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Fabrication of electrical porcelain insulator from ceramic raw materials of Oromia region, Ethiopia

Andualem Merga [a], H.C.Ananda Murthy [b], Enyew Amare [b], Kalid Ahmed [a], Eshetu Bekele [b,*]

[a] Department of Materials Science and Engineering, Adama Science and Technology University, P O Box 1888, Adama, Ethiopia
[b] Department of Applied Chemistry, Adama Science and Technology University, P O Box 1888, Adama, Ethiopia

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ABSTRACT

Electrical porcelain insulator was fabricated from local ceramic raw materials, Bombowha kaolin/clay, Arero feldspar and Arero quartz available in Ethiopia. The raw materials mineralogy, chemical composition, and thermal properties were characterized by using x-ray diffractometer (XRD), atomic absorption spectrometer (AAS) and thermogravimetry (TGA), respectively. Plasticity of clay was determined according to Atterberg plasticity test. Based on the raw materials chemical composition, five different porcelain insulator test bodies were prepared at firing temperature of 1000 °C, 1100 °C, 1200 °C and 1300 °C. Water absorbance, apparent porosity, bulk density, dielectric strength and microstructure of fired porcelain insulators were studied as a function of firing temperature. The XRD and AAS results revealed that in Bombowha clay, kaolinite mineral was found to be a major mineral constituent with appreciable silica (46.84 wt%) and alumina (36.74 wt%) content with moderate plasticity (PI = 19–21%). The Arero feldspar belongs to anorthoclase feldspar minerals with less alkali content (Na_2O + K_20) of <7wt %. Among the tested porcelain insulator bodies, the test body with composition of 45% kaolin, 45% feldspar and 10 % quartz exhibited superior properties of having a water absorbance of 0.010%, porosity of 0.088%, density of 2.466 g/cm^3, dielectric strength of 8 Kv/mm at firing temperature of 1300 °C with mullite and quartz phase embedded in sufficient glassy phase. Therefore, the experimental result confirmed that standard porcelain insulator can be fabricated from locally available ceramic raw materials (clay and quartz) in Ethiopia at optimized condition.

1. Introduction

The consumption of electric energy has been significantly increasing 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 (Mondal et al., 2018). Hence, the power industries work all the way to develop high voltage and long distance transmission. For safe transmission and distribution of the electric power, application of insulator is very much essential to prevent the flow of current from the wire to the earth through ground supporting tower or poles (Ezenwabude and Madueme, 2015).

Among the insulator materials utilized in electric power transmission and distribution system porcelain insulator is the most commonly used material for overhead insulators (Ovri and Onuoha, 2015). Porcelain insulators were found to exhibit excellent properties such as high mechanical strength, high electrical stability and corrosive resistance even in humid environment (Meng et al., 2012, 2014, 2016). Moreover, the raw materials used for its production are also naturally available compared to other type of insulators which needs industrially processed materials. Ceramic industries in Ethiopia are producing porcelain insulators from ball clay material, which is not locally available. Therefore, the development of porcelain insulators from locally available raw materials will have a significant contribution to the economy of the country by import substitution and exploring and promoting underutilized resources.

Electrical porcelain insulators are the most complex multiphase ceramic materials used as overhead insulator for both low- and high-tension insulation (Yaya et al., 2017). It basically produced from natural ceramic raw materials such as clays (ball clay, china clay or kaolin), feldspar and quartz (Akwilapo and Wiik, 2003, 2004).

These ingredients go through different physical changes and react together under thermal condition to produce the final product (Yaya

* Corresponding author.
E-mail address: eshetubekele@gmail.com (E. Bekele).

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et al., 2017). The quality and quantity of the raw materials plays a significant role on the properties of blended green body and the fired body/microstructure of porcelain body that ultimately affect the performance of electrical porcelain insulators. The clay [$Al_2Si_2O_5(OH)_4$] content when wet, acts as a binder for the other body ingredients in the green state which confirm plasticity of the body for easy molding and shaping, while feldspar [$K_x Na_{1-x} (AlSi_3)O_8$] serve as flux and alternative source of alumina and silica, whereas quartz (SiO_2) used as a filler material helps to maintain the shape of porcelain body at green state and during firing (Ngayakamo and Park, 2018). Various scholars designed efficient high quality porcelain insulator using ball clay as a plastic materials (Anih et al., 2005; Oladiji et al., 2010). But high quality ball clay that makes up a large proportion of a porcelain insulator's are very scarce and found in very few places around the world. As a result the sustainable development of porcelain insulator requires searching for alternative clay materials that partially or fully supplement the current need of scarce ball clay.

The most desirable properties of a porcelain insulator for applications in electric power distribution and transmission system includes, high electrical resistivity, high dielectric strength, good mechanical properties, and excellent heat radiating and insulating capacity even in humid and corrosive environments (Liebermann, 2003; Islam et al., 2004; Meng et al., 2014). Among those properties, dielectric strength and mechanical strength are the two most important determinant properties which must be taken in to consideration to produce quality porcelain insulator (Moyo and Park, 2014). These two properties of porcelain insulator are mainly affected by major phases of porcelain materials namely mullite and glassy phases which are developed at high firing temperature (Moyo and Park, 2014).

A crystalline alumino-silicate mullite ($Al_6Si_2O_{13}$) compound primary originated from clay relictcalled primary mullite and has a cuboidal structure under SEM analysis (Carty and Senapati, 1998; Iqbal and Lee, 2000; Lee and Iqbal, 2001; Lee et al., 2008). Whereas, the glassy phase or liquid phase originated during sintering of feldspar, causes densification of the ceramic bodies (Ngayakamo and Park, 2018). But an excess amount of glassy phase promotes free movement of ions in the porcelain bodies that result in poor electrical insulation. Hence, by varying the raw material composition (clay to feldspar ratio) and the firing temperature, it is possible to influence the properties of the fired porcelain body.

Therefore, the present study was aimed to develop good quality electrical porcelain insulator by replacing ball clay by locally available clay materials, characterize the properties of locally available ceramic raw materials (Bombowha clay, Arero feldspar and Arero quartz) and Optimize batch composition to influence important properties such as dielectric strength and mechanical strength by varying the quantity of clay and feldspar as well as firing temperature.

2. Materials and methods

2.1. Source of raw materials

The selected raw materials for this study (Bombowha clay, Arero feldspar and Areroquartz) were collected from two different sites, Guji and Borena zones of Ethiopia. The raw materials owned their name from the place where they found. Bombowha was found in Guji zone (6° 05′ 20″ N and 38° 46′ 30″E), while Arero was found in Borena zone (4° 45′ 00″Nand 38° 49′ 00″E) of Oromia, Ethiopia.

2.2. Raw materials characterization

The oxide composition analysis of raw materials (SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, TiO_2) of all samples were done at Ethiopia Geological survey laboratory using Atomic Absorption Spectrometry (AAS -model, spectra AA-20 plus) and loss on ignition was evaluated by measuring mass difference of sample heated at 100 °C and 1000 °C for 2 h.

The Differential Thermal Analysis (DTA) and Thermogravimetry Analysis (TGA), of clay samples analyzed using Shimadzu DTG-60H, operating under inert atmosphere condition, the sample was heated from room temperature up to 1100 °C at a rate of 10 °C/min in platinum cup and other empty platinum cup was used as a control.

The mineralogical analysis of the raw materials and phase analysis of fired product were conducted using x-ray diffractometer (XRD) (Shimadzu x-ray diffractometer 7000), the mineralogy of feldspar and quartz were scanned at bulk state, whereas Bombowha clay was scanned in bulk state and after fractionation (clay fraction <2 μm), and heated clay fraction (<2 μm) at 550 °C for 2 h, using CuKα_1 radiation ($\lambda = 1.5418$Å) generated by accelerated voltage of 40 kv and filament current 30 mA. The samples were scanned from 5-80^o 2θ in step size of 0.02^o 2θ, the diffraction patterns of the samples were analyzed by search matched against International Center for Diffraction Data (ICDD) database.

The plasticity parameter of clay, liquid limit (LL), plastic limit (PL) and plastic index (PI), PI = LL-PL were determined by Casagrande method (LCPC, 1987) in accordance with the French standard NF P 94–051.

2.3. Fabrication of electrical porcelain insulator

The raw materials were oven dried and ground separately. Clay and feldspar were passed through 75 μm SI sieve, while quartz through 45 μm SI. The resultant materials were blended according to desired batch composition as given in Table 1. The batch compositions were designed based on the assertion stated by Okolo et al. (2014) with little modification by considering raw materials chemical composition and the mixture was dry ball milled for 12 h. A cylindrical mold test sample of 20 mm diameter and 5 mm thickness was prepared by using hydraulic press and then a test sample from each batch was fired at a temperature of 1000 °C, 1100 °C, 1200 °C and 1300 °C, separately with heating and cooling rate of 6 °C/min and 1-h socking time. The firing temperature were selected based on the study conducted by Iqbal and Lee (2000) and Iqbal (2008) on effect of firing temperature on microstructure evolution and glassy phase formation in triaxial porcelain.

2.4. Characterization of fired porcelain materials

The physical properties (water absorption, apparent porosity and bulk density) of insulator samples were determined by using boiling method according to (ASTM C838-96, 2010).

Dielectric strength of insulator bodies was computed by measuring their break down voltage using high voltage testing machine (model TERCO HV 1103) at Electrical Engineering laboratory, Addis Ababa University. The positive and negative terminals of the instrument were connected at either end of the insulator body, then the voltage was gradually increased from control disk until the voltage increment break and began to drop display on control disk which indicate the break down voltage of the sample then the dielectric strength of the insulator is calculated by using Eq. (1).

$$\text{Dielectric strength} = \frac{\text{break down voltage (kv)}}{\text{thickness of sample (mm)}} \quad (1)$$

The morphological features of insulator bodies were evaluated by using Field emission scanning electron microscope (FESEM/FIB-model Neon-40), at Nano manufacturing technology center (NMTC), CMTI, India and INSPECT T50 FEI at Addis Ababa Science and Technology

Table 1
Batch composition of porcelain samples.

Samples	Batch -1	Batch -2	Batch -3	Batch -4	Batch -5
Clay (wt %)	60	50	45	40	30
Feldspar (wt %)	30	40	45	50	60
Quartz (wt %)	10	10	10	10	10

Table 2
Chemical composition analysis of clay, feldspar and quartz minerals in wt %.

Materials	wt. %									
Oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	TiO_2	LOI
Bo-clay	46.86	36.74	0.86	0.02	0.08	0.01	1.34	0.04	0.01	13.85
Feldspar	72.50	14.55	2.40	0.52	1.00	2.95	3.68	0.09	0.16	2.08
Quartz	96.66	0.87	0.68	0.16	0.10	0.01	0.85	0.04	0.01	0.36

Where: Bo-clay (Bombowha clay), LOI (loss on ignition).

University AASTU, Ethiopia.

3. Results and discussion

3.1. Raw materials characteristics

As shown in Table 2, the chemical composition analysis result revealed that Bombowha clay contains 36.74 wt. % Al_2O_3, 46.86 wt. % SiO_2, 0.86 wt.% Fe_2O_3 and 0.01 wt. % TiO_2. The ratio of Al_2O_3/SiO_2 was remarkable amount for mullite phase formation during sintering the porcelain body. Whereas color forming impurities like Fe_2O_3 and TiO_2 were found to be at low level. 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 (Chen et al., 2000; Olupot et al., 2010; Gralik et al., 2014). Moreover Bombowha clay contain high loss in ignition (LOI) (13.85wt.%) this due to the loss of structural hydroxide occurred during the transformation of kaolinite clay to metakaolinite phase formation around 500 °C, which it further stated on thermal analysis result in Fig. 1. In general the result obtained in this study is in agreement with the results reported earlier by Fentaw and Mengistu (1998) and Bombowha clay in terms of its chemical composition meets the chemical purity requirement of clays for insulator fabrication sated by Meng et al. (2012). The Arero feldspar has relatively small amount of alkaline oxide ($Na_2O + K_2O < 7$wt.%) compared to the feldspar compositional purity required to be used as raw materials for insulator production, which is an alkaline content of a minimum of 12 wt

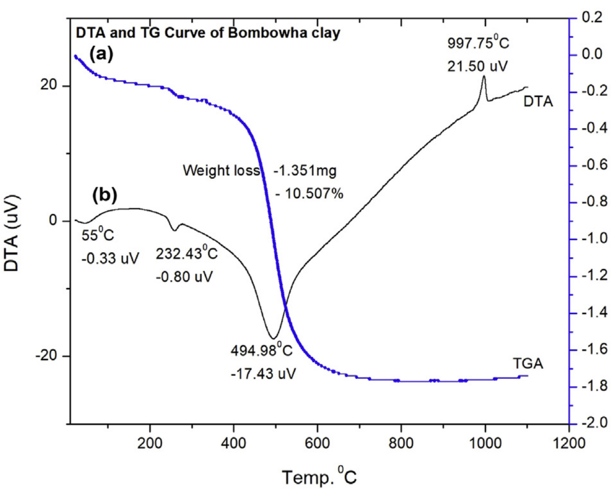

Fig. 1. Thermal analysis curve of Bombowha clay: (a) TGA curve and (b) DTA curve.

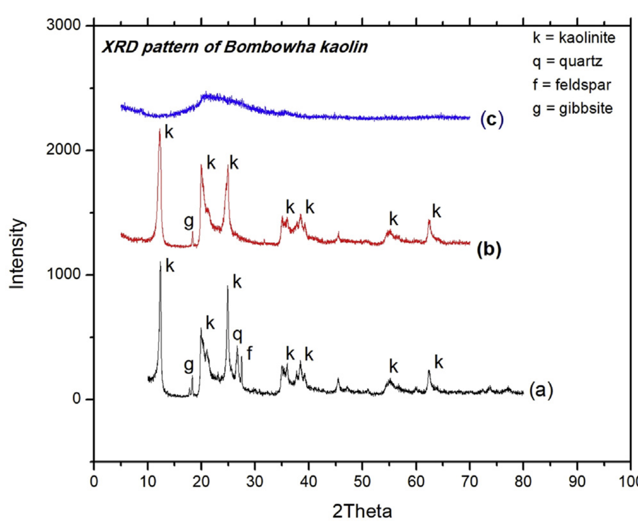

Fig. 2. Powder x-ray diffractogram (PXRD) spectra of Bombowha clay scanned in: (a) bulk state, (b) normal or clay fraction, and (c) heat treated at 550 °C. The diffraction in the diagrams identified as: k: kaolinite, q: quartz, f: feldspar, g: gibbsite sheet.

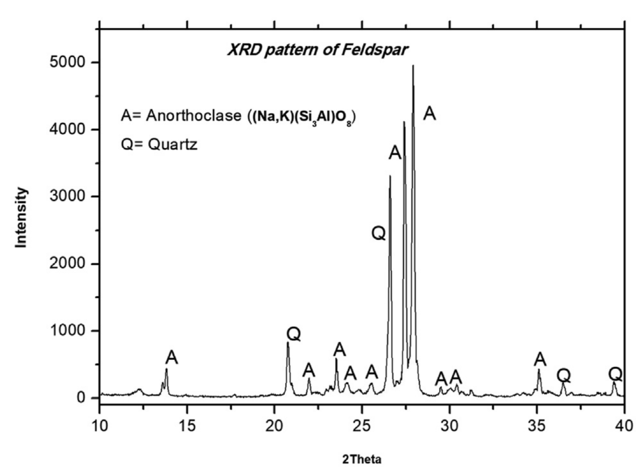

Fig. 3. Powder x-ray diffractogram of feldspar.

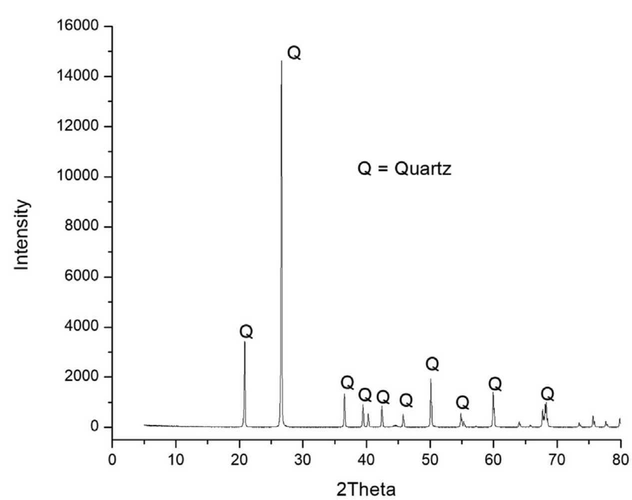

Fig. 4. Powder x-ray diffractogram of quartz mineral.

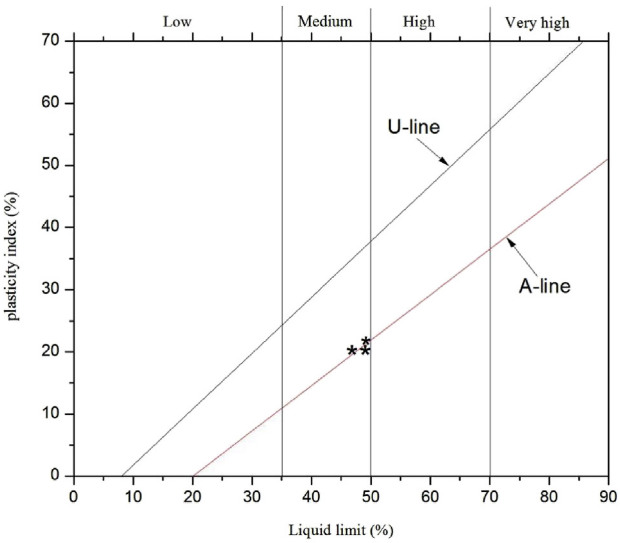

Fig. 5. Position of Bombowha clay sources on the Holtz and Kovacs plasticity chart.

% (Moyo and Park, 2014). This indicates, Arero 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. On the other hand quartz used in this study found to contain an amount very close to pure SiO_2 (96.66 wt. %) and low iron content (<1wt %).

The Thermogravimetry Analysis (TGA) and Differential Thermal Analysis (DTA) result of Bombowha clay is presented in Figs. 1a and 1b. As observed in DTA curve (Fig. 1b), the small endothermic peak around 55 °C and 232 °C may due to the presence volatile organic compounds and free gibbsite sheets, respectively (Fentaw and Mengistu, 1998). The observed intense endothermic peak at a temperature of 495 °C is found in the temperature range of (420–660 °C), which is the characteristics temperature for metakaolin phase formation from kaolinite type clay mineral (Iqbal and Lee, 2000; Iqbal, 2008). In this temperature range dehydroxylation of kaolinite occurred to form metakaolinite amorphous phase, this is due to the loss of structural hydroxide in the form of water from octahedral coordinate of aluminum sheet in kaolinite mineral (Al_2O_3. $2SiO_2$. $2H_2O$) (krupa and Malinaric, 2015). The loss confirmed by corresponding mass loss (10.5%) observed on TGA curve (Fig. 1a). A 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. An exothermic peak observed in DTA curve at a temperature of 997.8 °C (Fig. 1b), indicates the formation of crystalline mullite phase.

The powder XRD patterns shown in Fig. 2 describe Bombowha clay samples scanned in bulk, normal and heat treated at 550 °C states.

The bulk state of clay sample contains predominantly kaolinite type clay mineral, where quartz, feldspar and gibbsite sheet present as minor minerals (Fig. 2a). The normal state reflection of clay fraction (particle size less than 2 μm) helps to identify the clay minerals in the absence of other non-clay minerals intervention (Senoussi et al., 2015). So in this study, major XRD reflection of normal state (Fig. 2b) indicates the presence of kaolinite type clay minerals, which further confirmed by the complete disappearance of peaks for heat treated state as indicated in Fig. 2c. This is possibly due to the transformation of kaolinite clay to metakaolinite amorphous phase at 550 °C which strongly agreed with the DTA assertion on Fig. 1b. This metakaolinite amorphous phase scatters x-ray in many directions due to the lack of long range order of lattice or crystal which leads to a large hump distribution in a wide range 2theta, instead of high intensity narrower peaks as observed in Fig. 2c.

XRD patterns of feldspar and quartz minerals were presented in Figs. 3 and 4 respectively.

Arero feldspar contain mainly free quartz (SiO_2) and anorthoclase (Na, K) ($Si_3Al)O_8$feldspar minerals (ICDD PDF-2 #, 00-009-0478) which is in agreement with chemical analysis result, whereas quartz was found in almost pure state and its diffraction patterns are belong to quartz mineral in reference with ICDD database (PDF-2 # 00-046-1045).

The multiple plasticity test of Bombowha kaolin result shows that its liquid limit varies between 47 to 49 % and the plastic limit varies between 27.3 and 28.2% (Fig. 5). The observed result is found to be in the middle range of plasticity (14% < PI > 20%), and also found in kaolinite domain medium position on Holtz and Kovacs diagram as shown in Fig. 5 (Mahmoudi et al., 2017). This confirms suitability of Bombowha clay for plastic mold formation during the production of porcelain insulators.

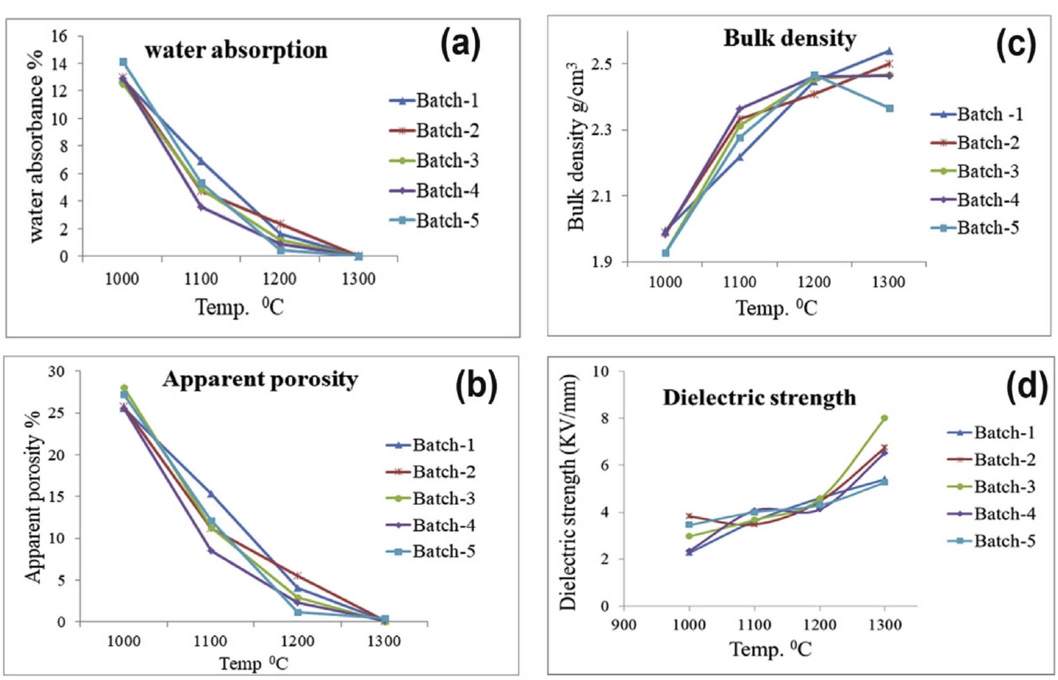

Fig. 6. Variation in (a) water absorption, (b) apparent porosity, (c) bulk density and (d) dielectric strength, of samples with temperature.

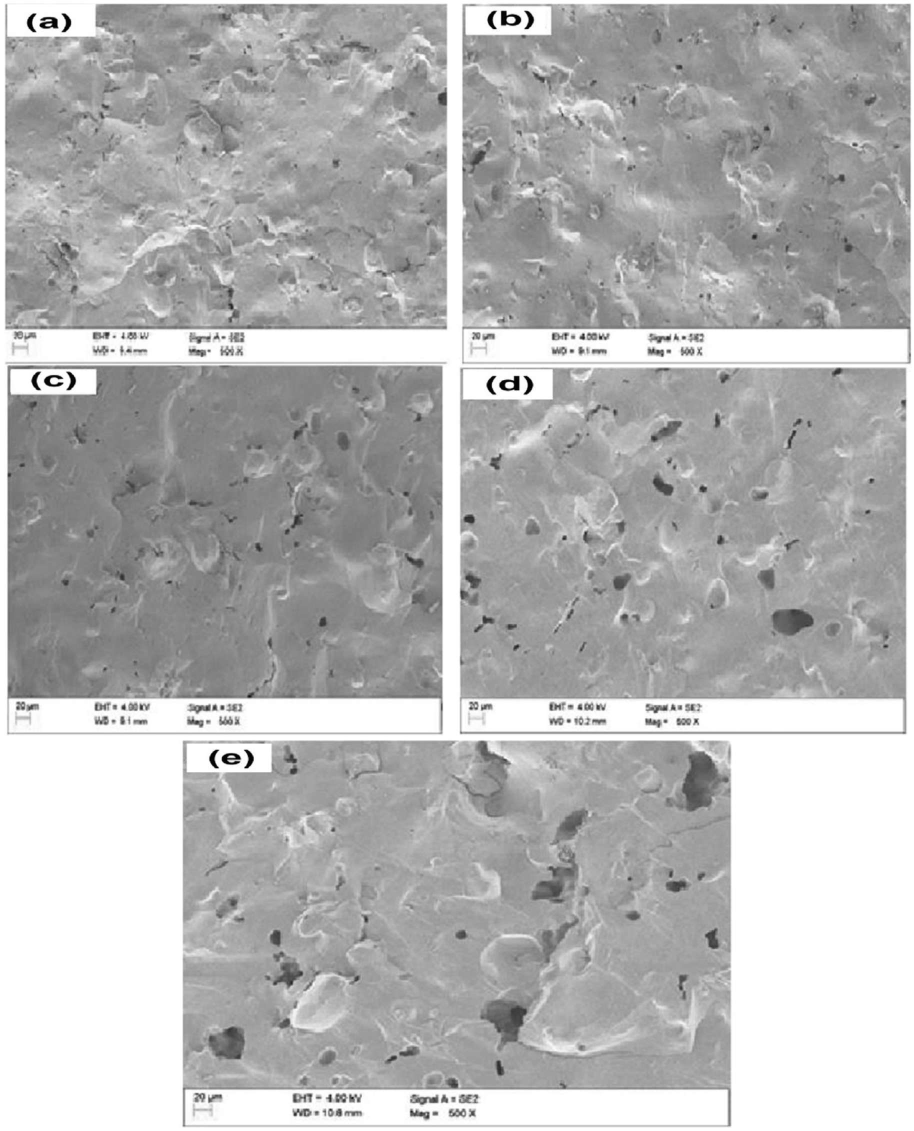

Fig. 7. SEM image of surface porosity of: (a) batch -1, (b) batch-2, (c) batch-3, (d) batch-4, and (e) batch-5, at firing temperature of 1300 °C.

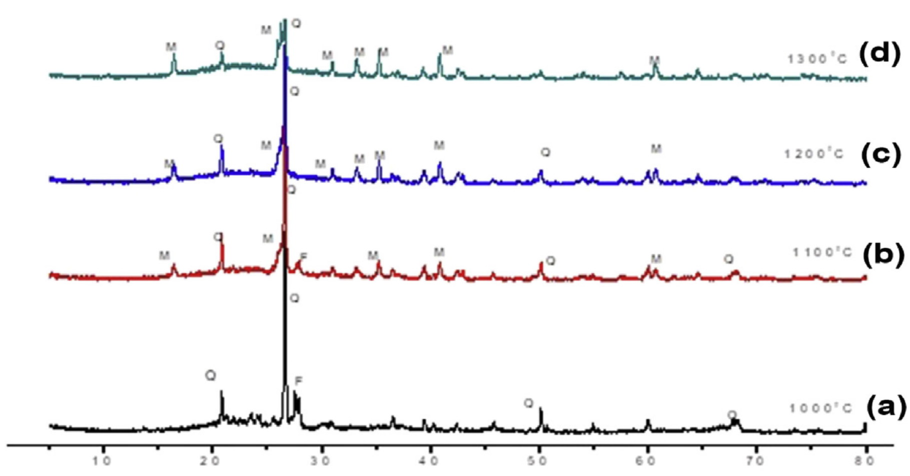

Fig. 8. Powder X-ray diffractogram of samples of batch-3 fired at: (a) *1000 °C, (b) 1100 °C, (c) 1200°C and (d) 1300°C.* The reflection on the diffractogram identified as M: mullite, Q: quartz and F: feldspar).

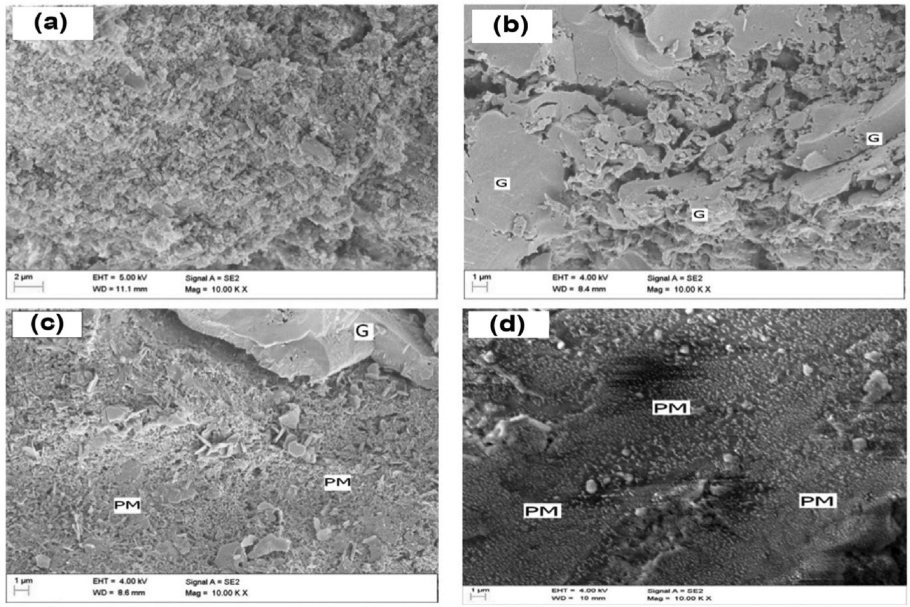

Fig. 9. SEM image of samples of batch-3 fired at (a) *1000 °C, (b) 1100 °C, (c) 1200 °C and (d) 1300 °C*. Where, G refers to glassy phase, PM refers Primary mullite, and SM refers to secondary mullite).

3.2. Properties of fired porcelain

The physical properties such as water absorption and apparent porosity of all batch samples decreased with increase in firing temperature and reaching to zero at firing temperature of 1300 °C (Fig. 6a and b). This could be attributed to the melting of feldspar at a firing temperature above 1100 °C resulting in liquid or glassy phase which fills the gaps or voids in the microstructure and lead to densification of the body (Iqbal, 2008). The maximum densification obtained at a relatively higher firing temperature (1300 °C) compared to the temperature reported by Akwilapo and Wiik (2003) to achieve maximum densification (1200 °C), may be due to the low level of fluxing agent in the feldspar utilized in this study required high firing temperature in order to obtain sufficient glassy phase in the microstructure.

Fig. 6c depicts increase in the bulk density of all the samples as firing temperature increases. This result is expected since bulk density has an inverse relation with apparent porosity and water absorbance. But the observed decrease in the bulk density of batch- 3, 4 and 5 at firing temperature of 1300 °C was believed to be due to increased feldspar to clay ratio across the batch. As feldspar to clay ratio increased high amount of low viscos liquid phase was expected to be formed due to the complete melting of feldspar at the specified temperature and other low temperature melting materials and results with the coalescence of pores formed which increase the size of pores in the microstructure. This is confirmed by SEM micrographs of all batch samples prepared at firing temperature of 1300 °C (Fig. 7), as result the pore size was found to increase across the batches and higher porosity was observed for batch- 5 sample.

As observed from Fig. 6d, the dielectric strength of porcelain insulators were found to increase with increasing firing temperature and reaches a maximum of 8 kv/mm at a firing temperature of 1300 °C. The increasing of the dielectric strength may be due to increased vitrification range of the electrical porcelain samples at the optimized firing temperature (Ngayakamo and Park, 2018). Among the desired batch composition, the dielectric strength of batch-2, batch -3 and batch- 4 found to fall in the specified range of 6.1–13 kv/mm for porcelain insulator (Olupot et al., 2010).

3.3. Microstructure analysis

XRD patterns- and SEM microstructure-of Batch- 3 (which possess relatively better physical and electrical properties), are shown in Figs. 8 and 9, respectively. The XRD diffractogram shows at firing temperature of 1000 °C, only quartz and feldspar peaks were found without any peaks for kaolinite (Fig. 8a). This is due to the transformation of kaolinite clay to metakaolin amorphous phase above 420 °C which exhibited no reflection on XRD and it remained up to 1100 °C until the formation of mullite crystalline phase.

Appearance of new peak above firing temperature of 1100 °C, indicates the formation of new crystalline phase named primary mullite (Islam et al., 2004), designated as M on XRD diffractogram (Fig. 8b) and PM on SEM image (Fig. 9d). As the firing temperature goes beyond 1100 °C the feldspar reflection disappeared from XRD diffractogram instead the glassy phase hump reflection increase and at 1300 °C the intensity of mullite phase get higher as observed in XRD and SEM figures (Fig 8c and d). It is possibly due to the fact that feldspar begins to melt above 1100 °C which is confirmed by its decreasing peak intensity on XRD diffractogram and formation of glassy phase (G) on SEM image (Fig. 9b and c).

4. Conclusion

The observed characteristics of the raw materials for the first time confirmed that standard porcelain insulator can be fabricated from locally available ceramic raw materials. In this investigation a porcelain insulator from local raw materials with composition of clay (40–50%), feldspar (40–50%) and quartz 10% at firing temperature of 1300 °C was found to have met the required standard with respect to good physical properties and appreciable dielectric strength for electrical porcelain insulator fabrication. Therefore, there is a potential opportunity in Ethiopia to produce standard porcelain insulators by replacing the scarce ball clay by local clay materials (Bombowha clay) with proper formulation and at optimized condition. However, forthcoming study should consider partial/full substitution of feldspar by economic materials like recyclable materials that contain high silica and sufficient amount of alkaline oxide to yield the required glassy phase at lower firing temperature.

Declarations

Author contribution statement

Eshetu Bekele, Andualem Mergaa: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Enyew Zereffa, H. C. Ananda Murthy: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Kalid Ahmed: Conceived and designed the experiments; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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