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Ceramic Raw Materials in Tanzania – Structure and Properties for Electrical Insulation Application

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***Abstract*— Characterization of ceramic raw materials from Tanzanian deposits is carried out in order to investigate their potential as raw materials for production of electrical insulators. The raw materials utilized in this study are: Pugu kaolin, quartz supplied by Kilimanjaro Industrial Development Trust (KIDT), and Kilimanjaro feldspar.**

Increasing Pugu kaolin beyond 48 wt. % and reducing Kilimanjaro quartz content below 6 wt. % is leading to the reduction of electrical insulation and bending strength. The mix with constituent's percentage composition of 48 wt. % Pugu kaolin, 46 wt.% Kilimanjaro feldspar and 6 wt. % quartz is possessing the highest strength of 53.525 MPa. Moreover, this mix proportion shows insulation resistance of 34812 Mega ohms at injection of 1000 volts. In this regard, it is observed that a high quality electrical insulator can be achieved from Tanzania-originated ceramic materials.

Keywords: Ceramic raw materials, Electrical Insulation, Bending Strength, Porcelain, Mullite

I. INTRODUCTION

Electrical insulators are materials which inhibit the current flowing in electrical circuits [1]. In transmission and distribution system the overhead conductors are generally supported by towers or poles which are properly grounded. For this reason, there must be an insulator between tower or pole body and conductors to prevent the flow of current from conductors to the earth through grounded supporting towers or poles [2]. The electrical insulation is important for preventing damage and reliability of electrical system and equipment. On the other hand, it is a basis for protecting individuals from electric shocks and assures safety of personnel while carrying out electrical works. For this reason, there must be an insulator between the tower body and conductors to prevent the flow of current from conductors to the earth through grounded supporting towers [2].

Generally, the properties required for material being an insulator are high resistivity, high dielectric strength, good mechanical properties and protection of a conductor from severe environment like humidity and corrosiveness [1]. Dielectric strength and mechanical strength are two most important properties which must be taken into consideration. Electrical insulation resistance is a test which can be carried instead of dielectric strength test.

According to the international electrical testing association the minimum recommended value of insulation resistance of electrical systems and equipments is 1000 Meg ohms at the injection of 1000DC voltage however there is specific values of insulation resistance for a particular injected DC voltage [3] In the consideration of mechanical strength the Japanese Industrial Standards and their counterpart requires a minimum strength of 65MPa.

In application the insulation can be group to that for either high voltage or low voltage depending on the voltage involved. The International Electrotechnical Commission and its national counterpart terms low voltage as the voltage between 120 to 1500DC voltage and high voltage as the voltage above 1500DC voltage [4]. Dielectric strength is the measure of materials to withstand high voltage. The higher the dielectric strength the better is the electrical insulation [1]. For high tension electrical insulation the dielectric strength has to be above 3kV/mm [5].

The insulators are made from nonconducting materials such as porcelain, glass and composite polymers. Each of these materials has a number of advantages, 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 tendency of allowing path to leakage current once the air dust is deposited to the wet glass surface [2]. 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 [6].

Porcelain is the most commonly used material for overhead insulators. Porcelains are resistant to high temperature, electricity, and harsh environment than polymers [7]. Therefore, the use of porcelain insulators is highly recommendable for these reasons. Porcelain is a ceramic material primarily composed of clay, quartz, and feldspar. Each of these materials plays its respective role in the properties of the blend formed from green to the fired body. Clay [$Al_2Si_2O_5$ $(OH)_4$] gives plasticity to the ceramic mixture; flint or quartz (SiO_2) maintaining the shape of the formed article during firing, and feldspar [KxNa1-x ($AlSi_3$) O_8] serves as flux to lower the melting point of the mixture. These three constituents place electrical porcelain in the phase system [(K, Na) 2O-Al_2O_3-SiO_2)] in terms of oxide constituents hence the term triaxial porcelain [8, 9].

These raw materials are readily available at lower cost compare to other types of insulators which are based on industrially processed materials. Under controlled heating and cooling rates as well as firing cycles, it is possible to influence the properties of the final products which originate from the blend produced from these raw materials [10]. Also different properties can be achieved by varying the constituent's percentage compositions of materials.

Over a period of time different researchers came up with number of alternatives in researching material performance in terms of both mechanical and dielectric properties. Quartz as a filler material has been pointed out to have detrimental effect in the performance of ceramics product. Excessive amount of quartz may lead to the initiation of non-coherent interface in structure, micro crack formation and decrease of mechanical properties [11-13]. Different studies have been made in an attempt of minimizing the use of quartz as filler materials. Some of studies are: replacement of quartz with alumina [11, 13]; substitution of fly ash for quartz [14] ; and the substitution of quartz by rice husk ash and silica fume [15].

The dielectric and mechanical properties of ceramics are affected by the phases which are developed on sintering. Phases which are important for proper electrical insulation and mechanical strength are mullite and glassy phase. Mullite phases particularly the one which is needle like shaped proved to perform well in electrical insulation property. On the other hand, existence of excessive amount of glassy phase promotes free movement of ion hence poor electrical insulation properties [1]. In alumina based insulators corundum phase proved to have great contribution to electrical insulation and mechanical properties [11].

Evaluation of the structure and properties of raw materials is a primary step which leads to proper design of a particular structural component for intended performance. Through characterization of materials, chemical components of interest and harmful ingredients can well be quantified and checked if they comply with the requirements. The aim of this work was to characterize the local ceramic materials from some selected Tanzanian deposits to evaluate their potentials as raw materials for production of electrical insulators.

II. EXPERIMENTAL PROCEDURES

A. Raw Materials

The analysis of raw materials involved feldspar from Kilimanjaro, and quartz supplied by Kilimanjaro Industrial Development Trust (KIDT .After crushing and grinding the raw materials to powder form, pellets of respective raw materials were formed by pressing The prepared pellets were fired at the temperatures ranging from 600ºC to 1400ºC .The crystalline structural phases for each firing temperature are determined by X-ray diffractometer of Rigaku Corporation/D/max 2200V/PC having a 3kW X-ray generator Cu-target. Physical properties such as water absorbance, apparent porosity, apparent density and bulk density of samples sintered at different temperatures were determined by Archimedes method.

B. Blends formed from Raw Materials

For investigating the electrical insulation and mechanical strength, cylindrical samples of 60mm length and 10mm diameter from six blends of Pugu kaolin, quartz, and feldspar were fabricated by slip casting followed by air drying. Then samples were bisque fired at 800ºC before being sintered at the maximum temperature of 1300ºC in an industrial furnace at the approximate rate of 100ºC/h with one hour soaking time.

Insulation resistance of the fired samples was measured by (Megohmmeter AEMC instrument model 1060) by subjecting the test samples to 1000 DC voltage for 1 minute and recording the displayed value of insulation resistance. Bending strength of samples was determined by three point bending test strength machine manufactured by MFG CO.LTD model No. 704372. The load at failure in Kgf was recorded for ten test samples. The span of 50mm was used in testing the samples.

$$\text{Bending strength} = \frac{Fs * L}{\pi R^3} \quad (1)$$

Fs = Load at Failure
R = Radius of a sample
L = Span (Centre to centre from suport)

TABLE 1. BATCH COMPOSITIONS (WT. %)

Component	**Batches**					
	C1	C2	C3	C4	C5	C6
Al_2O_3	25	30	35	40	45	50
SiO_2	80	75	70	65	60	55
K_2O	15	15	15	15	15	15

Values from theoretical batch calculations (Combination of Pugu kaolin, Quartz and Feldspar)

III. RESULTS AND DISCUSSION

A. Properties and Structure of Raw Materials

- Chemical composition of raw materials

The chemical composition of raw materials used in this study is shown in Table 2. The composition purity requirements of raw materials for insulators application are: in clays (Fe_2O_3, TiO_2) <3.5%; in quartz; SiO_2 >99%; and in feldspar Fe2O3 <1%; (Ka_2O, Na_2O) >12% [16].

This chemical composition analysis is showing that the content of components is closely related to the requirements for insulators manufacturing. Kilimanjaro Feldspar composed of relatively small amount of detrimental oxide which meets the percentage purity requirements of raw materials for electrical insulator application as reported by (Meng, 2012) [16]. The amount of flux (K_2O Na_2O) in feldspar is 14.94% which complies with the composition purity requirement for raw materials since (K_2O Na_2O) has to be greater than 12%.

TABLE 2. CHEMICAL COMPOSITION OF RAW MATERIALS

Oxide	Feldspar	Quartz
SiO_2	53	97.7
Al_2O_3	19.1	-
Fe_2O_3	0.24	-
TiO_2	-	-
CaO	0.09	-
MgO	0.01	-
Na_2O	2.04	-
K_2O	12.9	-
Loss on Ignition	12.62	2.3

- Crystallographic Structure of Raw Materials

The XRD results showed that feldspar the raw materials contains albite, and microcline, tridymite and quartz as other phases developed on sintering as indicated in Fig. 1. The feldspar major components of interests are: potash feldspar ($K_2O.Al_2O_3.O.6SiO_2$); soda feldspar ($Na_2O.\ Al_2O_3.O.6SiO_2$); and lime feldspar ($CaO.Al_2O_3.O.6SiO_2$). Potash feldspar is usually crystallized in monoclinic form as orthoclase or in triclinic form as microcline where as lime and soda feldspar crystallizes in triclinic form as anorthite and albite [17].

The results indicate that feldspar under study contains high content of potash feldspar compared to soda feldspar since the chemical composition by XRD shows K2O is 12.9% while Na2O is only 2.04%.

The XRD pattern in shown in (Fig.1) started to change beyond 1200ºC, this is because beyond 1200ºC there was a phase change from crystalline to amorphous this is well demonstrated by the sharp peaks below between 600 and 800ºC and spread with almost no sharp peaks above 1200ºC.

With amorphous phase: X-rays will be scattered in many directions leading to a large bump distributed in a wide range (2 Theta) instead of high intensity narrower peaks.

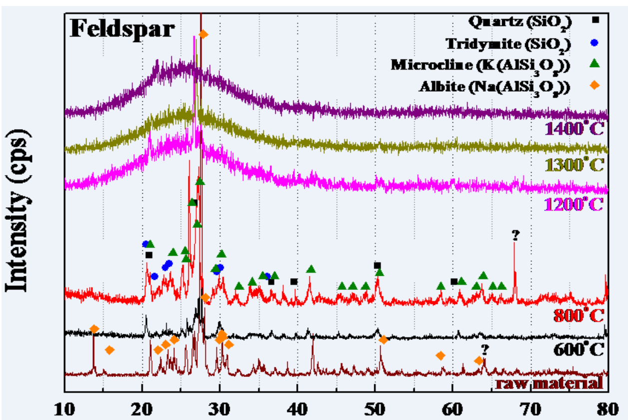

Fig. 1. X-ray Diffraction Patterns for Kilimanjaro feldspar .

In the XRD- crystallographic study of quartz the maximum peak is revealed around 25 (2θ-degree) which is typical diffraction angle for quartz. The 2.3% loss on ignition in quartz raw materials in Table 1 demonstrate that quartz content was not 100% which implies there was some water contained in quartz.

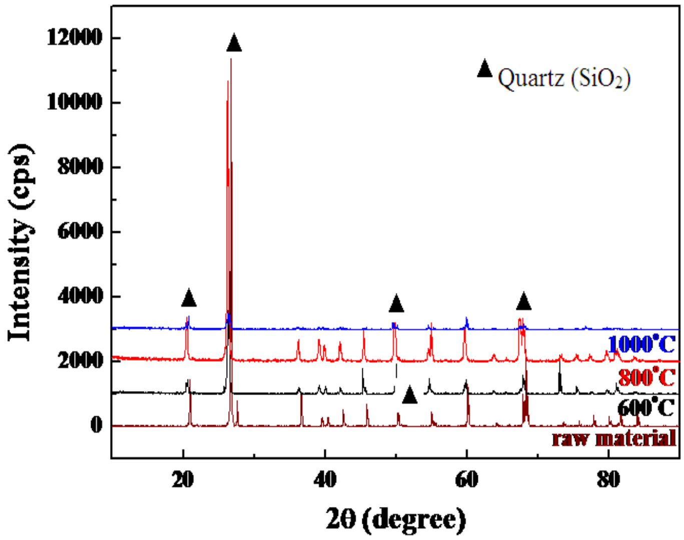

Fig. 2. X-ray Diffraction Patterns for Pugu kaolin

On the other hand, the study made to Pugu kaolin by (Hashimu. Hamis, 2014) [18] is revealed the development of mullite phase when fired at 1400ºC. Mullite is a very important phase in promoting the mechanical and dielectric properties.

- Bulk Properties of Raw Materials

On sintering feldspar samples, the linear shrinkage continued to increase up to 800ºC and in further increase in sample's firing temperature the decrease in linear shrinkage was noted as indicated in (Fig.3). Water absorption of the sintered feldspar samples is found to increase above 1200ºC and started to drop abruptly beyond 1300ºC. In connection with the results in Table 3, the maximum densification with low level of apparent porosity was observed at 1200ºC and above this temperature densification decreased with increase in apparent porosity which implies that the optimum sintering temperature for feldspar is 1200ºC.

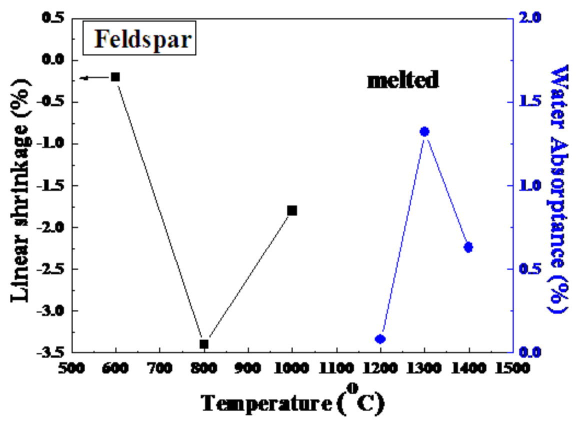

Fig. 3. Linear Shrinkage and Water absorption for feldspar

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TABLE 3. BULK DENSITY AND APPARENT DENSITY (FELDSPAR)

Heat treatment temperature (°C)	Apparent density (g/cm^3)	Bulk density (g/cm^3)	Apparent Porosity (%)
1200	2.318	2.313	12.3
1300	2.299	2.232	11.5
1400	2.284	2.251	12.7

B. Properties of Blends formed from Raw Materials

- Bending Strength

The highest bending strength of 53.525MPa is achieved to samples composed of 48% Pugu kaolin, 46wt% Kilimanjaro feldspar, and 6% Kilimanjaro quartz. Strength is found to increase with an increase in content of Pugu kaolin while reducing the content of Kilimanjaro quartz. Decreasing quartz beyond 6wt% and increasing Pugu kaolin beyond 48wt% is leading to the reduction of strength as indicated in Table 5, and (Fig.4).

TABLE 4. MIX PROPORTION OF RAW MATERIALS FOR BATCHES OF TABLE 1 (NORMALIZED WT. %)

Raw Material	Batches					
	C1	C2	C3	C4	C5	C6
Pugu Kaolin	9	22	33	41	48	54
Quartz	19	14	11	8	6	4
Feldspar	72	64	56	51	46	42

The samples with high content of Kilimanjaro quartz are found to be weaker in bending strength. Low strength is accredited by the development and propagation of cracks which is due to quartz and glass thermal mismatch [17] .Similarly, increasing the content of Pugu kaolin is leading to the increase in alumina content hence increase in strength this argument is well supported by the chemical composition study where by Pugu kaolin is found to possess the highest amount of 34.7% alumina content.

- Electrical Insulation Resistance

The samples of mix proportion “C2” with 14wt% Pugu kaolin, 22wt% Kilimanjaro quartz, and 64wt% Kilimanjaro feldspar revealed the highest value of insulation resistance of 42750MΩ at the maximum injection 1000 volts but this sample was characterized by very poor bending strength.

The lower strength is attributed by the cracks and flaw developed to samples of this mix proportion. For this reason, to take care of both the mechanical strength and insulating property; the mix proportion “C5” is acceptable so long as it has shown good performance in both strength and electrical insulation and the samples of this mix proportion were free from cracks and flaws (Fig.5) and Table 5. International Electrical Testing Association recommends the minimum insulation resistance of 500Meg ohm at the injection 1000DC voltage. With this test sample “C5” the insulation resistance of 34812 Meg ohms at injection of 1000 DC voltage is achieved.

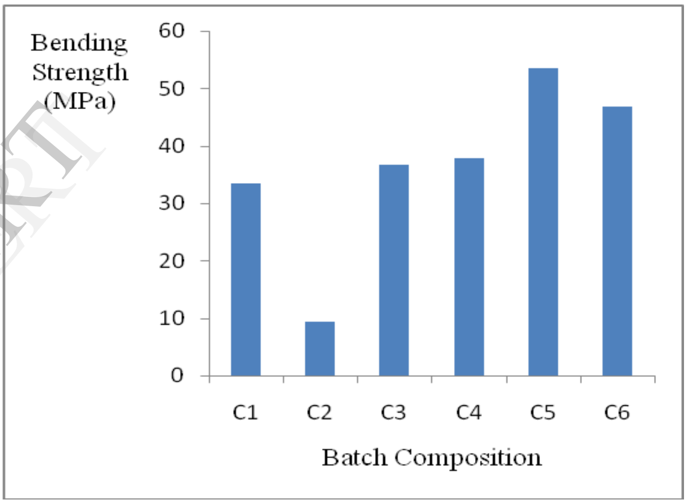

Fig. 4. Bending Strength of Samples from different Mix Proportion

TABLE 5. INSULATION RESISTANCE AND MECHANICAL STRENGTH OF PREPARED BATCHES

Mix proportion	Insulation Resistance at the injection of 1000V (MΩ)	Linear Shrinkage (%)	Bulk density(g/cm3)	Water absorption (%)	Strength (MPa)
C1	25592	11.917	2.855	0.21	33.52
C2	42750	13	2.213	0.11	9.421
C3	11720	12	2.288	0.32	36.72
C4	10404	11	2.028	0.22	37.86
C5	34812	9.5	1.988	0.77	53.53
C6	16844	10.167	1.823	1.24	46.88

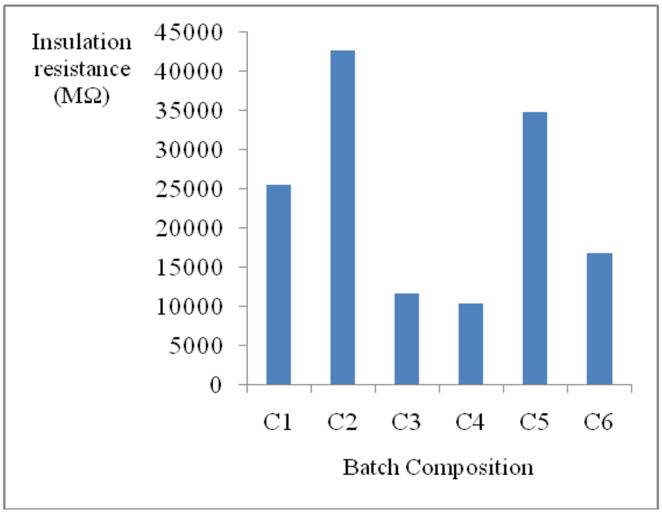

Fig. 5. Electrical Insulation Resistance of samples from different Mix Proportion

- Total shrinkage

The linear shrinkage percentage of porcelain was found to decrease with increasing kaolin content while reducing the content of quartz and feldspar as indicated in Tables 5 and (Fig.6). This is attributed by the nature of kaolin as a clay material. The experienced shrinkage is due to drying and firing of the porcelain. The samples with low shrinkage values are established to be accompanied with low bulk density and high strength comparing to those with high values of shrinkage.

- Bulk Density

The bulk density is decreasing with decrease in the content of Kilimanjaro feldspar. This is because feldspar is low melting minerals and serves to lower the temperature at which viscous liquid forms. The liquid phase reacts with other components and fills the pores leading to its densification [17]. Thus, with high content of Kilimanjaro feldspar, the density is high which continued to decrease as the content of Kilimanjaro feldspar is reduced (Fig.7) and Table 5.

This trend in bulk density is also accompanied with increasing the content of Pugu kaolin while reducing the content of Kilimanjaro quartz. On the other hand, bulk density is found to increase with increase in linear shrinkage, this suggests that interparticles distance between particles has been reduced and pores have been minimized leading to increase in density.

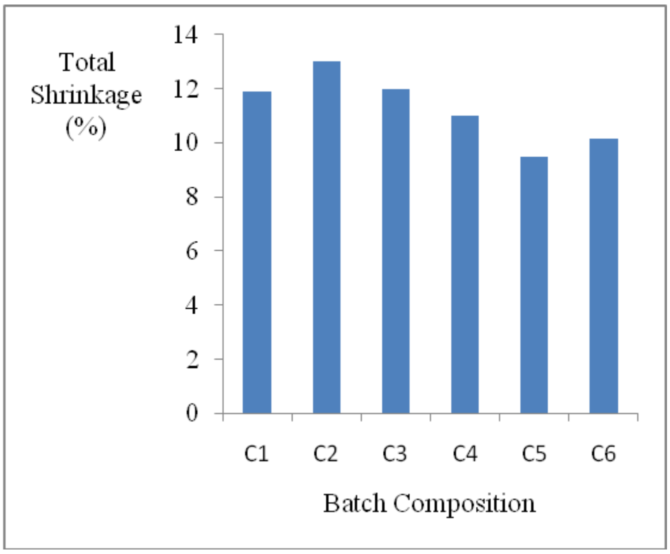

Fig. 6. Linear shrinkage of samples from different Mix Proportion

- Water Absorption

Water absorption is observed to decrease with increasing kaolin content and reduction of feldspar as indicated in Tables 5 and (Fig.8). Feldspar as a flux form viscous liquid which permits better flow of the mixture by doing so it bridges the pores and reduces water absorption. In this regard, reducing the content of feldspar creates more porosity hence higher water absorption.

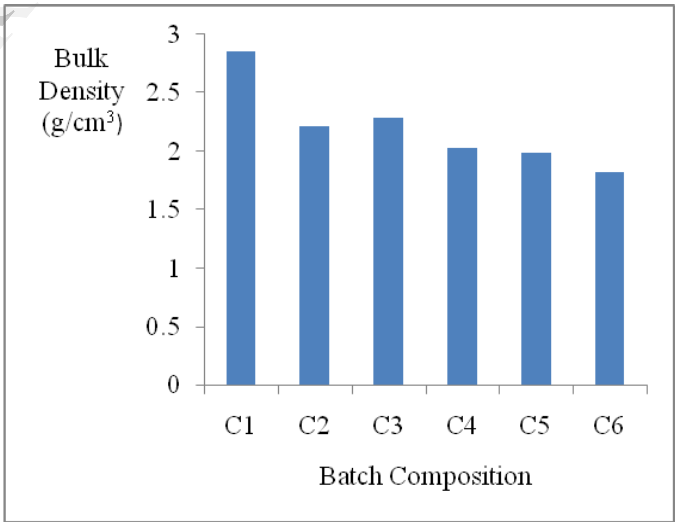

Fig. 7. Bulk density of samples from different Mix Proportion

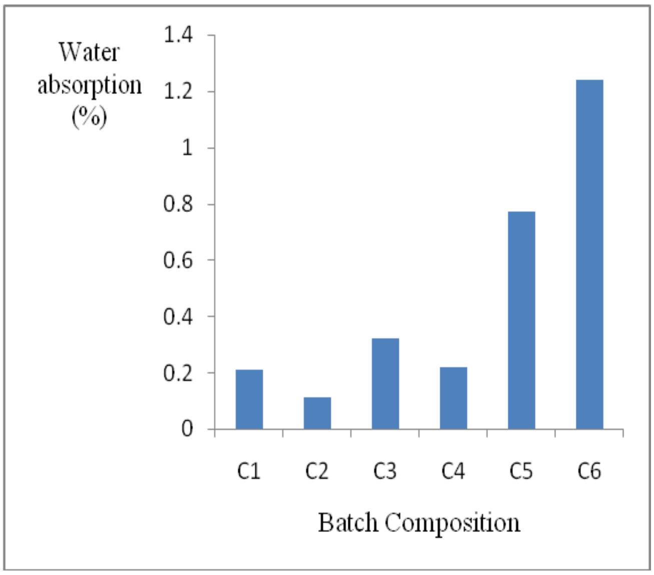

Fig. 8. Electrical Insulation Resistance of samples from different Mix Proportion

IV. CONCLUSION

Electrical insulation and bending strength is increasing with reduction of Kilimanjaro quartz content while increasing the content of Pugu kaolin. Essentially, increasing Pugu kaolin beyond 48 wt. % and reducing Kilimanjaro quartz content below 6 wt. % is leading to reduction of electrical insulation and bending strength. In addition, the mix with constituent's percentage composition of 48 wt. % Pugu kaolin, 46 wt.% Kilimanjaro feldspar and 6 wt. % Kilimanjaro quartz is possessing the highest strength of 53.525 MPa.

This mix proportion shows the electrical insulation resistance of 34812 Meg ohms at injection of 1000 volts where the required minimum insulation resistance at the injection of 1000DC voltage is 500 Mega ohms.

To this end, use of Pugu kaolin for production of electrical insulators is encouraged as formation of mullite phase improves the mechanical strength and insulation resistance. In this aspect, these results are indicating that a high quality electrical insulator can be achieved from Tanzanian originated ceramic materials.

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