Evaluation of Kalalani Vermiculite for Production of High Strength Porcelain Insulators

Blasius Ngayakamo*, S. Eugene Park
Nelson Mandela African Institution of Science and Technology, Department of Materials and Energy Science and Engineering, P. O. Box 447 Arusha, Tanzania

Abstract:
The present work has evaluated Kalalani vermiculite as a potential raw material for the production of high strength porcelain insulators. Three porcelain compositions were prepared to contain 0, 20 and 30 wt% of Kalalani vermiculite. Porcelain samples were fabricated using a semi-drying method. The chemical, mineralogical phases and microstructural characterization of the raw materials were carried out using XRF, XRD, and SEM techniques, respectively. Water absorption, bulk density, dielectric and bending strengths were performed on porcelain samples fired up to 1300 °C. However, at the sintering temperature of 1250 °C, the porcelain sample with 20 wt% of Kalalani vermiculite gave the dielectric strength of 61.3 kV/mm, bending strength of 30.54 MPa, bulk density of 2.21 g/cm³ and low water absorption value of 0.21 % which is the prerequisite properties for high strength porcelain insulators. It was therefore concluded that Kalalani vermiculite has the potential to be used for the production of high strength porcelain insulators.

Keywords: Kalalani vermiculite; Porcelain insulators; Sintering; Densification.

1. Introduction

Higher strength porcelain insulators are in need for power industry for transmission and distribution [1]. It becomes challenging when the porcelain insulator fails to provide required strength when subjected to the high signal voltage [2]. The most required properties of the porcelain insulators are high mechanical strength and high dielectric strength in order to withstand high voltage [2, 3]. However, high mechanical resistance, low prosperity and water absorption are among other essential properties of electrical porcelain [4]. The high strength of electrical porcelain may be achieved by a specific composition of raw materials but due to geological and geophysical characteristics the raw materials may have various chemical compositions and specifications [5].

Porcelain insulators are widely used electrical devices in power transmission system due to their high stability in terms of the electrical, mechanical and thermal properties [6]. Popular porcelain insulators are primarily made from clay, quartz, and feldspar. Each of these materials plays specific role in the properties of both the green body and the fired body. Clay [Al₂Si₂O₅(OH)₄] provides plasticity to the ceramic mixture, quartz (SiO₂) maintains the shape of the formed porcelain structure during firing, and feldspar [KₓNa₁₋ₓ(AlSi₃)O₈] promotes the development of a glassy phase at lower sintering temperatures. These three raw materials place electrical porcelain in the phase system [(K,Na)₂O-Al₂O₃-SiO₂] of triaxial porcelain.

* Corresponding author: henryblasius@gmail.com
Taking into consideration that porcelain insulators requires higher dielectric and mechanical strengths for high voltage power transmission and distribution, several modifications have been attempted in order to increase the strength of electrical porcelain [7]. However, it has been reported that, most widely used quartz electrical porcelains have weak strength [4]. The decrease in strength of quartz electrical porcelain is due to \( \alpha \) to \( \beta \)-phase transformation of the quartz which results in tensile and compressive stresses [5]. The stresses tend to increase when temperature rises. The increased stress at elevated temperature can result in the development of microcracks which act as stress concentration centers, and may cause catastrophic failure of the working insulator while suspended in power lines [5]. Due to shortcomings of quartz in porcelain insulators there are several modifications which have been done and have been successful such as the replacement of quartz with soda lime glass [8], substitution of quartz with alumina [5], and use of barium carbonate and alumina to increase the electrical porcelain strength [4].

Vermiculite is characterized by low density, fine thermal and insulation properties, chemically inert and fire resistant material, which makes vermiculite as a good material for use as lightweight aggregate and filler for heat insulation applications [9]. The melting point of vermiculite is 1350 °C whereas the maximum sintering temperature is 1260 °C. This is why vermiculite is considered for the production of insulating material and fireproof products [10]. However, there is very limited information on the use of vermiculite in ceramic production particularly in the porcelain insulators [11]. Vermiculite is readily available and is found in Kalalani village in Korogwe Tanga and Nyang’wambe village in Mikesor Morogoro in Tanzania. However, this study intends to evaluate Kalalani vermiculite as a potential material in place of quartz for production of high strength porcelain insulators.

2. Materials and Experimental Procedures

Kalalani vermiculite sample was collected from Kalalani, 90 km southeast of Korogwe Tanga in Tanzania. Pugu Kaolin was collected from Pugu Hills, 26 km southwest of Dar es Salaam Tanzania, Same Clay and feldspar were collected from Same, Kilimanjaro region in the northern zone of Tanzania.

The dried locally sourced -raw materials were crushed and later were milled by using stainless steel ball mills for the duration of 3 h for each sample. The particle size of the raw materials less than 106 µm was achieved by a sieve shaker (Model AS200 digit) manufactured by Retsch Inc, in Germany. The chemical composition of the raw materials was done by using X-Ray Fluorescence (XRF) PANalytical, Model: Minipal4 (PW4030)-Rh X-Ray Tube, 30 kV, 0.002 mA. The mineralogical composition and phase analysis for each ceramic raw material was done by X-ray diffractometer Model: Bruker D2-PHASER-40 K/v/44mA. The examination of surface morphology and elemental maps was done by Scanning Electron Microscope integrated with Energy dispersive spectroscopy (SEM/EDS) Model: JEOL JSM-6335F having a resolution of 5 and 10 µm at 2 kV. Four porcelain green bodies P-1 to P-4 were fabricated by following the procedures indicated in Figure 1. by adding 20 % of Kalalani vermiculite to P-3 composition, 30 % of Kalalani vermiculite to P-1 and P-2 compositions and 0 % of Kalalani vermiculite to P-4 as shown in Table I. The powder mixtures were wet homogenized in a laboratory milling jar for 30mins to obtain normal size distribution. Afterwards, the wet powder mixtures were uniaxially compacted into rectangular shape at 10 MPa. The molded rectangular specimens with dimensions 160 mm x 40 mm x 20 mm were produced and subjected to drying.

The samples were air dried at a room temperature in indoor for 5 days. The aim was to eliminate partially the shaping water and to homogenize the residual humidity. The specimens were turned twice per day to prevent warping. The green bodies were then oven
dried at the temperature of 110 °C for 24 h by an oven with a model number: 10AF-1 manufactured by Humboldt Incorporation, USA.

| Sample | Quantity (g) | Pugu kaolin (%) | Same clay (%) | Kalalani vermiculite (%) | Feldspar (%) |
|--------|--------------|------------------|---------------|--------------------------|-------------|
| P-1    | 100          | 30               | 10            | 30                       | 30          |
| P-2    | 100          | 10               | 30            | 30                       | 30          |
| P-3    | 100          | 20               | 20            | 20                       | 30          |
| P-4    | 100          | 50               | 30            | 0                        | 20          |

Sintering was done by Carbolite box furnace Model: RHF 14/8 manufactured by Keison products Incorporation in the UK. The dried samples were fired up to 1300 °C for 1.5 h at a ramp rate of 10 °C/min for each firing. The aim of sintering process was to achieve vitrification and densification of the porcelain samples. After firing the sintered porcelain samples were left to cool to room temperature. The samples which were sintered at 1200 °C and 1250 °C each was subjected to physical, mechanical properties and dielectric strength analysis. Water absorption and bulk density were performed on porcelain samples using the Archimedes method in accordance with ASTM C373-88. Bending strength was done by using bending tester with a Model: MEGA 10-200-10 DS manufactured by Prufysteme Incorporation in Germany. Bending strength results were obtained by a three-point testing. The load was applied uniaxially on rectangular bars until failure occurred. The manometer readings were recorded in MPa. The dielectric strength test was done at Tanzania Electric Supply company limited (TANESCO) by using a DC high voltage tester (Model: Megger 220163-47) manufactured by Biddle Instruments Incorporation in the USA having a maximum output voltage of 160 kV. During dielectric strength measurement, the voltage was applied across the sintered porcelain body using two electrodes at the rate of 1 kV per second until a cracking sound was heard from the porcelain sample. The reading for each tested porcelain sample was recorded in kV/mm.

![Flow diagram for porcelain samples production.](image-url)
3. Results and Discussion

Table II shows the XRF results, which reveals that the ceramic raw materials and Kalalani vermiculite have higher content of silica and alumina in their composition as shown in Table II. Both alumina and silica are essential for the formation of mullite and glassy phase which improves the dielectric and physical-mechanical properties of porcelain insulators. Kalalani vermiculite revealed to have higher content of hematite (Fe₂O₃) compared to other deposits. The literature reports that small amount of coloring oxides such as Fe₂O₃ and TiO₂ less than 0.9 % may be accepted for porcelain wares production. Hematite promotes glassy phase formation and at the same time may affect glassy phase formation due to its reduction to FeO₄ at higher sintering temperature [12, 13].

Tab. II Chemical compositions of the raw materials.

| Oxides     | Pugu kaolin | Same clay | Kalalani vermiculite | Feldspar |
|------------|-------------|-----------|----------------------|----------|
| SiO₂       | 60.00       | 60.40     | 33.30                | 57.10    |
| Al₂O₃      | 30.30       | 13.90     | 13.00                | 14.00    |
| TiO₂       | 0.14        | 1.22      | 3.04                 | 3.79     |
| Cr₂O₃      | 0.09        | 0.00      | 0.20                 | 0.92     |
| Fe₂O₃      | 1.95        | 1.40      | 11.24                | 2.08     |
| MnO        | 0.02        | 0.00      | 0.19                 | 0.32     |
| MgO        | 0.00        | 0.00      | 14.90                | 0.01     |
| CaO        | 0.39        | 0.00      | 4.85                 | 1.00     |
| Na₂O       | 0.00        | 0.04      | 0.06                 | 0.20     |
| K₂O        | 2.14        | 22.60     | 5.85                 | 12.09    |
| LOI        | 3.96        | 0.44      | 13.37                | 8.49     |

When the porcelain samples were fired up to 1300 °C, high vitrification and densification of the porcelains was observed at 1250 °C, however at the sintering temperature greater than 1250 °C porcelains became more porous and did not maintain their regular shapes and started to melt as shown in Figure 2. This might be due to over sintering phenomenon which occurred in the porcelain samples [14].

![Fig. 2. Pictures of Porcelain samples fired up to 1300 °C.](image)

Scanning electron micrographs of the sintered porcelain samples are presented in Figure 3. The SEM micrographs 3a) and 3b) show densification of the porcelain sample when fired at 1200 °C The SEM micrographs 3c) and 4d) show the change on the surface morphology of porcelain sample P-3 when fired at 1250 °C. The sintering temperature
reduced the pores and promoted high dielectric and mechanical properties of the porcelain samples.

![Fig. 3.](image1)

**Fig. 3.** 3a) and 3b) SEM micrographs for porcelain samples P-1 and P-2, 3c) SEM micrograph showing densification of P-3 sample at 1200 °C 3d) SEM micrograph showing densification of P-3 sample at 1250 °C.

![X-ray diffraction patterns](image2)

**Fig. 4.** X-ray diffraction patterns of: 4a) Pugu kaolin, 4b) Same clay, 4c) feldspar, and 4d) Kalalani vermiculite [15].
The mineralogical phase content analysis of the raw materials is presented in Figure 4. as reported in the previous work [15]. In Figure 4, Pugu kaolin sample was found to contain clay mineral kaolinite (Al₂Si₂O₅(OH)₄) and non-clay mineral quartz (SiO₂) while Same clay was found to contain kaolinite and quartz. Feldspar sample consisted of microcline and quartz which shows to be potassic feldspar while Kalalani vermiculite in powder form shows the interstratified structure of vermiculite which does not contain a hydrated phase. It is evident that alumina (Al₂O₃), silica (SiO₂) and fluxing agents (K₂O and Na₂O) supplied by the raw materials form glassy and mullite phase at the firing temperature of 1250 °C [15] as shown in Figure 5. The glassy and mullite phase [(K,Na)₂O-Al₂O₃-SiO₂] promote maximum vitrification and densification which improved the mechanical and dielectric properties of porcelain samples.

![X-ray diffraction pattern of porcelain sample fired at 1250 °C.](image)

**Fig. 5.** X-ray diffraction pattern of porcelain sample fired at 1250 °C.

Table III shows the changes in the values of water absorption by varying the amount of Kalalani vermiculite and the sintering temperature. The porcelain samples P-1, P-2 and P-3 have lower values of water absorption than their counterpart P-4 at 1250 °C. By decreasing the amount of Kalalani vermiculite and increasing the sintering temperature reduced pores in the porcelain samples. The increase in vitrification range and densification of the porcelain sample was mainly caused by the sintering temperature and formation of liquid phase due to the melting of feldspar which filled the pores. The results of the study are in agreement with the work of Olupot et al., [16]. The author observed the decrease of water absorption in the electrical porcelain sample with composition 30 % of kaolin, 20 % of Ball clay, 20 % of feldspar, and 30 % of flint from 2.5 % at 1200 °C to 0.5 % at 1250 °C while investigating ceramic raw materials for electrical porcelain production. The author reported that, the decrease of water absorption values of the electrical samples was due to densification and vitrification at high firing temperatures which is influenced greatly by the melting of feldspar. The water absorption of electrical porcelain bodies decreased, and glassy phase content increased with increasing firing temperature [5].

The water absorption values of porcelain samples P-1 and P-3 are within the standard requirements for porcelain insulators which are less than 0.5 % as recommended by ISO-13006. If the porcelain insulator is manufactured with high porosity, it may absorb moisture
from air. It will decrease the insulation capacity of a working porcelain insulator and may result to its catastrophic failure due to flowing of current through it.

Table III Water absorption of porcelain samples sintered at 1200 and 1250 °C.

| Porcelain samples | W.A. (%) at 1200 °C | W.A. (%) at 1250 °C |
|-------------------|---------------------|---------------------|
| P-1               | 0.45                | 0.31                |
| P-2               | 0.67                | 0.43                |
| P-3               | 0.41                | 0.21                |
| P-4               | 2.95                | 1.75                |

Table IV shows the differential changes in bulk density of porcelain samples by varying the amount of Kalalani vermiculite and the sintering temperature. The trend shows that at 20 %wt of Kalalani vermiculite the bulk densities changed from 1.81 g/cm³ at 1200 °C to 2.00 g/cm³ at 1250 °C. The change of the bulk densities of the porcelain samples indicates that, densification increased due to the decrease of closed porosity which was promoted with an increase in sintering temperature [17]. However, at 30 wt% of Kalalani vermiculite the bulk densities were 1.73 g/cm³ at 1200 °C and 1.69 g/cm³ at 1250 °C. This indicates that Kalalani vermiculite content above 20 wt% in the batch formed densification was not well achieved during sintering process.

The results of the current study are in agreement with the work of [5]. The author reported that, bulk density changed from 2.43 g/cm³ at 1250 °C to 2.46 g/cm³ at 1300 °C and 2.48 g/cm³ at 1350 °C while evaluating the effect of alumina on the mechanical and electrical properties of electrical porcelain with composition 35 % of kaolin, 25 % of Ball clay,15 % of feldspar, 5 % of alumina and 20 % of silica. The bulk densities results obtained in this study were within established standards for porcelain body 1.71-2.1 g/cm³ [18]. However, the variation of bulk densities of the porcelain samples in this study as shown in Table IV might have been caused by the method of production adopted composition of the raw materials made and the sintering temperature.

Table IV Bulk density of porcelain samples sintered at 1200 and 1250 °C.

| Porcelain samples | B.D. (g/cm³) at 1200 °C | B.D. (g/cm³) at 1250 °C |
|-------------------|--------------------------|--------------------------|
| P-1               | 1.83                     | 1.69                     |
| P-2               | 1.67                     | 1.75                     |
| P-3               | 1.91                     | 2.21                     |
| P-4               | 1.71                     | 1.89                     |

Table V shows that P-3 sample has the highest bending strength of 30.54 MPa at 20 wt% of Kalalani vermiculite content when sintered at 1250 °C. This might be due to vitrification and densification which filled the microcracks and voids in the microstructure of the porcelain sample [19]. Therefore, the mechanical properties of ceramic sample are strongly dependent on composition made, the sintering temperature and the sintering time [20]. The results of the study are in agreement with the works of [5, 16]. The author [16], observed an increase of bending strength in the electrical porcelain sample from 37 MPa at 1200 °C to 51 MPa at 1250 °C while the author [5], reported the increase of bending strength of electrical porcelain bodies from 39 MPa at 1250 °C to 50 MPa at 1300 °C. The increase of the bending strength of the electrical porcelain samples from both studies was due to sintering temperature which influenced densification and decreased microcracks and closed pores in the porcelain samples. It is therefore concluded that porcelain sample P-3 with 20 wt% Kalalani vermiculate produced the highest bending strength value of 30.54 MPa at 1250 °C which is close to 35 N/mm² as recommended by ISO-13006 for porcelain ware.
Tab. V Bending strength of porcelain samples sintered at 1200 and 1250 °C.

| Porcelain samples | Bending strength (MPa) at 1200 °C | Bending strength (MPa) at 1250 °C |
|-------------------|----------------------------------|----------------------------------|
| P-1               | 10.83                            | 12.70                            |
| P-2               | 6.34                             | 11.75                            |
| P-3               | 24.91                            | 30.54                            |
| P-4               | 7.71                             | 10.89                            |

Figure 6 Shows that, there is an increase of the dielectric strength of the porcelain samples at 20 wt% with an increase of the sintering temperature. At 20 wt% of Kalalani vermiculite the dielectric strength increased from 50.8 kV/mm at 1200 °C to 61.3 kV/mm at 1250 °C. This may be due to extensively increase of vitrification range exhibited by the porcelain samples at high sintering temperature. The author [16] reported that at optimum sintering temperature and composition a considerable amount of quartz and mullite crystals exist in the glassy phase which influence the dielectric properties of the electrical porcelain samples. Therefore the glassy phase has great influence to the dielectric properties of the sintered porcelain samples. However, the dielectric properties of electrical porcelain sample is determined by the concentration and mobility of K⁺, Al³⁺ and Na⁺ ions in the glassy phase [21].

Fig. 6. Dielectric strength of porcelain samples sintered at 1200 and 1250 °C.

4. Conclusion

The potential of using Kalalani vermiculite for the production of high strength porcelain insulators has been evaluated in this study. The porcelain sample P-3 with 20 wt% composition of Kalalani vermiculite gave the best physical-mechanical and dielectric properties. The resultant values are satisfactory for production of high strength porcelain insulators. It is therefore concluded that Kalalani vermiculite has the potential to be used for the manufacture of porcelain insulators. However, the method of production of porcelain samples adopted should be improved as less pressure was used to compact the powder samples which might have affected the physical-mechanical and dielectric properties of the porcelain samples during the sintering process. Moreover, care on the exfoliation nature and
the inability of Kalalani vermiculite to withstand high sintering temperature above 1250 °C should be taken into consideration.

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