uniform paste. A portion of the paste was placed in the Casagrande cup and leveled. A groove was cut at the center of the clay paste using the standard grooving tool. Four test trials had been carried out for each proportion of both clays by adjusting the water contents so that the number of blows required to close the groove fall within the range of 15 to 35 blows. The water content of the clay taken near the closed groove was found out the water content of the clay samples and the cup was altered. The test trials were repeated. A plot of water content against the log of blows was made, and the water content at 25 numbers of blows was determined as the liquid limit.

On the other hand, the plastic limit (PL) was determined by taking 15 gm of clay samples passing through a sieve. No. 40 was mixed thoroughly with water. The samples were rolled on a flat glass plate with hand until it becomes 3-4 mm in diameter. This procedure of mixing and rolling was repeated until the samples shows signs of crumbling and the diameter becomes 3 mm. The moisture content at which the threads of clays started to crumble, at the specific diameter, was recorded as the plastic limit (PL) of that clay sample. Finally, the Plasticity indices of clay will be calculated by subtracting the result of the plastic limit from the liquid limit.

PI = LL – PL ……………………………………………………………..(1)

3.4.5. Particle Size Distribution of Clays

The particle size distribution of clays finer than 75μm can be done by hydrometer test and courser than 75μm by sieving (wet sieve analysis) following ASTM D422-63 test method (ASTM D422, 2007).

The wet sieve analysis was carried out by sieving a 1000 gram weight of air-dried clay samples through the set of sieves placed one below the other after washing by water. The washed air-dried samples retained on a 75μm sieve were dried in an oven for 24 hours at 110 °C. After dried, the sample was sieved so that the openings decrease in size from the top sieve down, with a pan at the bottom of the stock after oven-dried of the sample. The whole set of sieves were given a horizontal shaking for about ten minutes until the weight of clay samples remaining on each sieve reaches a constant value. The hydrometer test method was conducted for samples particle size smaller than 75μm (passing 200 mesh sieves). In general, it was conducted to know the silt and clay fractions based on the ASTM test standard (ASTM D422, 2007). A 50 gm of soil passing sieve No. 200 were agitated with water and dispersing agent (Sodium hexametaphosphate) in a 1000 ml jar. Readings were taken at intervals of 0.75, 1, 2, 4, 8, 15, 60, 120, 240, and 1440 minutes with the hydrometer remaining in the suspension. The corresponding temperature of the suspension was also recorded with a thermometer. After the twenty-four-hour reading, all the reading data were compiled and determined for different sieve sizes for the different hydrometer reading values. Then, the combined grain size distribution curve for particles wet sieve (retained on No.200 sieve) and hydrometer tests (passing No.200 sieve) was drawn.

3.3.Porcelain Electrical Insulator Bodies Formulations and design of experiments

An experimental design was formulated to examine the effects of the selected waste (SCBA) and raw materials (BC, AF, WF, and CS) which possess relatively better chemical and mineralogical properties and plasticity for clays, on porcelain insulator body properties (physical, electrical and mechanical properties) at various firing temperature and dwelling time. Accordingly, a total number of 54 porcelain electrical insulator bodies (combination of six porcelain insulator formulations, fired at three firing temperature (1200 °C, 1250 °C, and 1300 °C) for three dwelling time (1.5 h, 2 h, and 2.5 h) plus 14 selected samples which possess good electrical properties were used in this study.

The six porcelain insulator bodies were formulated by keeping the feldspar proportions constant and varying the relative proportions clay and quartz in the first three batches (Batch-1, Batch-2, and Batch-3). In the subsequent three batches (Batch-4, Batch-5, and Batch-6), the SCBA proportion of 0, 10, 15, and 20 (wt. %) were used as feldspar replacements in the optimized batch composition, which was 50% clay, 40% feldspar, and 10% quartz, that was named as Batch-1 on this study as indicated in Table 3. The batch compositions were designed based on the findings of our previous work Merga et al., (2019), with little modification by considering raw and waste materials chemical composition used in this specific study. For instance, in place of the Arero feldspar mixed feldspar from two deposits: Arereti and Wolkite was used to solve the low amount of fluxing oxides (K_2O and Na_2O) on the individual feldspar as shown from the chemical composition result (table 4.1). In addition to the natural raw material, it was also used the recyclable material (SCBA) to partially replace the natural feldspar to get the optimum alkaline oxide content (Moyo & Park, 2014) so that to lower the firing temperature and save natural raw material usage. The prepared samples were allowed to be fired at temperatures, 1200

°C, 1250 °C, and 1300 °C for 1.5 h, 2 h, and 2.5 h time at a heating rate and cooling rate of 6 °C /min (Merga et al., 2019).

Table 3 Formulation of Porcelain Insulator bodies (wt%)

	Formulation					
	Batch-1	Batch-2	Batch-3	Batch-4	Batch-5	Batch-6
Clay	50	45	40	50	50	50
Quartz	10	15	20	10	10	10
Feldspar	40	40	40	30	25	20
SCBA	0	0	0	10	15	20

3.4.Preparation of Porcelain Electrical Insulator

According to the percentage composition presented in Table 3, samples were carefully weighed using a digital scale from the six compositions. The weighed samples were placed into a ball mill containing porcelain grinding pebbles of different sizes and weights. The ball mill was powered to constantly roll for six hours for each of the six batch compositions before its content was discharged completely to achieve particle homogeneity throughout the body. The milled powder samples were adequately weighed, and 7% of water was added to make it suitable for dry pressing. A hydraulic jack of 10-ton capacity was used for the dry pressing. This was actualized by measuring each sample into an iron steel mold to shape the pieces into the desired dimension. For this study, a cylindrical shaped 80mm diameter and 5mm thickness were prepared from each batch for physical (water absorbance, bulk density, apparent porosity) and electrical (dielectric strength) properties test. At the same time, a rectangular-shaped test body of 75 mm L x 38 mm W x 7 mm H was designed from the selected batch (14 samples in triplicate which possess good electrical properties) for mechanical properties test. The mold was done using a hydraulic press, using a pressure of 20 MPs and approximately 3 minutes loading. After the dry pressing, the samples were allowed to dry at room temperature and later placed in the kiln for firing at the specified temperatures. All batches at each specific firing temperature were fired at the specified dwelling times with a heating rate of 10°C /min and 5°C /min cooling rate.

3.5. Characterization of fired porcelain materials

3.5.1. Water absorbance, apparent porosity and bulk density

The physical properties (water absorbance, apparent porosity and bulk density) of porcelain insulator samples were determined by using boiling method according to ASTM standard C 373-88 (ASTM C373-88, 1999). The dry weight of the fired porcelain insulator sample was carefully placed in a water bath filled with distilled water then subjected to a two hour boiling followed by 24 h water soaking. During soaking the fired piece were completely immersed in water throughout the boiling period. Then after, suspended weight of soaked sample was taken from the beam of balance in a vessel of water (under consideration of completely immersed in the water without touching the side of the vessel). Following this step, the samples were taken out from the water and its surface water was removed carefully by tissue paper and saturated weight (soaked weight) was measured. All the weight measurement was taken immediately to avoid errors. Accordingly the physical properties were calculated as follows:

$$\text{Water absorbance (\%)} = \frac{Ws-Wd}{Wd}\ x\ 100 \quad (2)$$

$$\text{Apparent Porosity (\%)} = \frac{Ws-Wd}{Ws-Wsp}\ x\ 100 \quad (3)$$

$$\text{Bulk density (g/ml)} = \frac{Wd}{Ws-Wsp} \quad (4)$$

Where: W_s = soaked weight, W_d = dry weight, W_{sp} = suspended weight

3.5.2. Electrical properties test: Dielectric strength

Dielectric strength of porcelain insulator samples were computed by measuring their break down voltage using high voltage testing machine (model TERCO HV 1103), found at Addis Ababa University, department of electrical engineering. The positive and negative terminals of the instrument was connected at either end of the insulator sample then the voltage was gradually increased from control disk until the voltage increment break and began to drop displayed on control disk which indicate the break down voltage of the sample (*Ezenwabude and Madueme, 2015*), then the dielectric strength was calculated as:

$$\text{Dielectric strength} = \frac{break\ down\ voltage\ (kv)}{thickness\ of\ sample\ (mm)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

3.5.3. Mechanical Strength Test: Flexural Strength/Modulus of Rupture

The flexural strength of the porcelain insulators were tested according to three point loading method (ASTM D790M-9) using a flexural breaking load machine (model MOR 5-TS/185) at Ethiopian conformity assessment enterprise laboratory. A rectangular-shaped sample with dimensions 75mm x 38mm x 7mm were used for the three-point bending/loading test. The support span and the rate of crosshead motion were 50 mm, and 2.08 mm/min, respectively. A loading force (F), was directed to the center of the sample and up on breaking the maximum fracture load was noted, and Modulus of Rupture (MOR) / flexural strength of three-point test were calculated as follows:

Flexural strength=$3FL / 2Wd^2$ ………………………………………………………….. (6)

Where F= maximum load, L = sample length, W = sample width, D =depth of sample

3.5.4. Morphology analysis

Scanning electron microscope/ electron dispersive x-ray spectroscopy (SEM/EDX) analysis were carried out using a field emission scanning electron microscope (Carl Zeiss, Merlin; IST Austria) coupled with a Fissons Quantum EDX detector to determine the microstructure of fired samples (such as the type of phase appears-, availability of micro-pore-, and e.t.c. in the microstructure) and chemical composition of the surface of solid. The result was supplemented by X-ray Photoelectron Spectroscopy (XPS) spectra of the solid samples obtained using a Thermo Scientific (Seoul, South Korea) K-α XPS spectrometer with micro-focused monochromatic Al Kα X-ray radiation (hν = 1350 eV) and interpreted to determine the chemical composition of the surfaces of solid samples quantitatively. This analysis was conducted at South Korea,

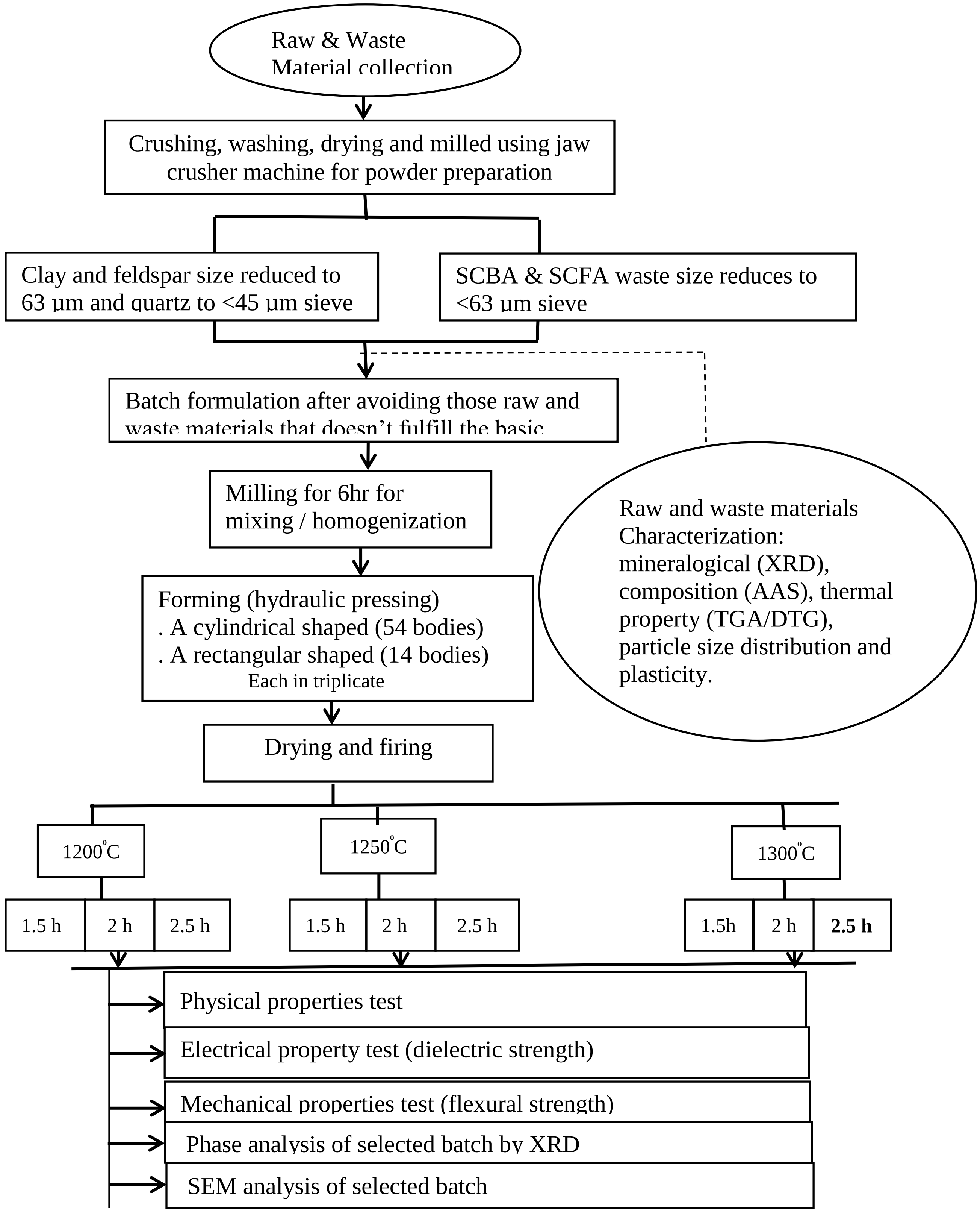


Figure 2 Conceptual framework for the methodology followed

4. Results and discussions

4.1. Characteristics of raw materials

4.1.1. Chemical Composition of raw materials

The chemical composition analysis and LOI results of the raw materials (clay, feldspar, and quartz) and sugarcane wastes were given in Table 4. The chemical composition analysis results shows that the oxides content of both Bombawuha clay (BC) and Denkaka clay (DC) are comprised mainly of silica (46.72% for BC & 47.90% for DC) and alumina (35.32% for BC & 27.84 % for DC) with a low percentage of other oxides such as Iron oxides and fluxing oxides. The ratio of the principal oxides (SiO_2 to Al_2O_3) for BC is 1.3, and DC was about 1.7, which indicated BC is much closer to the value of pure kaolinite clay, but DC has a value slightly far from pure kaolinite (1.18) (Mahmoudi et al., 2017). Moreover, the composition of the materials with respect to CaO, is very low for BC (0.74%) and relatively higher (5.54%) in DC (Table 4). This suggests that a higher amount of gases may be formed during sintering, which may cause cracks on the fired bodies and led to high porosity and water absorption in the porcelain insulator bodies prepared from DC (Aghayev & Küçükuysal, 2018). Another important aspect concerning the chemical composition of the clay materials is the observed difference in the total amount of alkaline oxides (K_2O and Na_2O) that acting as fluxing materials, which is higher in BC (1.62%) than DC (0.46%). The loss on ignition (LOI) value of BC (13.85%) and DC (13.41%) is comparable with classical kaolinitic clays (14%) and it is related mainly with the presence of clay minerals, hydroxides, and organic matter (Tsozué et al., 2017; K. C. P. Faria et al., 2013). In general, the results confirmed that the clay materials are kaolinite clay minerals. Moreover, the amount of color forming impurities Fe_2O_3 and TiO_2 in the clay materials is within the standard requirement for porcelain insulator production and in addition, the low iron content in the composition has an advantage to reduce gas formation at high temperature which occurred during transformation of Fe_2O_3 to Fe_3O_4 and enhances the action of alkalis flux, causing melting to start at lower temperatures with more abundant liquid phases (Souza et al., 2011; Meng et al., 2012). On the other hand, the relative purity of BC (having the ratio of Al_2O_3/SiO_2 close to pure kaolin), the low level of calcium oxide, and high amount of alkaline oxide present in it make BC is much more suitable for the fabrication of electrical porcelain insulators than DC. The ratio of

Al_2O_3/SiO_2 was remarkable amount for mullite phase formation during sintering the porcelain body (Chen et al., 2000; Olupot et al., 2010; Gralik et al., 2014).

All the natural feldspars contained SiO_2/silica as major oxides and followed by Al_2O_3 (Table 4). The amount of silica in Arerti feldspar (AF), Arero feldspar (ARF), and Wolkite feldspar (WF) samples was 72.70%, 73.56%, and 78.12%, respectively (Table 4). Implied, these feldspars are in the range reported to be suitable for producing porcelain bodies (66.3-79.5%) (Kimambo, 2014). Moreover, percentage compositions of Al_2O_3 and LOI of all the three type of feldspars were within the range for feldspar to be used in the porcelain body (Kimambo et al., 2014). The chemical analysis result further shows, the percentage of Fe_2O_3 was high in the raw feldspars, which were 1.84% for AF, 2.00% for ARF, and 1.34% for WF, respectively (Table 4). The maximum allowed limit of Fe_2O_3 must not be more than 0.3%, as presence of Fe_2O_3 more than the allowed limits will contribute to unwanted variations of the color towards grey rather than white and causes bloating due to the escape of entrapped gases during sintering (Ochen et al., 2019). Thus, pretreatment such as magnetic separation might be carried out to decrease the iron oxide contamination of the feldspar deposits. The percentage of fluxing oxides (K_2O and Na_2O) 6.42% in AF, 3.62% in WF, and 4.68% in ARF was low compared to the requirement for porcelain insulator production, which is >12% (Meng et al., 2012). This indicates, the feldspar must be used in either at higher concentration or need higher firing temperature in order to achieve optimum glassy phase in the porcelain body (Moyo and Park, 2014). In general, the chemical composition result obtained for AF, WF, and ARF agrees with the results reported by (Merga et al., 2019; Ochen, 2019) and in terms of its chemical composition meets the chemical purity requirement of feldspars for porcelain insulator fabrication (Merga et al. 2019).

The chemical composition of Chancho sand (CS) reveals that the amount of silica and alumina in the quartz sample was 92.68% and 2.94%, respectively (Table 4). The presence of higher amount of silica (92.7 %) than other chemical elements and the amount detected in other ceramic raw materials confirmed it is the major component of sand fractions (Anbalagan et al., 2010). However, the amount of silica obtained is lower than the amount reported in Arero Sand (99%) by Merga et al. (2019) and does not meet required specification for quartz to be considered suitable for the production of porcelain body (98.0-99.1%) according to Kimambo et al., (2014). Hence, the study materials CS can be incorporated in the production of porcelain insulator by using the optimized amount and reducing the grain size to the required level, as the size of quartz primarily determines its dissolution rate and subsequent use as filler materials in porcelain composition and increases the strength in a porcelain body (Wiedmann 1959; Rado 1971).

Table 4 Chemical compositions and loss on ignitions (LOI) in (w %.) of the raw materials and sugarcane ash wastes.

Oxides	Bombawuha clay (BC)	Denkaka clay (DC)	Arerti feldspar (AF)	Wolkite feldspar (WF)	Arero feldspar (ARF)	Chancho Sand (CS)	SCBA	SCFA
SiO_2	46.72	47.90	72.92	78.12	73.56	92.68	65.06	66.16
Al_2O_3	35.32	27.84	14.52	13.20	15.32	2.94	10.88	10.91
Fe_2O_3	0.83	0.32	1.84	1.34	2.00	0.48	4.08	4.06
CaO	0.74	5.54	0.18	1.32	<0.01	0.42	1.14	1.04
MgO	0.16	0.18	0.20	0.64	0.68	0.12	1.30	1.18
Na_2O	0.54	Trace	4.66	1.36	1.46	Trace	2.06	0.24
K_2O	1.08	0.46	1.76	2.26	3.22	0.78	6.60	5.00
MnO	<0.01	Trace	0.06	0.04	0.04	<0.01	0.10	0.12
P_2O_5	0.20	0.05	0.14	0.08	0.04	0.02	0.79	0.78
TiO_2	0.13	0.33	Trae	Trace	0.10	0.12	0.24	0.27
H_2O	1.76	3.50	1.60	1.26	0.28	0.44	0.66	0.73
LOI	13.85	13.41	1.48	1.63	1.80	1.54	4.75	8.92

LOI = loss on ignition

trace = quantity detected below 0.1

SCBA = sugarcane bagasse ash

The sugarcane bagasse ash (SCBA) and sugarcane fly ash (SCFA) wastes contained SiO_2 (65.06%, 66.16%) as a major oxide, followed by Al_2O_3 (10.88 %, 10.91%). Moreover, in both materials significant proportions of Fe_2O_3, and K_2O were recorded, while Na_2O, CaO, MgO, TiO_2, and P_2O_5 are present only in small quantities (Table 4). Their relative proportions was comparable to the natural feldspar used in this study, except for the silica, which is present in a lower amount when compared with natural feldspar and iron oxide content, which are presents in high amount (4.06+%). Based on the chemical composition analysis results, the partial replacement of feldspar by both SCBA and SCFA wastes appeared to be very plausible in the production of porcelain electrical insulators even if the level of iron oxides needs some pre-treatment. The higher alkaline oxides (K_2O and Na_2O) content in SCBA (8.66%) as compared to SCFA (5.24%) may be a plus for SCBA to be a preferred material over SCFA to be used as alternative to substitute the natural feldspar (Table 4). The higher fluxing oxides in SCBA are important to lower the melting temperature and play a significant role in liquid phase formation, phase transformation, and mullite grain growth in the porcelain body formation (Ngayakamo & Park, 2018). Their formation enhanced the mechanical strength, physical and dielectric strength of porcelain insulator properties. The chemical composition of the waste materials obtained in this study agrees with the results reported in different literature in which they are comprised of mainly silica and contained relatively higher content of potassium oxides and LOI than natural feldspar (Ochen, 2019; Faria et al., 2013). A higher LOI value in the wastes indicates unburned carbon (Agredo et al., 2014). However, there is a slight variation in the percentage composition of the oxides content presented in the current and previous studies which can be explained in terms of the different soils in which sugarcane grow, process of making the SCBA and SCFA, as well as fertilization method, and soil management (Faria et al., 2013).

4.1.2. Mineralogical composition of raw materials

Figure 3 illustrates the X-ray diffractogram (XRD) pattern of the raw materials and sugarcane waste ashes. Bombawuha clay powder in a normal state, showed the presence of kaolinite (ICDD Card No: 01-080-0885), Illite (ICDD Card No: 00-029-1496), quartz (ICDD Card No: 01-085-0459), Gibbsite (ICDD Card No: 00-029-0041), and microcline (ICDD Card No: 01-083-1604) (Figure 3a (b)). Similarly, Denkaka Clay in a normal state, depicts kaolinite (ICDD Card No: 01-083-0971), Quartz (ICDD Card No: 01-085-1054), and nepheline (ICDD Card No: 01-079-0991) (Figure 3b (b)). In which, their intensity in the XRD pattern clearly indicated the BC contained kaolinite as the major crystalline phase and the non-clay minerals such as quartz, feldspar, and Gibbsite as the minor phase. While the XRD pattern of DC was characterized by dominance of kaolinite and quartz. Moreover, the disappearance of the diffraction peaks of kaolinite and the appearance of amorphous aluminosilicate, more specially for BC after heat treatment at 600 °C

(Figure 3a (a); Figure 3b(a)) further confirmed the presence of the kaolinite phase, which transformed to metakaolinite above 450 °C (Merga et al., 2019; Brindley & Nakahira, 2006). The observed diffraction peaks, which is more intense in the XRD pattern of DC after heat treatment is due to the quartz, which is remained intact at the calcination temperatures of 600 °C (Ayele, 2016). The XRD patterns of BC than DC were also in agreement with the chemical analysis result obtained from AAS (Table 4). In which, BC has relatively more kaolin mineral and minor amount of quartz than DC, resulting in a lower SiO_2/Al_2O_3 ratio for BC (1.32) than for DC (1.72). This implied, the BC is preferred clay minerals for quality porcelain insulator production as it has required amount of clay minerals for mullite phase formation during the porcelain body's sintering.

The XRD patterns of the feldspars revealed that the Arerti feldspar contains mainly albite (ICDD Card No: 00-083-1610) and microcline (ICDD Card No: 00-087- 1789) (Figure 3c (A)). Whereas, the Wolkite feldspar (WF) is predominantly composed of anorthoclase (ICDD Card No: 01-084-1455) and quartz (ICDD Card No: 01-078-1252) (Figure 3c (w)). This predominance of albite in AF agrees with the chemical analysis result, which indicated a higher amount of Na_2O in AF (Table 4). The XRD pattern also confirmed WF has similar mineral composition with that of Arero feldspar which contain mainly free quartz (SiO_2) and anorthoclase (Merga et al., 2019).

The X-ray diffraction analysis of SCBA confirmed the presence of anorthoclase (ICDD Card No: 01-075-1632) as the major mineral, followed by hematite (ICDD Card No: 01-073-0603) and quartz (ICDD Card No: 01-085-0797) (Figure 3d). The observed results are complementary to the composition analysis results in (Table 4), in which silica, alumina and hematite are found to be the major constituent of SCBA waste. Moreover, the XRD results are in agreement with the XRD data reported by (Faria et al., 2013; Souza et al., 2011; Teixeira et al., 2008). The result also confirmed that SCBA gives the mineralogical properties similar to natural feldspar specifically, Wolkite feldspar. The XRD patterns of CS are predominantly reflected the presence of pure quartz/silica and minor component of microcline (ICDD No 00-083-2465) (Figure 3d). The result supplement the observed result in Table 4 and in agreement with the generalization, sand is higher in silica (SiO_2) to the extent (>99%) as it is a mineral that consists of silica in crystal form (Boch and Niepce, 2001).

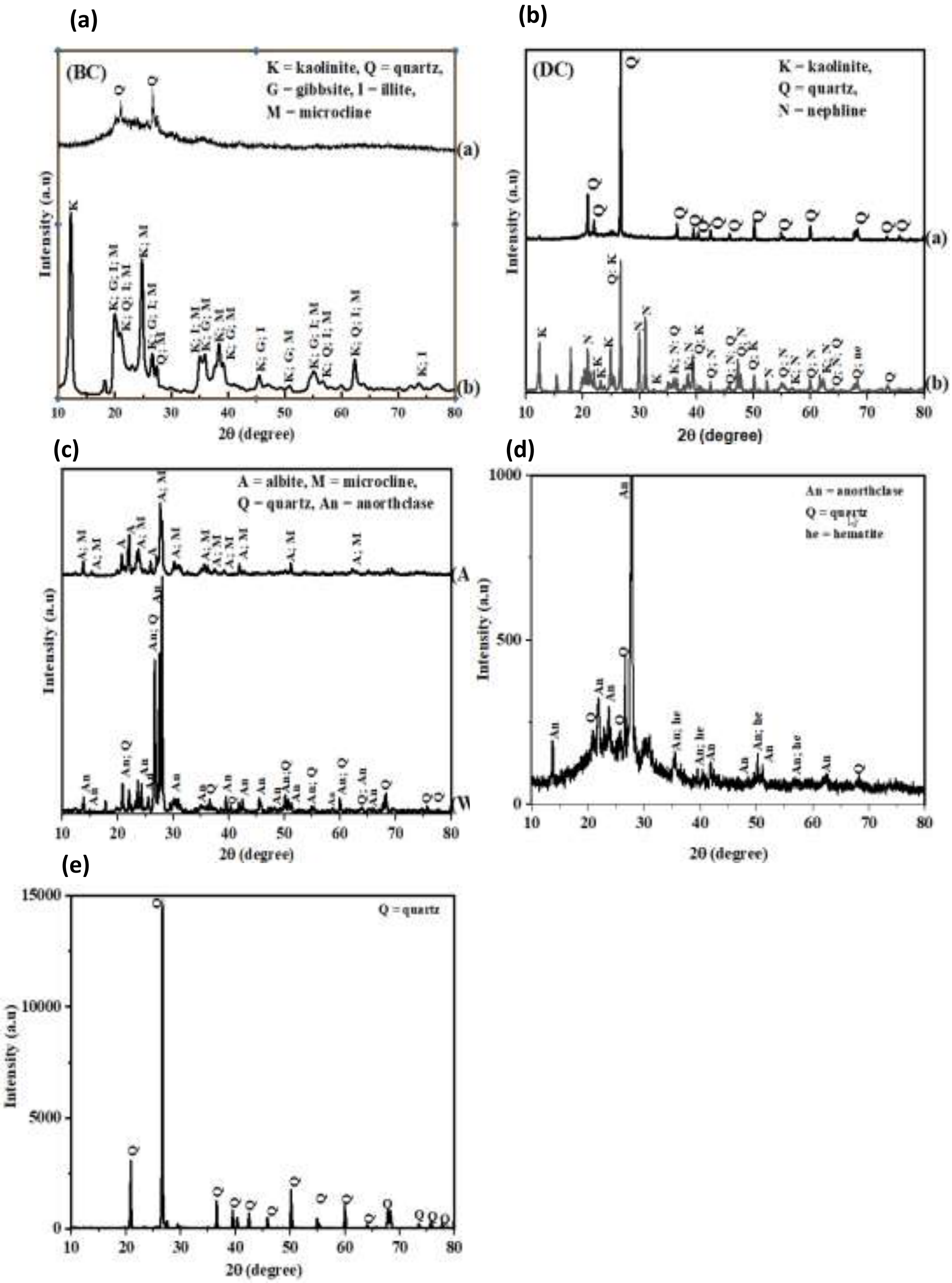


Figure 3 Powder X-ray Diffractogram (PXRD) spectra of: (a) Bombowha Clay, (b) Denkaka Clay scanned at normal state and after heat-treated at 600 °C, (c) Feldspar (A: Ararti and W: Wolkite), (d) Sugarcane Bagasse Ash, and (e) Chancho Sand.

4.1.3. Thermal properties of raw materials

The Differential Thermal Analysis (DTA) and Thermogravimetry Analysis (TGA) results of Bombawuha clay (BC) and Dankaka clay (DC) that shows the changes in materials that are caused by heat /thermal properties/ were shown in Figure 4. As shown in the DTA curve (Figure 4), the endothermic peak at 65.67 ºC for BC and at 53.93 ºC for DC was attributed to removing the water of clay minerals (Holanda, 2012), and the mass loss associated with this peak in TGA curve is about 1% for both clays. The weak endothermic valley at 260.38 ºC for BC could be related to the free gibbsite sheet (Mercury et al., 2011). This is consistent with the observed mineralogical composition results of BC in the XRD pattern (Figure 3). The broad endothermic band centered at 512.02 ºC for BC and 554.71 ºC for DC are within a characteristic temperature range (420 ºC to 660 ºC) for metakaolin phase formation as a result of the dehydroxylation of kaolinite and α→β-quartz transformation-more pronounced for DC as it contains higher level of quartz (Iqbal, 2008; Yaya et al., 2017). The result supports the XRD patterns that showed the phase transformations of kaolinite to metakaolinite upon heating to 600 ºC and higher level of quartz in DC than BC (Figure 3). The mass loss associated with this endothermic peak is 9.84% for BC and about 7.75% for the DC, as observed in the TGA curve (Figure 4). This is mainly due to the loss of structural hydroxide in water from the octahedral coordinate of aluminum sheet in kaolinite mineral ($Al_2O_3.2SiO_2.2H_2O$) at the specified temperature range (krupa and Malinaric, 2015). The result is consistent with the idea that clay minerals with high ratio of Al_2O_3/SiO_2 (higher kaolinite degree) exhibit a tendency to form high quantity of metakaolin phase, correspondingly loss high quantity of structural hydroxide. The small endothermic peak at 748.11 ºC for the DC can be attributed to the decomposition of calcite into calcium oxide (Çelik, 2017). The weight loss in the TGA curve associated with this was 5.5% which is in agreement with the observed chemical analysis result (Table 4). A more intense exothermic peak observed at 1001.23 ºC for BC compared to the observed exothermic peak at 1006.06 ºC for DC were due to mullite formation (Figure 4). This exothermic reaction that led to the crystalline mullite phase is mainly caused by the recrystallisation from metakaolinite (Celik, 2010).

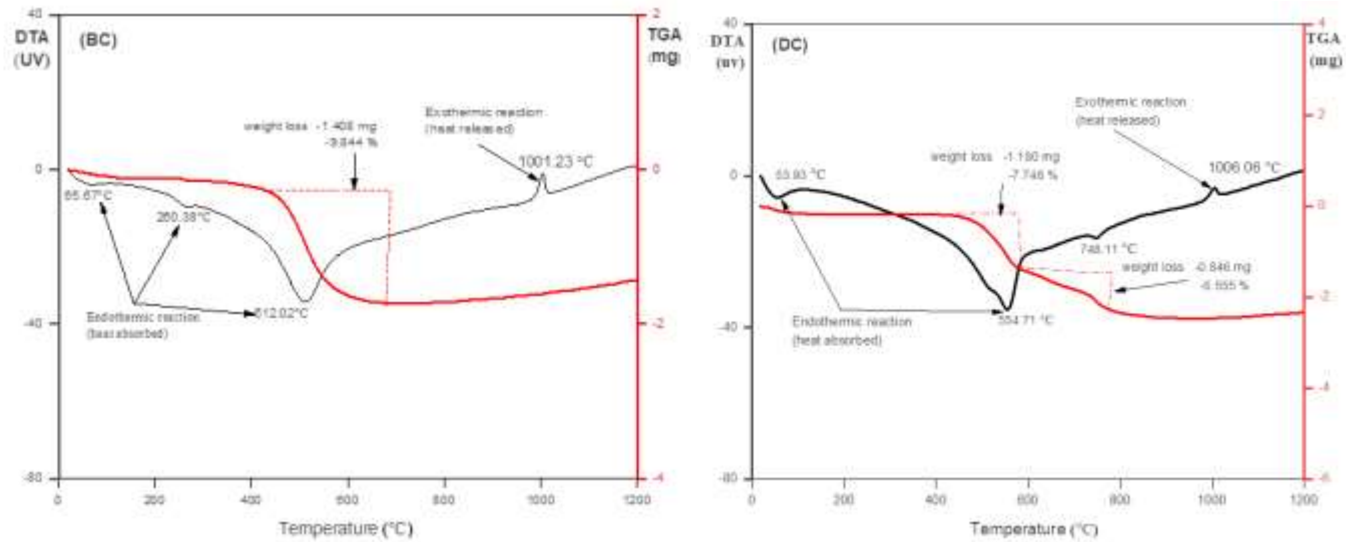


Figure 4 The Differential Thermal Analysis (DTA) and Thermogravimetry Analysis (TGA) analysis results of Bombawuha clay (BC) and Dankaka clay (DC)

4.1.4. Particle Size Distribution of clay materials

The particle size distribution (sand, silt and clay fraction) of BC and DC is summarized in Table 5 and Figure 5. The result shows the percentage of clay fractions (particles with sizes <0.002 mm) were about 20.58% for BC and 12.7% for DC; the silt fraction (particles with sizes between 0.075mm and 0.002mm) was approximately 79.11% for BC and 56.03% for DC; and the sand fraction (particles with sizes 4.75mm – 0.075 mm) was about 0.39 % for BC and 31.8% for DC (Table 5). The result confirmed BC had relatively higher level of clay fractions than DC; accordingly it has higher plasticity. Moreover, the high silt fractions in both BC and DC indicates the need of pre-treatment such as crushing and sieving before using them for the manufacture of porcelain insulators.

Table 5 Particle Size Distribution expressed in weight percentage (wt %.) of Bombawuha clay (BC) and Dankaka clay (DC).

Particle size distribution	Sample name	
	BC (wt %.)	DC (wt %.)
<0.002 mm	20.50	12.17
0.075 – 0.002mm	79.11	56.03
4.75 – 0.075 mm	0.39	31.8

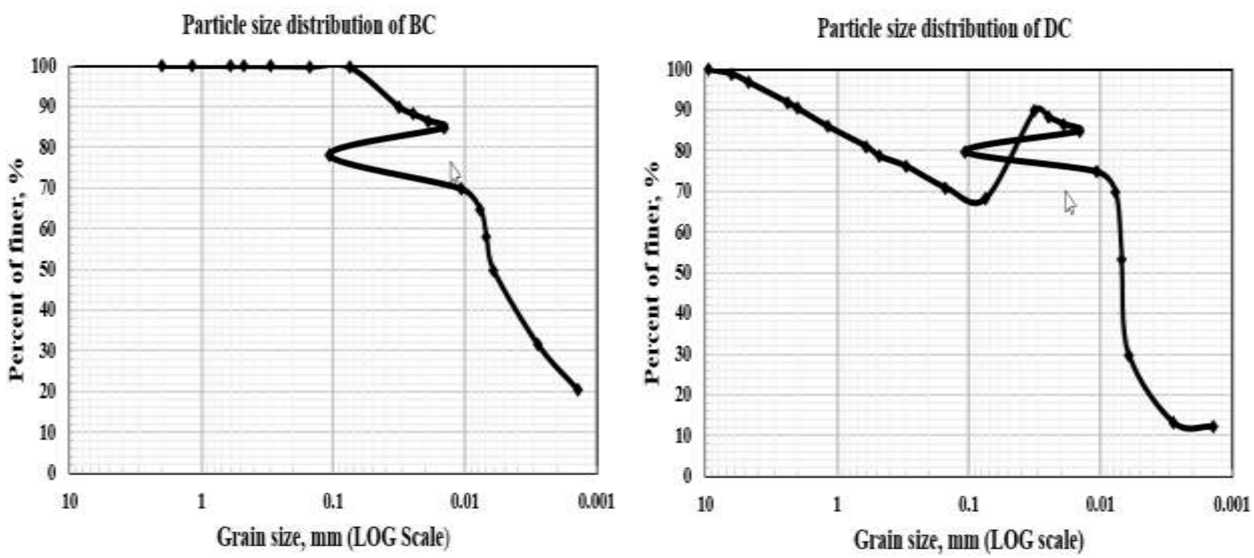


Figure 5 Particle Size Distribution of Bombawuha clay (BC) and Dankaka clay (DC)

4.1.5. Plasticity (Atterberg Limit) Analysis

The plastic limit (PL), liquid limit (LL), and plastic index (PI) values of Bombowha clay (BC) and Denkaka clay (DC) were presented in Table 6. The plasticity test result of BC and DC shows that the liquid limit (LL) was 32% for BC and 21.7% for DC, while the plastic limit (PL) was 20.8% for BC and 17.5% for DC. Based on the Atterberg limits, the plastic index (determined by using a formula PI = LL – PL) is 11.2% for BC and 4.2% for DC. The observed PI implies BC is characterized by the middle range of plasticity (7 % < PI> 17 %), whereas DC exhibits low range of plasticity (PI<7%) as shown in Figure 6, according to Atterberg classification (Roy & Kumar

Bhalla, 2017). This higher plastic index (PI) of BC than DC was due to the presence of higher clay fraction (<2μm) in BC as indicated in the particle size analyses result (Table 5). This justification is supported by (Skempton, 1984) that the plasticity index of clay increases linearly with the percentage of the clay-sized fraction. (Laskar & Pal, 2012). Similarly, as shown in Figure 6, the calculated consistency limits confirms BC accommodates in a medium plastic zone, while DC is located in the low plastic region (Holtz et al., 2013). This ensures the plasticity values of BC are suitable and encouraging for optimal behavior in pressing and drying (negligible contraction and easy to dry) during the production of porcelain electrical insulators. This was due to BC containing a small amount of non-clay minerals such as quartz and interstratified clays like illite as shown in the XRD pattern (Figure 3), which give more plasticity for BC in comparison with DC (Bennour et al., 2015).

Table 6 Liquid limit (LL), plastic limit (PL), and plasticity index (PI) of Bombawuha clay (BC) and Dankaka clay (DC).

Atterberg limit tests (wt %.)	BC	DC
Liquid limit (LL)	32	21.7
Plastic limit (PL)	20.8	17.5
Plastic index (PI)	11.3	4.2

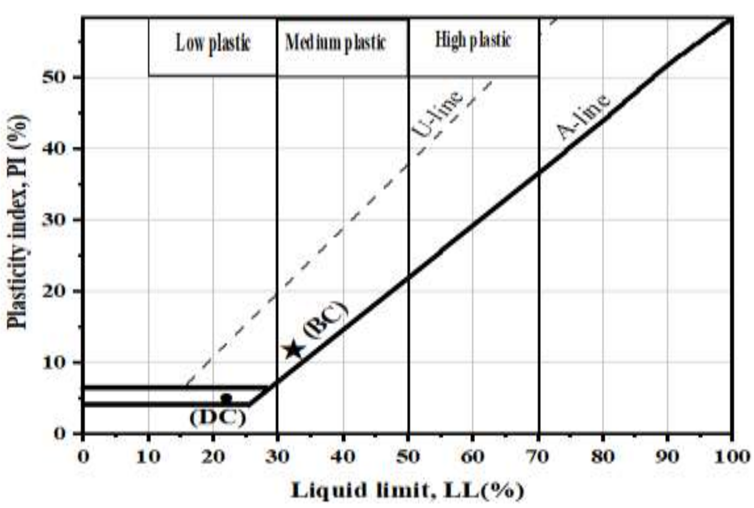


Figure 6 Position of Bombawuha clay (BC) and Dankaka clay (DC) sources on the Holtz and Kovacs plasticity chart.

4.2. Characteristics of Fired Porcelain Insulator

4.2.1. Diffraction Pattern of Fired Porcelain Insulator

X-ray diffraction patterns of different porcelain insulators fired at two different temperatures (1250 °C and 1300°C) and dwelling time (2h and 2.5h) with and without SCBA were shown in Figure 7. The X-ray diffraction pattern confirmed the presence of mullites as the major mineral, followed by quartz in all fired product. Whereas, the hematite crystalline phases are identified only in the XRD patterns of the composition containing SCBA waste (Figure 7d, e, f). The hematite peak might be from iron released during the breakdown of the structures of some SCBA minerals, which is consistent with chemical analysis result of the raw materials (Table 2).

As shown in Figure 7, the mullite peaks and the hematite peaks are nearly remained constant in all compositions, means that SCBA addition did not enhance mullite formation at higher temperature. The observed decrease in the intensity of quartz peaks as the temperature increased in the compositions containing lower proportions of SCBA (Figure 7d), may be due to their partial dissolution in the glassy phase (Gralik et al., 2014). Whereas the diffraction peaks of quartz for the samples containing higher proportions of SCBA (Figure 7e, f), shown increased intensity with increased firing temperature. The high peaks of quartz at increased temperature may indicate the formation of a high amount of free quartz mainly contributed from SCBA in the compositions. This confirms increased the temperature beyond 1250 °C may not be necessary to improve the porcelain insulator quality as it did not enhance/affect mullite formation. In contrast, it might affect the quality by decreasing the dielectric strength at a higher proportion of SCBA. Kausik Dana and Swapan Kumar Das, (2004) reported stable mullite pahase and quartz grains mostly dissolved in the glass at higher temperatures (1300 °C) in a sample containing 15 wt% fly ash. This might facilitate free movement of mobile ions such as Na^{+}, K^{+}, and Al^{3+}; as a result, it may lower the dielectric strength of the porcelain insulators (Belhouchet et al., 2019).

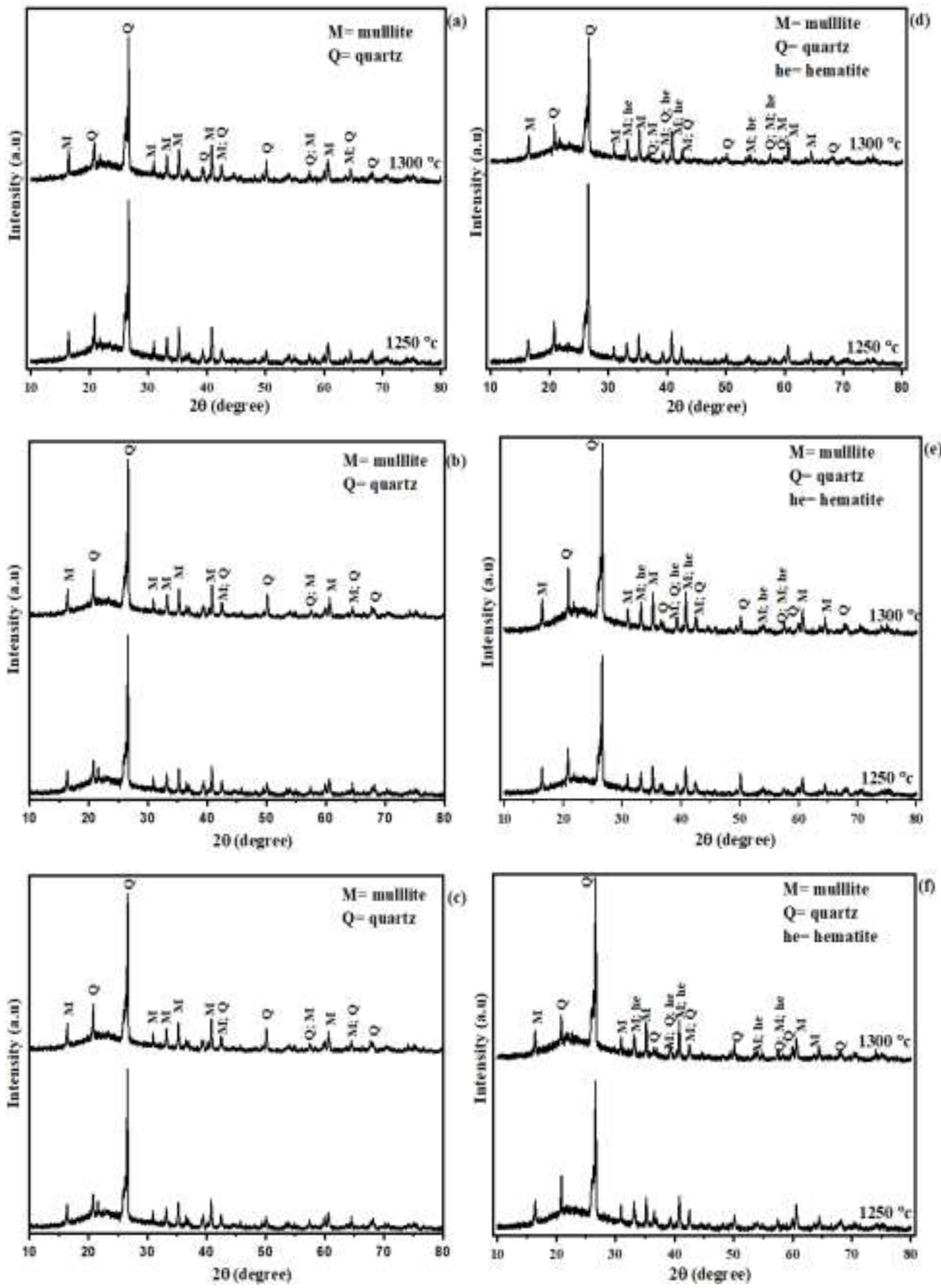


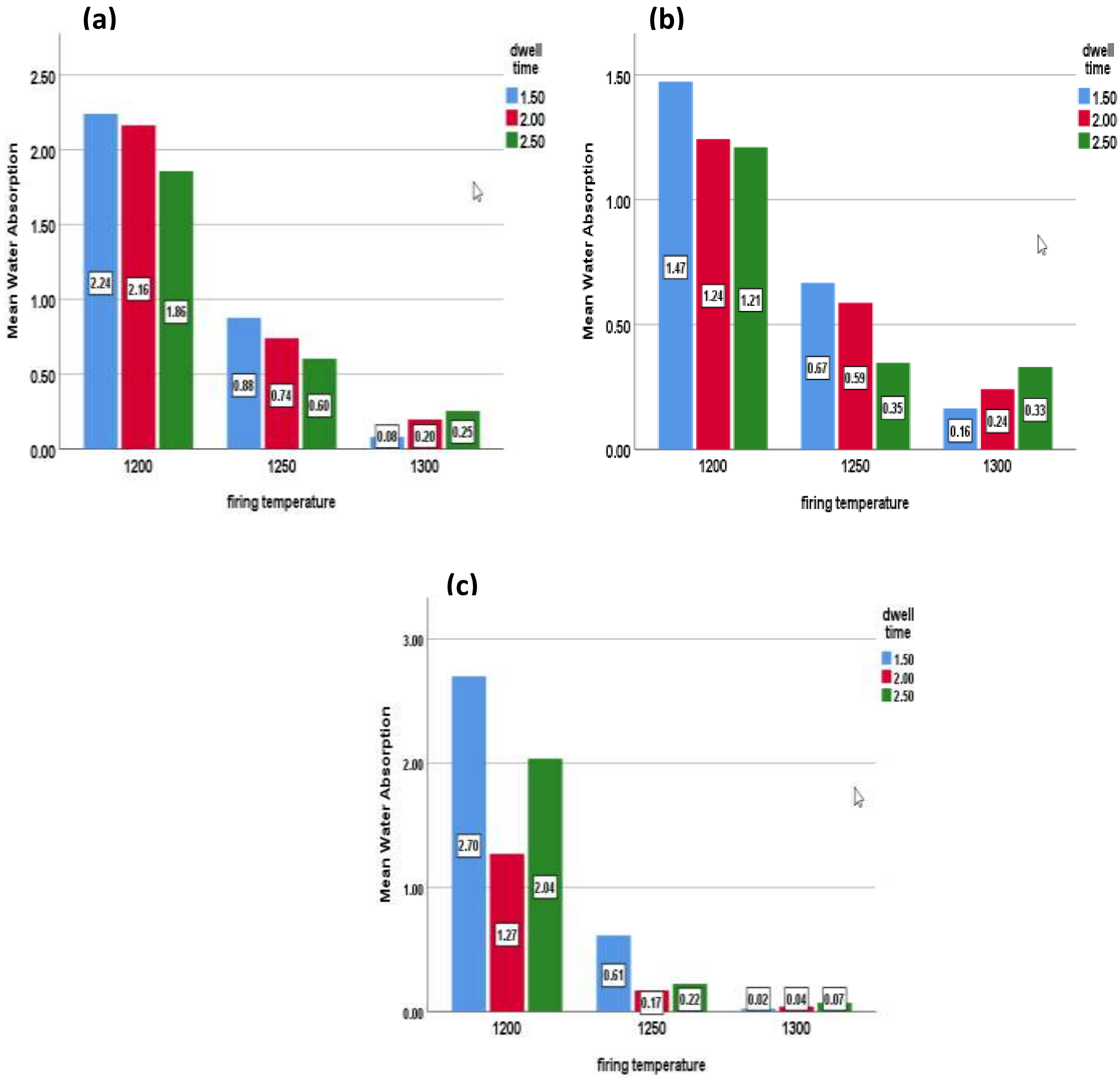
Figure 7 XRD patterns of porcelain insulator fired at two different temperatures (1250 ^{o}C and 1300 ^{o}C) for 2h (Batch$_{1-3}$ without SCBA) and for 2.5h (Batch$_{4-6}$ with SCBA): (a) Batch-1, (b) Batch-2, (c) Batch-3, (d) Batch-4, (e) Batch-5 (SCBA15), and (f) Batch-6 (SCBA20).

4.2.2. Water Absorption, Apparent Porosity, and Bulk Density of porcelain insulators.

4.2.2.1.Water Absorbance

Water absorbance of porcelain insulators at different firing temperatures (1200°C, 1250°C, and 1300°C) and firing times (1.5, 2, and 2.5h) with and without SCBA are shown in Figure 8. The water absorption which indicated the open pore amount and size of the fired body decreased as the firing temperature increased and reached a minimum at a temperature of 1300 ^{o}C for batches without SCBA waste (Fig. 8a, b, and c). Similar trend of water absorbance was also observed in a batch containing smaller proportion of SCBA (Fig. 8d). Whereas firing a porcelain insulators containing higher proportions of SCBA in their composition at a temperature beyond 1250°C led to an increase in the values of water absorption with firing time and reached maximum at firing temperature of 1300 ^{o}C and firing time of 2.5h (Fig 8e, f). It is also observed that percent water absorbance decreased in the order Batch-3<Batch-2< Batch-1 at optimized firing temperature of 1250 °C and firing time of 2h. This is conceded with the level of silica in the batch compositions, in which the higher silica level in the composition is accompanied by lower percentages of water absorbance.

Comparison among the percent water absorption of porcelain fired bodies containing a different proportion of SCBA indicated the lowest water absorption value was recorded in the sample body containing 10 w% bagasse ash at a relatively lower firing temperature (1250 ^{o}C) (Fig 8d). Moreover, at this optimum temperature (1250 ^{o}C) the lower water absorption percentage was obtained in sample body containing 10 w% bagasse ash compared to the batch which contain relatively lower silica content (Batch 1) achieved the minimum water absorption /maximum densification at 1300 ^{o}C (Fig 8a, d). This may be due to the enhanced level of a fluxing agent by partial substitution of the feldspar using SCBA, which required lesser firing temperature to obtain a sufficient glassy phase to fill the gaps or voids in the microstructure (Kimambo, 2014). The water absorption increases beyond a firing temperature of 1250 °C for the fired bodies containing higher proportion of SCBA specifically, Batch-5 and Batch-6 is caused by bloating. Bloating occurs due to the oxygen released from the transformation of Fe_2O_3 to Fe_3O_4, and the expansion of the air enclosed in the pores. (Taszic, 1993).


(a)
Mean Water Absorption
0.00
0.50
1.00
1.50
2.00
2.50
dwell time
1.50
2.00
2.50
2.24
2.16
1.86
0.88
0.74
0.60
0.08
0.20
0.25
1200
1250
1300
firing temperature
(b)
Mean Water Absorption
0.00
0.50
1.00
1.50
dwell time
1.50
2.00
2.50
1.47
1.24
1.21
0.67
0.59
0.35
0.16
0.24
0.33
1200
1250
1300
firing temperature
(c)
Mean Water Absorption
0.00
1.00
2.00
3.00
dwell time
1.50
2.00
2.50
2.70
1.27
2.04
0.61
0.17
0.22
0.02
0.04
0.07
1200
1250
1300
firing temperature

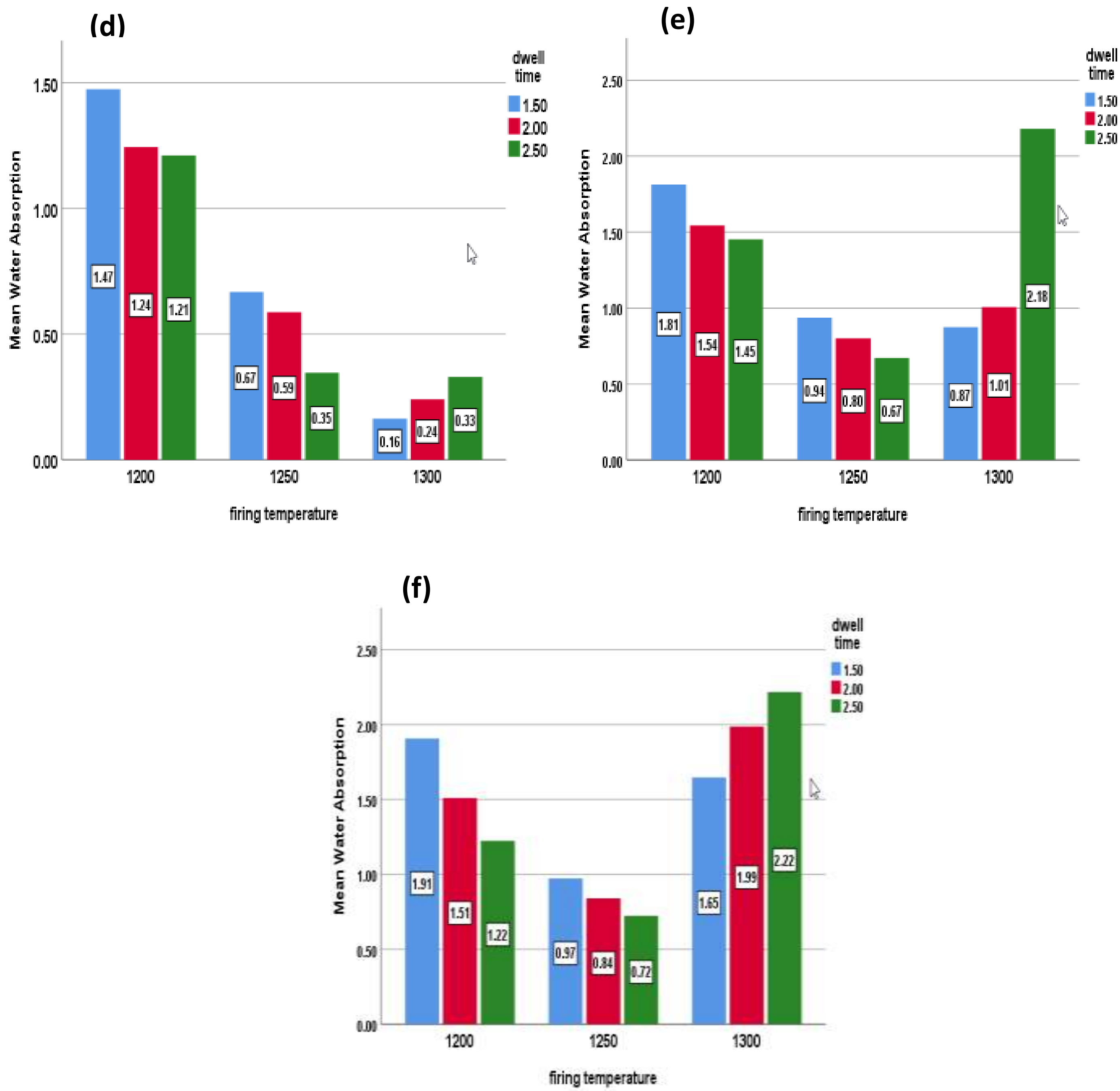


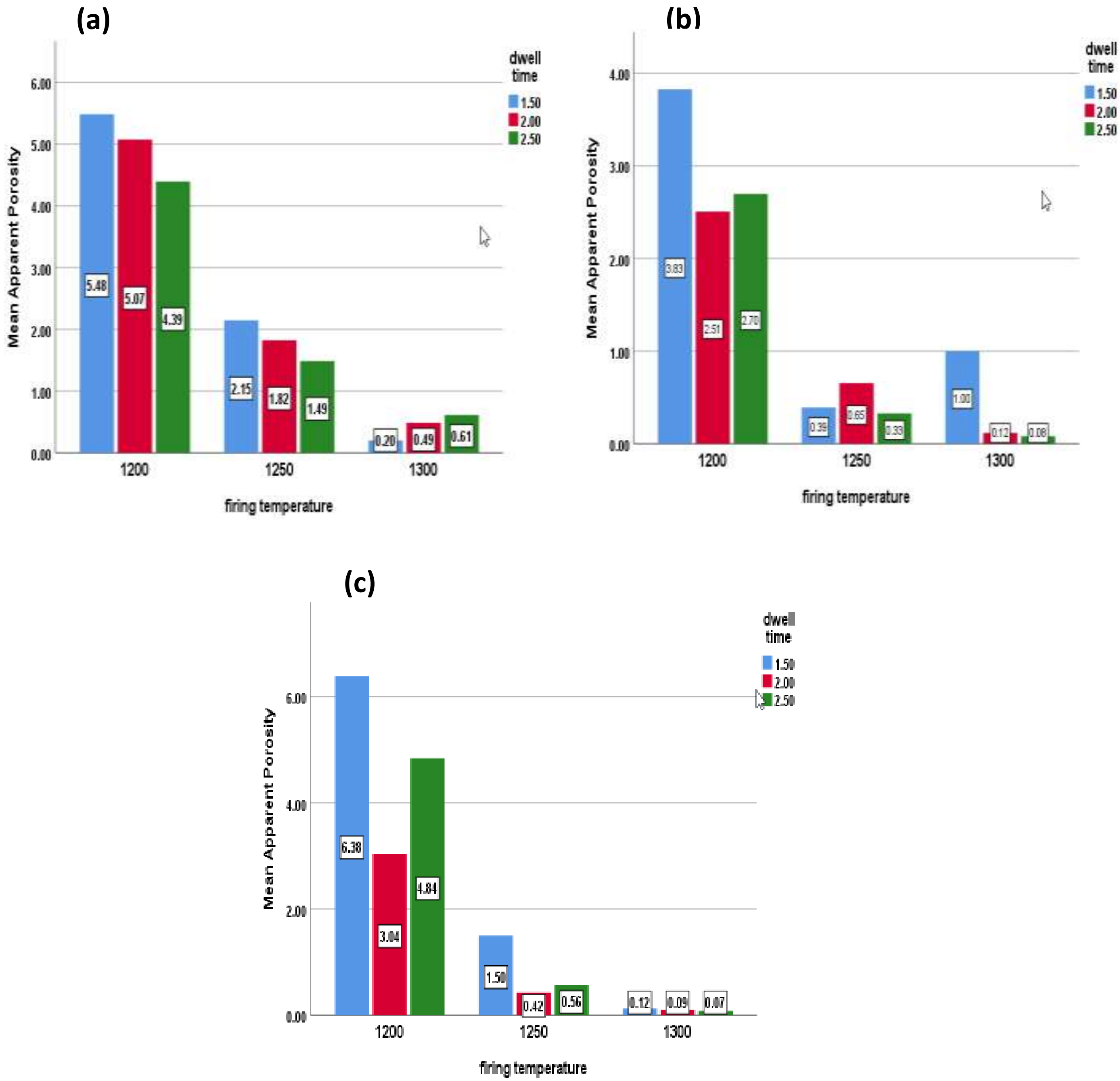
Figure 8 Percent Water Absorption of porcelain insulators at different firing temperatures (1200°C, 1250°C, and 1300°C) and firing times (1.5, 2, and 2.5h) without SCBA (a, b, c) and with SCBA (d,e,f)

In general, the batch composition containing relatively higher proportion of silica (Batch 2 and Batch 3) or enhanced level of fluxing agent (Batch 4) fired at firing temperature of 1250 °C and beyond and firing time of for 2.0h and/or 2.5h, generally has the lowest water absorption value that fulfills the standard requirement for porcelain electrical insulators, i.e., water absorption <0.5% (Ngayakamo & Eugene Park, 2019). The results also showed that the SCBA waste additions at higher proportions tend to decrease the quality of porcelain electrical insulators by increasing percentage water absorption. This signifies that high amounts of SCBA waste should be avoided.

4.2.2.2.Apparent porosity

Generally, the porcelain insulator needs to be fired at the firing time and temperature, giving the minimum value of the apparent porosity. This is because the optimum vitrification is achieved when the apparent porosity reaches a minimum value which is usually zero or just close to it (Kimambo et al., 2014). Figure 9 showed the result of the apparent porosity of the porcelain insulator as a function of different firing temperatures (1200°C, 1250°C, and 1300°C) at a firing time of 1.5h, 2h, and 2.5h. Similar to water absorbance, the apparent porosity decreased as the firing temperature increased and more or less reached a minimum at a temperature of 1300^{o}C for batches without SCBA waste or in a batch containing smaller proportion of SCBA (Fig. 9a, b, c and d). Batch-3 was given the minimum value of the apparent porosity (0.42%) at optimum firing temperature of 1250°C and time of 2.0h. Whereas firing a porcelain insulators containing higher proportions of SCBA in their composition at a temperature beyond 1250°C led to an increase in the values of apparent porosity gradually with firing time and reached maximum at firing temperature of 1300 ^{o}C and firing time of 2.5h (Fig 9e, f).

In general, the apparent porosity is expected to decrease with an increase in firing temperature. This is because high temperature results in enough liquid phases to progressively fill up the open porosity (Kimambo et al., 2014). This behavior is also due to the reduced porosity of the sample, as explained above, which leads to an increase in the amount of matter in the sample per unit volume (Fatai Olufemi, 2015). This phenomenon is observed in a porcelain insulator composition without SCBA (Batch$_{1\text{-}3}$) and composition containing only 10w% of SCBA (Batch-4).


(a)
dwell time
1.50
2.00
2.50
Mean Apparent Porosity
0.00
1.00
2.00
3.00
4.00
5.00
6.00
5.48
5.07
4.39
2.15
1.82
1.49
0.20
0.49
0.61
1200
1250
1300
firing temperature
(b)
dwell time
1.50
2.00
2.50
Mean Apparent Porosity
0.00
1.00
2.00
3.00
4.00
3.83
2.51
2.70
0.39
0.65
0.33
1.00
0.12
0.08
1200
1250
1300
firing temperature
(c)
dwell time
1.50
2.00
2.50
Mean Apparent Porosity
0.00
2.00
4.00
6.00
6.38
3.04
4.84
1.50
0.42
0.56
0.12
0.09
0.07
1200
1250
1300
firing temperature

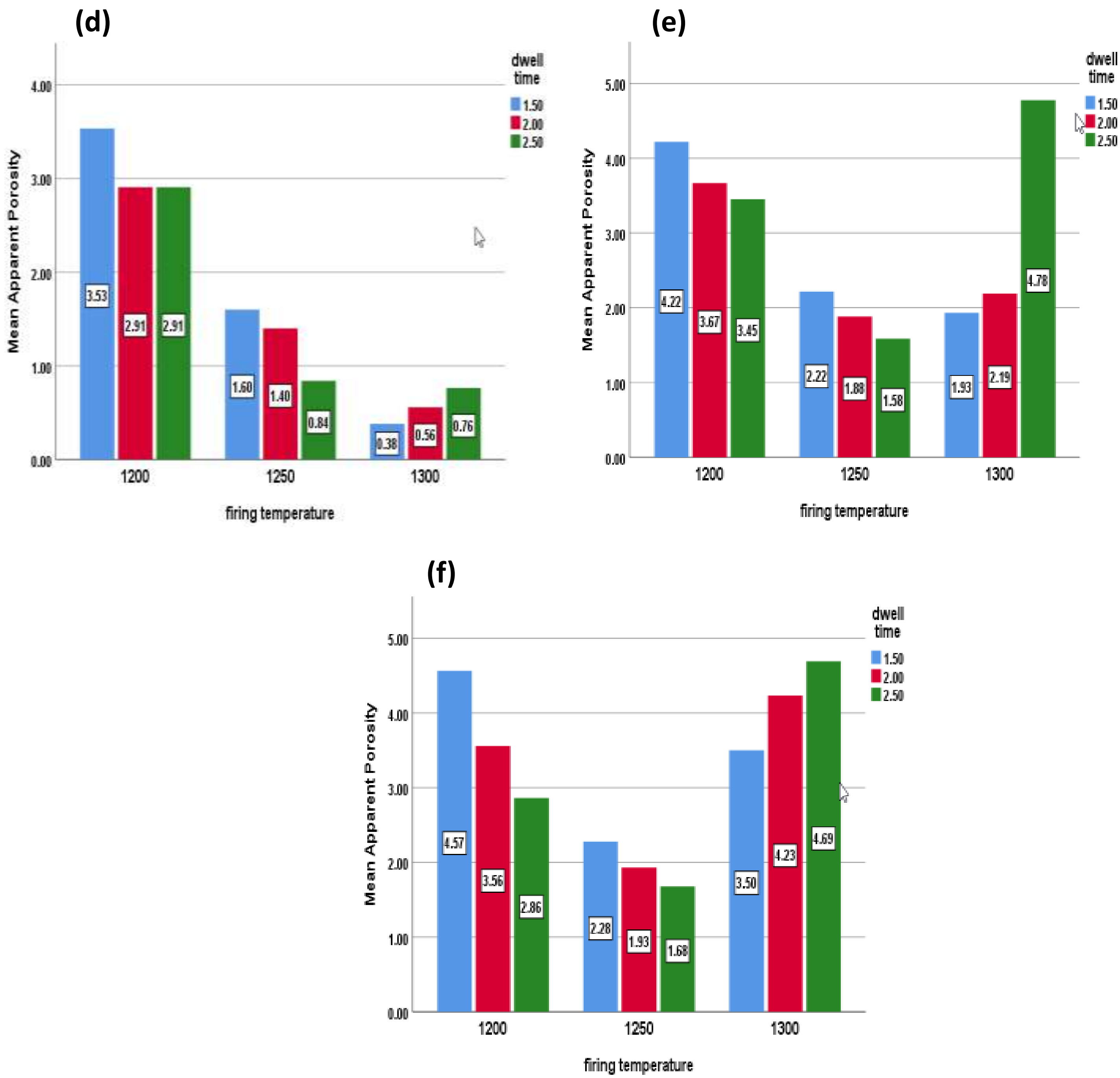
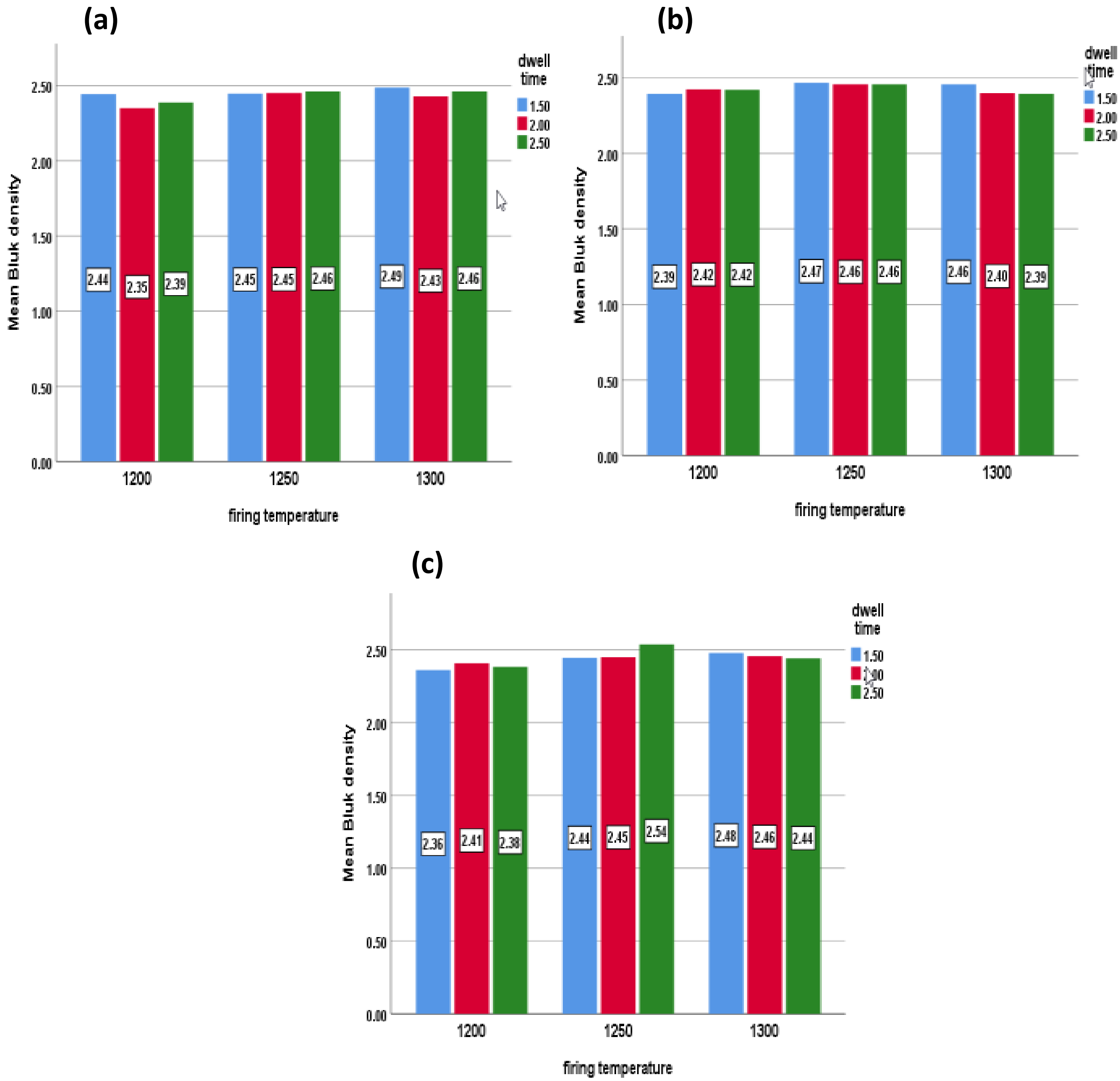


Figure 9 Percent Apparent porosity porcelain insulators at different firing temperatures (1200°C, 1250°C, and 1300°C) and firing times (1.5, 2, and 2.5h) without (a, b, c) and with SCBA (d,e,f)

However, this was not the case for some of the porcelain insulator made from higher proportions of SCBA (Batch-5) and SCBA (Batch-6). The increase in apparent porosity at higher firing temperature in these two batches thought to be caused by bloating, which takes place as a result of the oxygen released from the reaction of Fe_2O_3 to Fe_3O_4, the expansion of the air enclosed in the pores, and dehydration of OH from the crystal structure of kaolinite started at 500 °C but was trapped in the closed pores (Kitouni & Harabi, 2011). Another possibility to increase apparent porosity may be due to the appearance of a new phase (liquid phase) resulting from fluxing oxide (such as; K_2O and Na_2O) in the raw and waste material used. The appearance of the liquid phase at a higher temperature (1300 °C) allows an easy release of gas trapped in the closed pores, which leads to the formation of new open porosity (Belhouchet et al., 2019). The result confirmed the apparent porosity obtained was depended on the amount of SCBA waste and the relative proportion of silica added to the porcelain insulator.

4.2.2.3.Bulk Density

The variation in Bulk density (BD) as a function of temperature and dwelling time with and without SCBA waste was shown in Fig. 10. There was no significant change in BD of the porcelain bodies sintered at 1200 ^{o}C and 1250 ^{o}C and all test samples are showing a higher degree of densification. Whereas at the firing temperature 1300 ^{o}C, BD was lower for the samples containing higher proportions of SCBA waste (Fig 10e, f). These results for bulk density are partly consistent with those for water absorption and apparent porosity. In general, the batch composition Batch-2, Batch-3 fired at optimum temperature of 1250 °C for 2h, and Batch 4 (50% kaolin, 30% mixed feldspar, 10% SCBA, and 10% quartz) fired at 1250 °C with firing time 2.5h had good physical properties value that fulfills the standard requirement for porcelain electrical insulators, i.e., water absorption <0.5%, lower apparent porosity and bulk density (>1.71 g/cm^3) (Ngayakamo & Park, 2018). Additionally, these batch compositions fulfill the requirement for water absorbance, apparent porosity and bulk density (even with a better physical properties value) at firing temperature 1300 °C when compared to the value get in firing temperature 1250 °C. But from an economic perspective, it is better to use a lower firing temperature to save energy costs and production costs.


(a)
Mean Bluk density
2.50
2.00
1.50
1.00
0.50
0.00
2.44
2.35
2.39
2.45
2.45
2.46
2.49
2.43
2.46
1200
1250
1300
firing temperature
dwell time
1.50
2.00
2.50
(b)
Mean Bluk density
2.50
2.00
1.50
1.00
0.50
0.00
2.39
2.42
2.42
2.47
2.46
2.46
2.46
2.40
2.39
1200
1250
1300
firing temperature
dwell time
1.50
2.00
2.50
(c)
Mean Bluk density
2.50
2.00
1.50
1.00
0.50
0.00
2.36
2.41
2.38
2.44
2.45
2.54
2.48
2.46
2.44
1200
1250
1300
firing temperature
dwell time
1.50
2.00
2.50

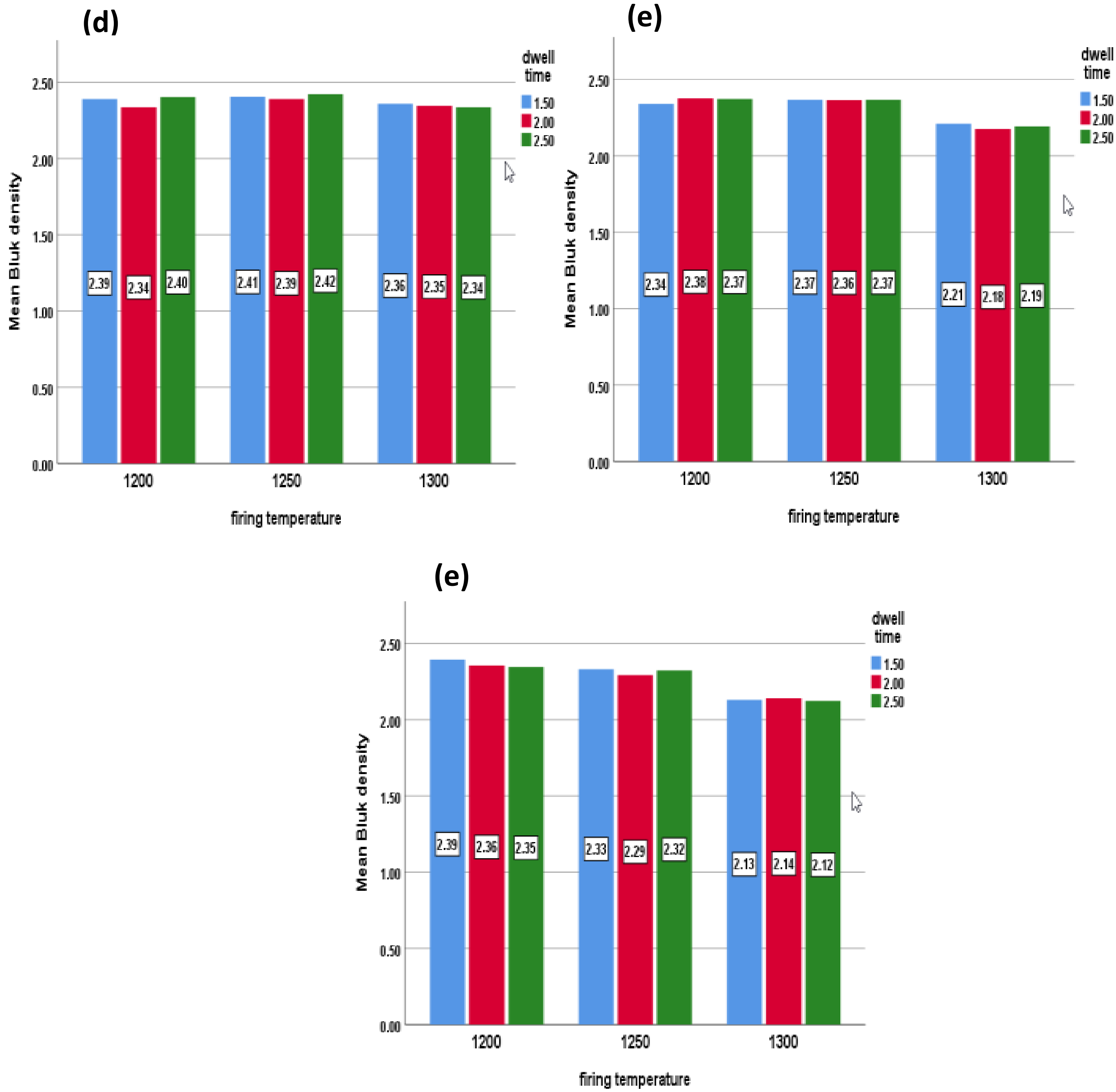


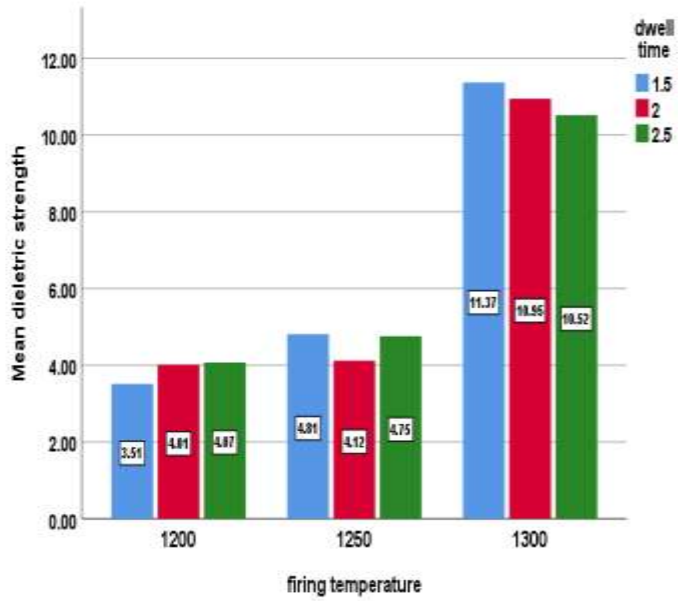
Figure 10 Bulk density (g/cm^3) of porcelain insulators at different firing temperatures (1200°C, 1250°C, and 1300°C) and firing times (1.5, 2, and 2.5h) without (a, b, c) and with SCBA (d,e,f)

4.2.3. Dielectric Strength of porcelain insulators

The values of the dielectric strength of the porcelain insulator sample as a function of firing temperature and firing time are presented in Figure 11. Dielectric strength is an important ceramic insulator property and it is found to be increased as the firing temperature increased and reached a maximum at a temperature of 1300 ^oC for batches without SCBA waste (Fig. 11a, b, and c). Similar trend of dielectric strength was also observed in a batch containing smaller proportion of SCBA (Fig. 11d). The dielectric strength values obtained for the batches without SCBA at optimized firing temperature and dwelling time (1250 ºC, 2.0h) are ranging from 6.24 kV/mm to 7.93 kV/mm (Fig 11b, c), which is within the specified range (6.1–13 kV/mm) porcelain insulators (Olupot et al., 2010). The values obtained at this optimized condition are the highest for Batch 3 (8.22 kV/mm) (Figure 11c). Whereas, the dielectric strength values obtained at a firing temperature of 1300 ^oC for Batch-1 are the highest of all samples (Figure 11a). Among the batch composition containing SCBA, the dielectric strength value of Batch 4 (6.14 kV/mm) at the firing temperature 1250 ^oC and firing time 2.5h fulfilled the specified range (6.1–13 kV/mm) for porcelain insulators (Olupot et al., 2010). Whereas the dielectric strength value for a porcelain insulators containing higher proportions of SCBA in their body composition (Batch-5 and batch-6) shows no significant change and give the values below the required standards at all temperature range and dwelling time (Fig.11e, f). The observed result is consistent with the physical test result such as water absorbance and apparent porosity.

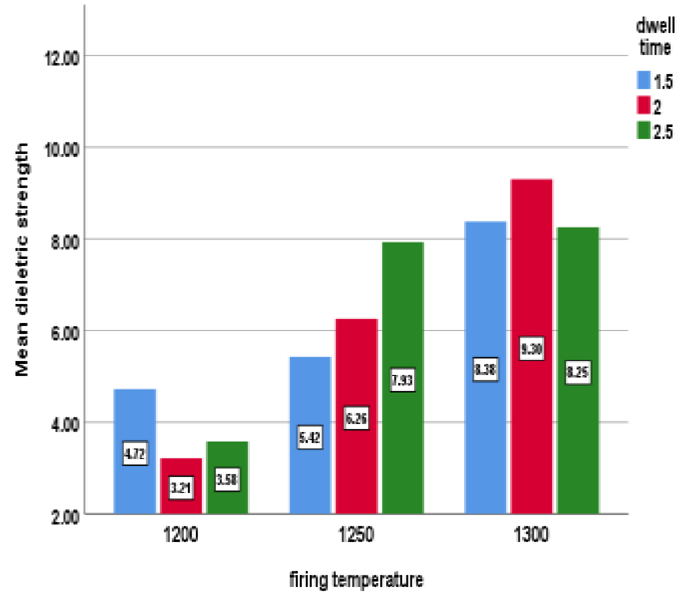
The dielectric strength values of all the Batches that fulfilled the requirement is associated with the glassy phase formation as it has a dominant influence on the dielectric properties of fired porcelain insulators (Islam et al., 2004; Kitouni, 2014). The glass phase formation at a relatively lesser firing temperature in Batch-4 unlike that of Batch-1 containing the same proportion of clay and sand content is attributed to an enhanced level of a fluxing agent with the addition of SCBA to partially substitute feldspar. On the other side, the observed low dielectric strength of porcelain insulator samples of batch-5 and batch-6 at all firing temperatures might be due to the high iron oxide content in the batch samples containing higher proportions of SCBA may cause bloating, which affects the porcelain insulators' dielectric strength by reducing densification and increasing the apparent porosity, as depicted in Figure 10. Means that the dielectric strength of porcelain insulator may not always increases with bagasse ash addition (Hariharan et al., 2013).

(a)



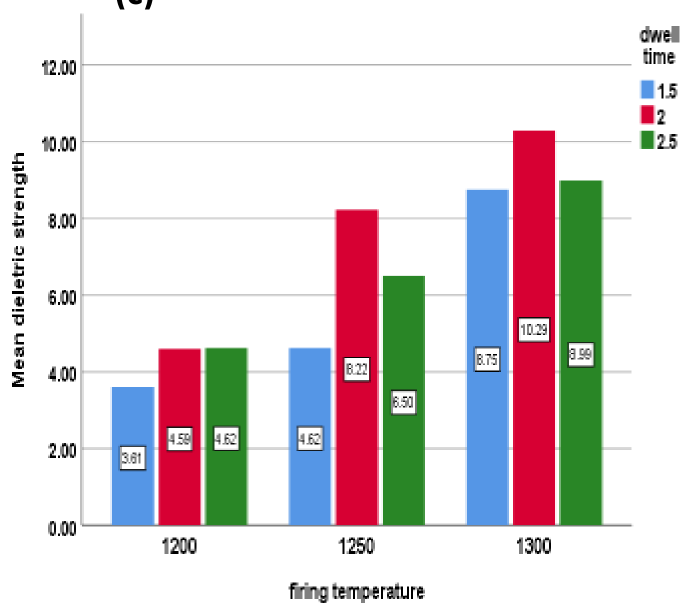
Mean dieletric strength
12.00
10.00
8.00
6.00
4.00
2.00
0.00
3.51
4.01
4.07
4.81
4.12
4.75
11.37
10.95
10.52
1200
1250
1300
firing temperature
dwell time
1.5
2
2.5

(b)



Mean dieletric strength
12.00
10.00
8.00
6.00
4.00
2.00
4.72
3.21
3.58
5.42
6.26
7.93
8.38
9.30
8.25
1200
1250
1300
firing temperature
dwell time
1.5
2
2.5

(c)



Mean dieletric strength
12.00
10.00
8.00
6.00
4.00
2.00
0.00
3.61
4.59
4.62
4.62
8.22
6.50
8.75
10.29
8.99
1200
1250
1300
firing temperature
dwell time
1.5
2
2.5

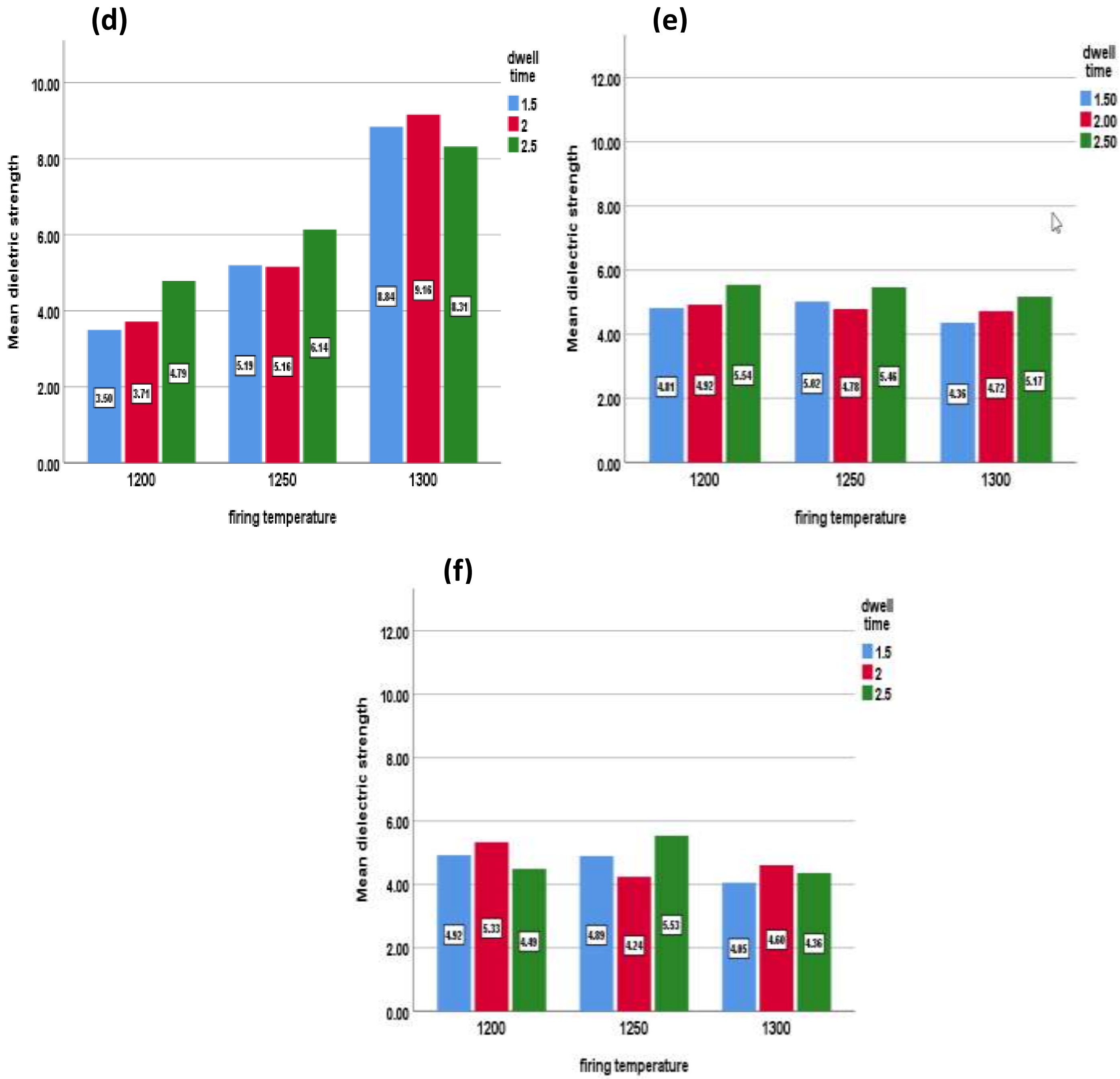


Figure 11 Dielectric strength (kV/mm) of porcelain insulators at different firing temperatures (1200°C, 1250°C, and 1300°C) and firing times (1.5, 2, and 2.5h) without (a, b, c) and with SCBA (d, e, f) in the composition.

The porcelain body is composed of phases such as mullite, quartz, and glass. Its electrical properties are dependent on each of these phases (Islam et al., 2004). However, the quartz phase plays a significant role in developing the ultimate properties of the product and appropriate microstructure; only a tiny portion of it gets dissolved in the melt during firing while a considerable amount remains unreacted (Mukhopadhyay et al., 2006). In the unreacted quartz phase during the cooling, there is a significant α-β transformation of quartz at 573 ºC resulting in a 2% decrease in the volume of quartz particles. The resultant volume change may lead to the initiation of the non-coherent interface in structure, microcrack formation, and lowering of electrical properties (De Noni et al., 2009; Moyo & Park, 2014; Sedghi et al., 2014). This may justify the observed result in batch-1 at lower temperatures (1200 and 1250 ^{o}C). On the other hand the observed higher dielectric strength in batch-2 and batch-3 can be justified by the increased silica content in their mixture dissolved in the liquid glassy phase that fills up the pores at the specified temperature, resulted in the increased dielectric strength of the porcelain insulator (Cajetan et al., 2015).

4.2.4. Flexural Strength of porcelain insulators

Figure 12 depicts the flexural strength of selected porcelain insulators which possess relatively better physical and electrical properties. The flexural strength of porcelain insulators for batches- 1 to 4 increased with increasing firing temperature. This is associated with the amount of liquid or glassy phase that cement all the surrounding constituents together and decrease pore structure (Darweesh, 2019). The observed highest flexural strength values for Batch-1 among the batch compositions without SCBA can be explained by the presence of relatively lower level of quartz, as flexural strength of the porcelain insulators increased as the content of quartz decreased in the batch composition and as the amount of mullite phase increased (Teixeira et al., 2008; A.E. Souza et al., 2011). However, for batch composition, with SCBA of 15 w% and SCBA of 20 w%, the flexural strength decreased with increasing firing temperature (Figure 12). The result indicated a high amount of SCBA content in the porcelain insulator is undesirable, especially with higher firing temperatures, as it is led to surface bloating in the transformation of hematite, which causes the increase in porosity and decrease in bulk density and subsequently flexural strength of the porcelain insulators (Darweesh, 2019; Kimambo, 2014). Hence, incorporation up to 10 w% of bagasse ash and fired at 1250 °C is optimum conditions to get a high strength of 42.53 MPa as required by ISO 13006 standard requirement (>35 MPa) (Ngayakamo & Eugene Park, 2019). However, all the selected porcelain insulator samples fired at 1250 °C for 2.0 h and 2.5 h fulfilled the flexural strength standard requirement for porcelain insulators (>35 Mpa) (Ngayakamo & Park, 2019).

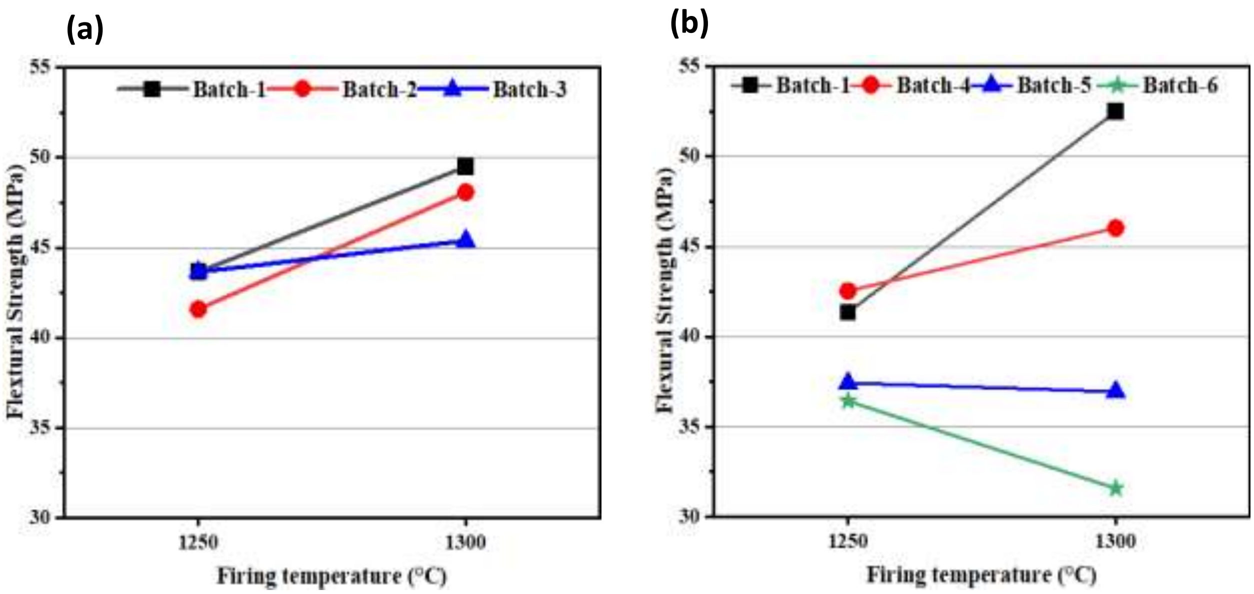
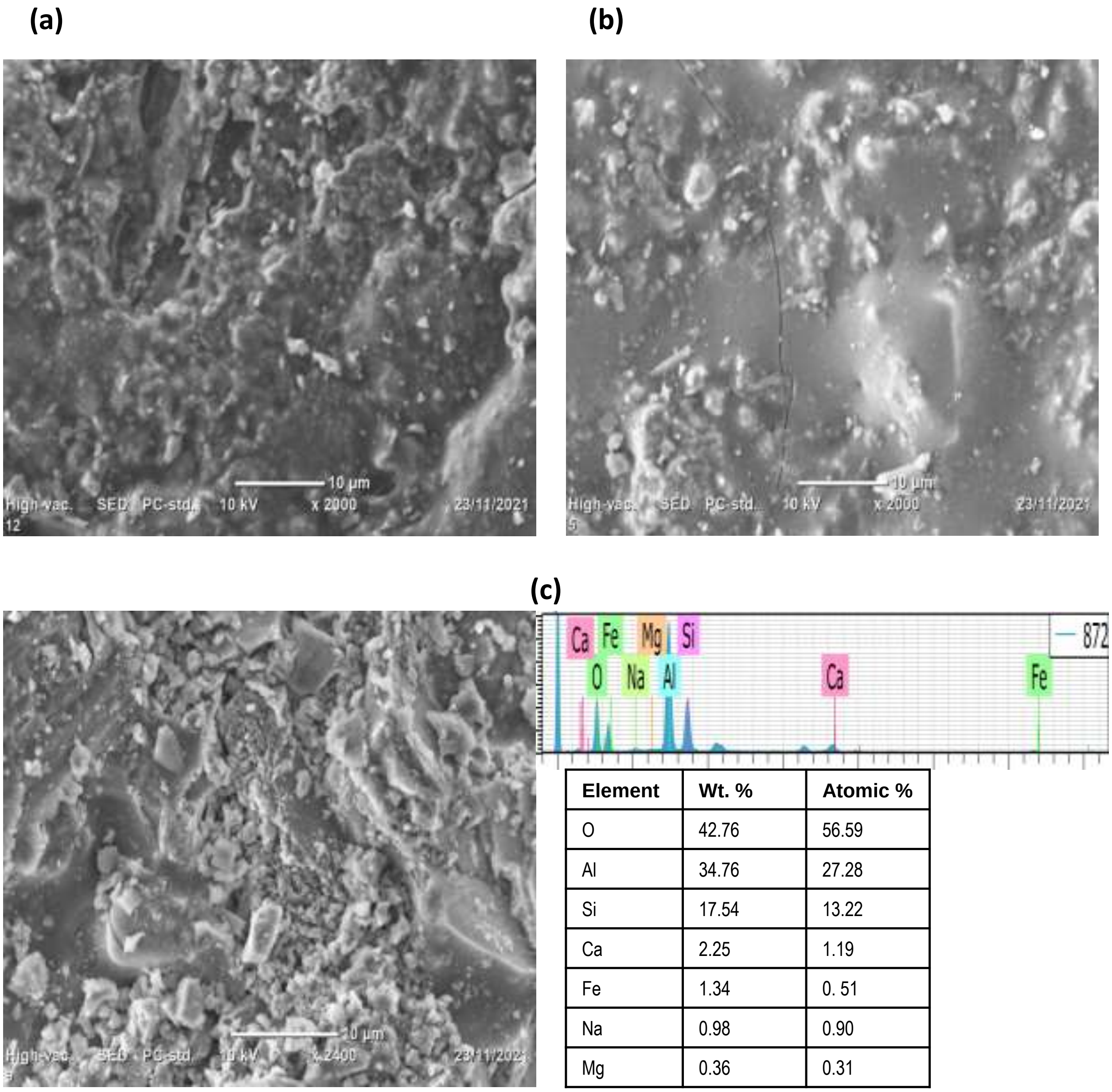


Figure 12 The flexural Strength/modulus of rupture (MOR) as a function of firing temperature (1250 ^{O}C and 1300 ^{O}C) for selected porcelain insulators: a) Batch$_{1-3}$ firing time of 2.0 h, b) Batch- 1, 4, 5, and 6 for firing time of 2.5 h.

4.2.5. The Scanning Electron Microscope (SEM) micrographs of porcelain insulator

The Scanning Electron Microscope (SEM) micrographs of porcelain insulator of batch$_{1-3}$ and the corresponding energy dispersive spectrometry (EDS) for Batch-3 (the batch which possess relatively better physical, electrical and mechanical properties) at optimized firing temperature of 1250 °C for 2.0 h are shown in figure-13a, b and c, respectively. The micrograph of batch-1 shows the presences of larger pores of different sizes and irregular morphology (Figure 13a). In batch-2 there was a decrease in porosity, but the observed crack is may be due to a larger difference in the thermal expansion coefficient of quartz particles and the glassy matrix during cooling (Das et al., 2013; Schettino et al., 2016). Batch-3 exhibited no observed porosity, in which a higher degree of glassy phase forming a smooth surface, and dense microstructure (Figure 13b). This confirms the observed low water absorbance percentage, real dielectric strength, and high flexural Strength in bach-3 than batch-2 and Batch-1, at the same firing temperature and firing time (Fig. 8-12). Energy dispersive spectrometry (EDS) mapping of batch-3 clearly demonstrates the presence of all the targeted elements, which are distributed homogeneously throughout the microstructure (Figure 13c).

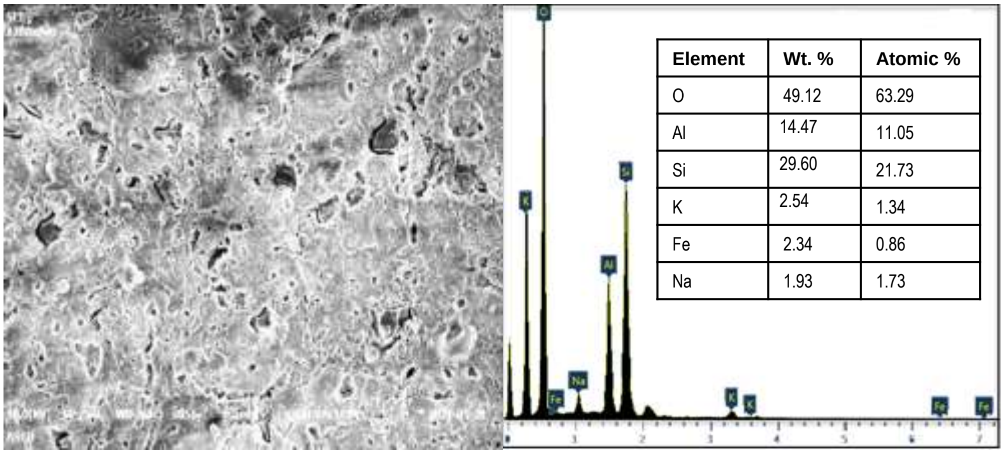


Element	Wt. %	Atomic %
O	42.76	56.59
Al	34.76	27.28
Si	17.54	13.22
Ca	2.25	1.19
Fe	1.34	0. 51
Na	0.98	0.90
Mg	0.36	0.31

Figure 13 Scanning Electron Microscopy (SEM) image with corresponding energy dispersive spectrometry (EDS) of fracture surfaces of porcelain insulators fired at 1250 °C for 2.0 h: (a) Batch-1, (b) Batch-2, and (c) Batch 3

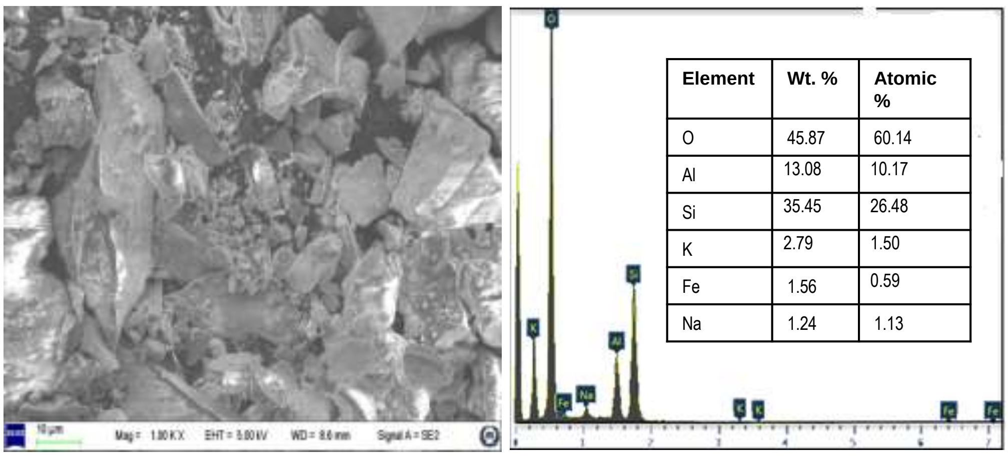
The Scanning Electron Microscope (SEM) micrographs of porcelain insulator of batch-1(the control), Batch-4 (which possess relatively better physical, electrical and mechanical properties) and Batch-6 (which contains higher proportion of SCBA and was not qualify the standards) at optimized firing temperature of 1250 °C for 2.5 h are shown in Figure-14a, b and c, respectively. The micrograph of Batch-1 and batch-6 shows a typical under firing ceramic microstructure with interconnected pores of different sizes and irregular morphology (Figure 14a, c) (Schettino et al., 2016). The porosity looks spherical, rounded, elliptic, open elongated, and uniformly distributed in the matrix. The samples with lower bagasse ash (Batch-4) exhibited no observed porosity; this is associated to the presence of fluxing agent which favors the formation of a vitreous phase forming a smooth surface, and dense microstructure (Figure 14b). This confirms the observed low water absorption percentage (0.33%), real dielectric strength (6.59 kV/mm) and high flexural Strength (42.53 MPa), in Batch-4 than the other two batches at the same firing temperature and firing time (Fig.8-13). The observed porosity in batch-1 may be due to a small liquid phase derived from the lower fluxing agent of the feldspar and un-dissolved quartz as a result of partial sintering. William Ochen et al., (2019) also reported the optimum sintering temperature of 1300°C in a lower flux oxide to form a vitreous phase that blocks the open pores in the microstructure. This negatively affects physico-mechanical and dielectric strength because an ample space around grains would be a source of crack propagation (Chibério da Silva et al., 2017; Salleh et al., 2017). These cracks are created due to a larger difference in the thermal expansion coefficient of quartz particles and the glassy matrix during cooling (Das et al., 2013; Schettino et al., 2016). Whereas the observed porosity for batch-6 likely associated to high content of iron oxide that led to surface bloating in the transformation of hematite and from carbonate decomposition with the evolution of CO_2. The corresponding energy dispersive spectrometry (EDS) mapping clearly demonstrates the presence of the highest content of iron and calcium in batch-6 (3.48 w%, 3.88 w%) compared the other batches, and the presence of all the targeted elements, which are distributed homogeneously throughout the microstructure (Figure 14). Moreover, with a molar ratio Al_2O_3/SiO_2 (>1.5) confirms the formation of mullite phase as it is always accompanied by increasing the total content of Al_2O_3 (Andreev and Zakharov, 2009).

(a)



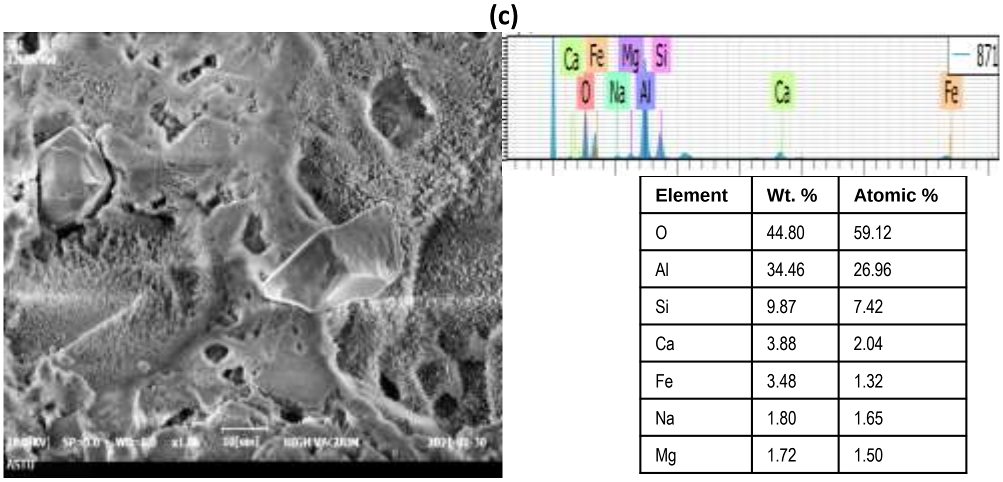
Element	Wt. %	Atomic %
O	49.12	63.29
Al	14.47	11.05
Si	29.60	21.73
K	2.54	1.34
Fe	2.34	0.86
Na	1.93	1.73

(b)



Element	Wt. %	Atomic %
O	45.87	60.14
Al	13.08	10.17
Si	35.45	26.48
K	2.79	1.50
Fe	1.56	0.59
Na	1.24	1.13

(c)



Element	Wt. %	Atomic %
O	44.80	59.12
Al	34.46	26.96
Si	9.87	7.42
Ca	3.88	2.04
Fe	3.48	1.32
Na	1.80	1.65
Mg	1.72	1.50

Figure 14 Scanning Electron Microscopy (SEM) image with corresponding energy dispersive spectrometry (EDS) of fracture surfaces of porcelain insulators fired at 1250 °C for 2.5 h: (a) Batch-1, (b) Batch-4, and (c) Batch-6

4.2.6. X-ray photoelectron spectroscopy (XPS)

The XPS analysis was carried out to provide additional details on the surface properties of procaine insulator samples. Figure 15a showed the wide-scan survey XPS profile of sample porcelain insulator bodies. Major peaks appear at 529.08 eV for O(1s), 75.20ev for Al2p, 103.08 for Si2p, 497.08eV for Na1s, 294.08eV for K2p, 351.06 eV for Ca2p, 711.08 eV for Fe(2p), and 284.8 eV for C1s (the reference binding energies). And the profile displayed core level bands of Al2p, Si2p, O1s, Na1s, K2p, and Fe2p (Fig. 15_{b-h}), which was consistent with the results of the chemical composition analysis and EDX analysis result.

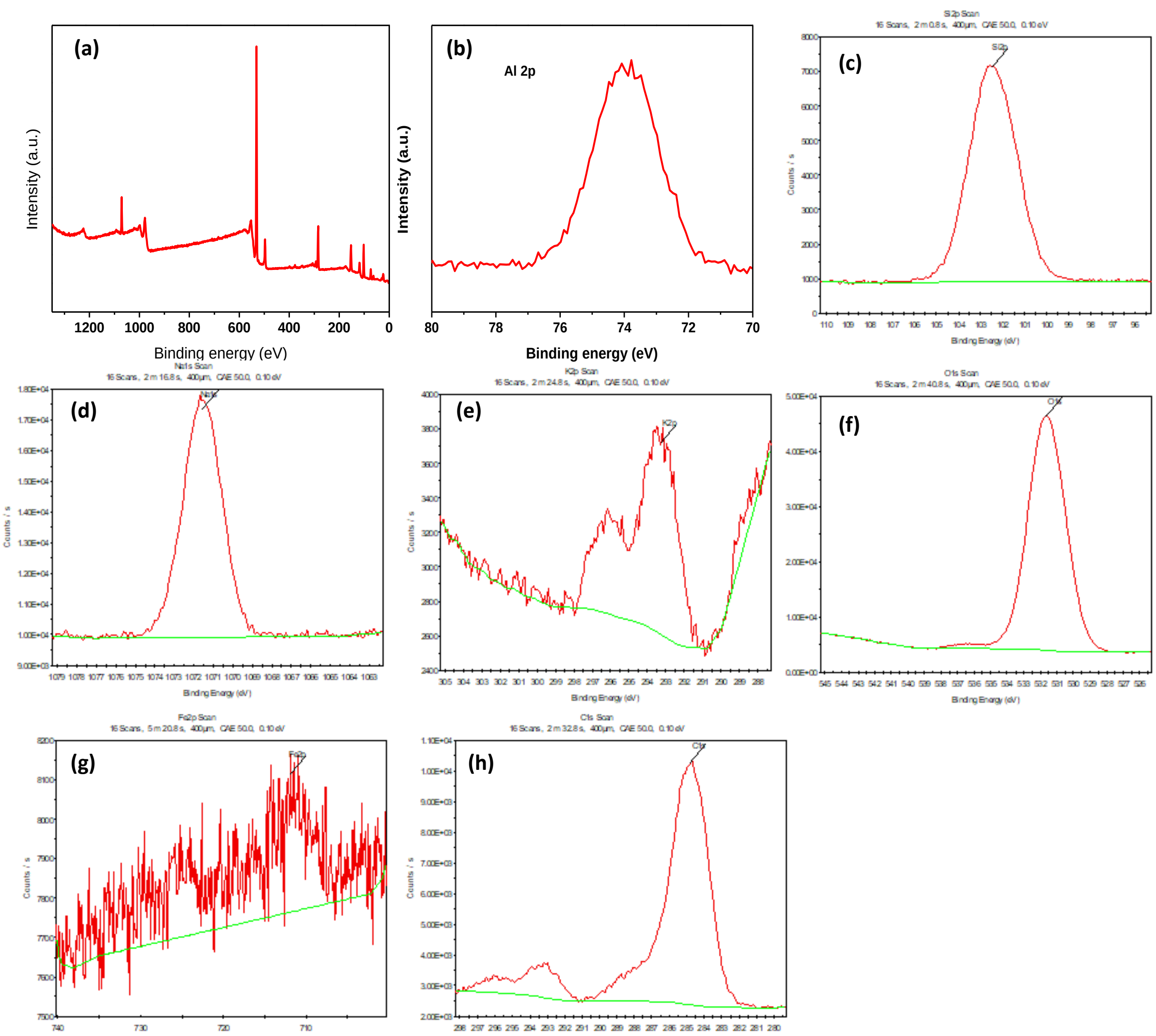


Figure 15 XPS high-resolution spectra of porcelain insulator sample: (a) full spectra, (b) Al2p, (c) Si2p, (d), Na1s and (e) K2p, (f) O1s, (g) Fe 2p of batch-1 and (h) C1s of the standard.

5. Conclusions and recommendations

The viability and prospects of future existence of a manufacturing industry depend on the development or use of locally available raw materials and on the uses of alternative materials such as wasted resources from different sectors/industry to partially substitute the raw materials demand. This would also promote appropriate utilization of the waste instead of discarding it to the environment, which causes adverse effects on human beings and environments. To this end, this study investigates the possibility of developing quality porcelain electrical insulators from locally available raw materials and by using sugarcane bagasse ash to partially substitute the raw materials which is scarce and costly.

The different analysis result of raw materials, sugarcane waste ashes and porcelain electrical insulators samples confirmed that:

Bombawuha clay (BC) deposits have suitable chemical composition to be used as raw materials for porcelain electrical insulator production. Specifically, the ratio of Al_2O_3/SiO_2 in BC is close to pure kaolin and in a remarkable amount for mullite phase formation during sintering the porcelain body. The purity of Chancho sand/quartz (CS) does not meet required specification for quartz to be considered suitable for the production of porcelain body. Hence, the study materials CS can be incorporated in the production of porcelain insulator by using the optimized amount and reducing the grain size to the required level, as the size of quartz primarily determines its dissolution rate and subsequent use as filler materials in porcelain composition and increases the strength in a porcelain body.

The feldspars (AF and WF) and the proposed alternatives (sugarcane waste ashes) have comparable chemical compositions and contained SiO_2/silica as major oxides followed by Al_2O_3. This indicated sugarcane waste ashes (specifically SCBA) can be used as alternative materials for the partial substitution of feldspar (up to 10 w %) for the production of porcelain electrical insulators that fulfilled the required ISO quality standards. The natural feldspars individually contained low fluxing oxides (K_2O and Na_2O) contents revealed, the feldspar must be used in either at higher concentration/mixing with one another to get a relatively higher amount of fluxing oxides or need higher firing temperature in order to achieve optimum glassy phase in the porcelain body. The uses of SCBA which contains fluxing oxides higher than the natural feldspars and SCFA in this study contributed to lowering the sintering temperature up to 50°C during the production of porcelain electrical insulators.

Among the batch composition without SCBA, Batch 3 which contain clay (40%), quartz (20%), and feldspar (40%), and fired at a temperature of 1250°C and firing time 2.0h, provide optimum mullite and quartz crystalline phase embedded in sufficient glassy phase forming a smooth surface, and dense microstructure with no observed porosity as characterized by XRD phase analysis, SEM-EDS and XPS; showed better physical properties (water absorption, apparent porosity, and bulk density), appreciable dielectric strength and mechanical strength that fall within the required standard for quality porcelain electrical insulators. Even with better physical, electrical and mechanical properties at firing temperature 1300 °C when compared to the value get in firing temperature 1250 °C. But from an economic perspective, it is better to use a lower firing temperature to save energy costs and production costs.

The results also confirmed the batch composition of batch-4, clay (50%), feldspar (30%), SCBA (10%), and quartz (10%) and fired at a temperature of 1250°C for 2.5h, meet the required standard for porcelain electrical insulators; having better physical properties (water absorption 0.33%,), the appreciable dielectric strength of 6.59KV/mm and mechanical strength 42.53MPa The result also indicated a high amount of SCBA content in the porcelain insulator is undesirable, especially with higher firing temperatures, as it is led to surface bloating in the transformation of hematite, which causes the increase in porosity and decrease in bulk density and subsequently electrical and flexural strength of the porcelain insulators. This signifies that high amounts of SCBA waste should be avoided.

In general, the result confirmed that it is possible to produce high-quality porcelain electrical insulators upon the proper formulation and at optimized conditions from locally available raw materials deposited in different locations (clay, feldspar, and quartz) and by partial substitution of feldspar with sugarcane bagasse ash in Ethiopia.

However, forthcoming study should consider impact of quartz size and the use of quartz alternatives to yield the required glassy phase and to overcome crack formation during the firing process at lower firing temperature; has a composition that indicates it can be used in a ceramic composition that it has further investigated to be used to make other practical glass-based products. It is also recommended to study the composition which contains higher proportions of SCBA (Batch-5 and batch-6) by undergoing pretreatment to minimize the level of iron oxides in the SCBA as well as iron oxide contamination of the feldspar deposits. as it is present in amount greater than the allowed limits and causes bloating due to the escape of entrapped gases during sintering. Otherwise to use for other ceramic ware which doesn’t consider the dielectric strength like ceramic wall tiles, etc., because this composition fulfills the requirement of flexural strength (modulus of rupture) (>35MPa) for ceramic wares.

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7. Appendices

Supplementary figures and publication

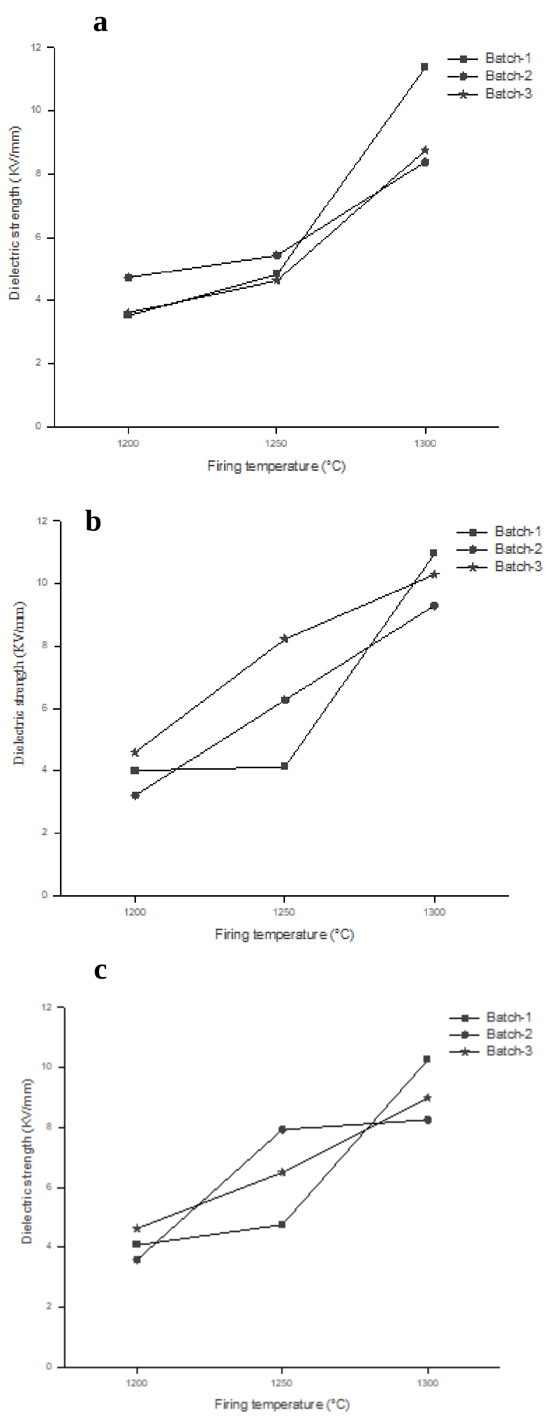

Fig. 16 Dielectric strength (kV/mm) of porcelain insulators (Batch-1, Batch-2, Batch-3) at different firing temperatures (1200 °C, 1250 °C, & 1300 °C) and firing times of (a) 1.5 h, (b) 2.0 h, and (c) 2.5 h

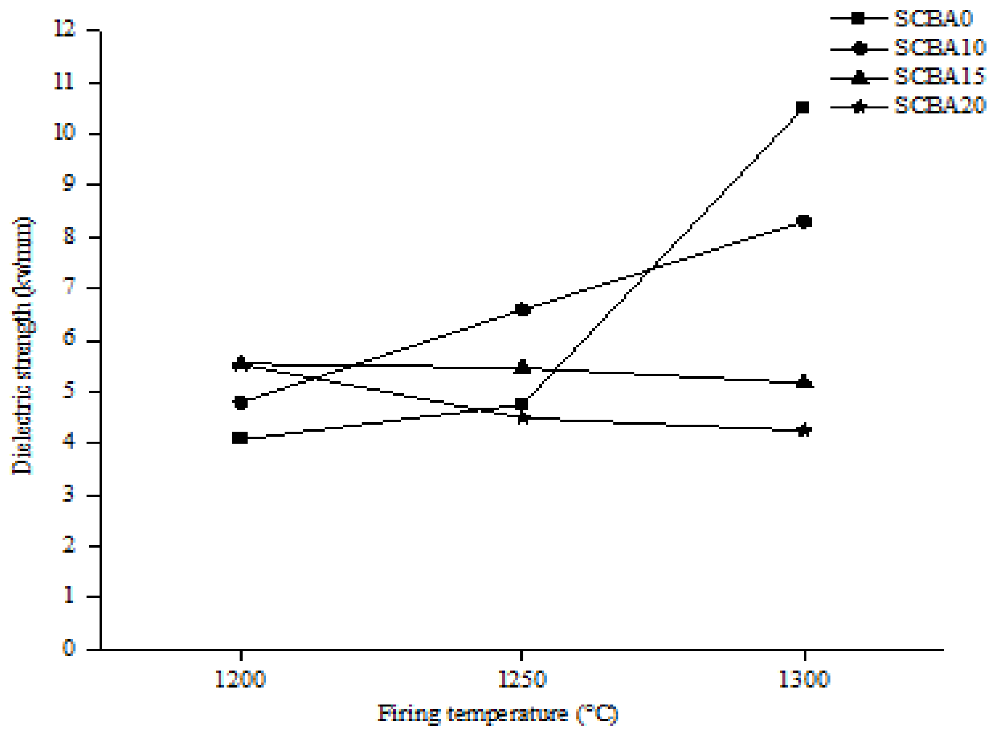

Figure 17 the dielectric strength (kV/mm) of porcelain insulators with SCBA at different firing temperatures (1200°C, 1250 °C, and 1300 °C) and optimized firing time of 2.5h in comparison to the control SCBA0

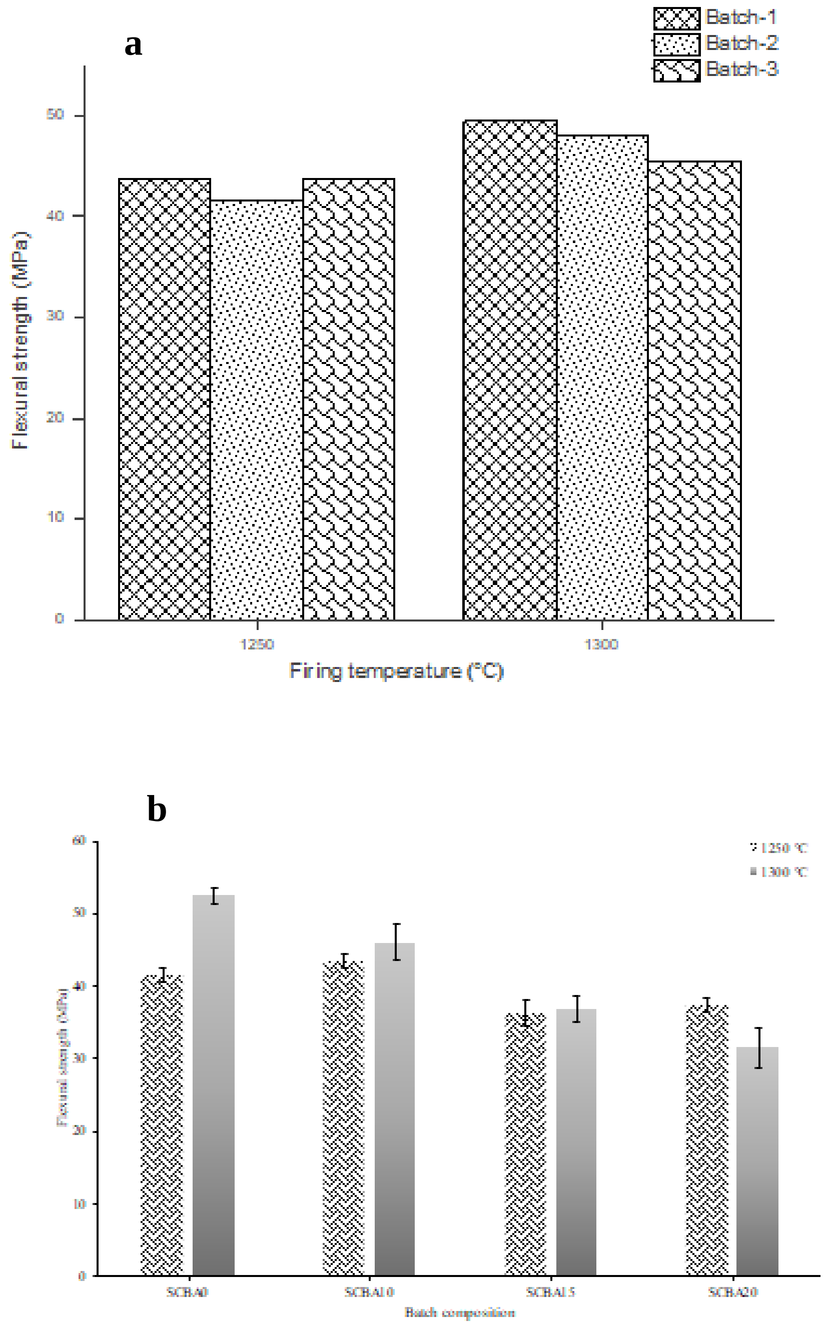

Fig. 18 The flexural strength/modulus of rupture (MOR) of selected porcelain insulators as a function of firing temperature (1250 °C and 1300 °C): a) without SCBA and at optimized firing time of 2.0h; b) with SCBA and optimized firing time of 2.0h

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Sugarcane Bagasse ash substituent feldspar for the production of porcelain electrical insulators

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