Influence of Alumina and Silica Addition on Structure and Properties of Ceramic Insulators

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Abstract—**Silica and Alumina based Porcelains are being majorly used in electrical applications. However, these porcelains have lower electrical strength due to the increased glass phase. This study aims to investigate a mechanically and electrically strong enough porcelain insulator by optimizing the chemical composition of Alumina and Silica. Here, three electrical porcelains have been prepared with different amounts of Alumina and Silica compositions and fired in an industrial furnace at 1300°C. The characterization techniques were adopted to evaluate the variations in structural and micro-structure, respectively, through enhancing and lowering the weight concentration of Silica and Alumina for the base composition of the porcelain insulator. The tensile strength and physical behavior measurement was analyzed for all the samples. The Alumina and Silica composition sample with 35 and 10 weight% indicates a maximum density of 2.50 grams per cubic centimeter with water absorptive of 1.83%. The highest tensile, compressive, and electrical strength values of 35 Mega Pascal, 178 Mega Pascal, and 23.1 kiloVolt per millimeter were achieved. Scanning Electron Microscopy revealed dense particles and uniform distribution of long and thin needle-shaped mullite are predominant in sample microstructures with the highest electrical strength.**

Index Terms—**Ceramic Insulator, Alumina Porcelain, Scanning Electron Microscopy (SEM), Silicate Porcelains.**

1. INTRODUCTION

Porcelain insulators are one of the crucial insulators used for more than 100 years among other insulators. The core areas of application of electrical porcelains are electricity transportation and distribution. These porcelains are used to insulate the electrical lines and separate them from support structures. Good electrical and mechanical properties are essential for these porcelains with more than 30 years of sustainable life [1-3]. Therefore, the high-voltage line is favorite area of application of it. The crucial aim of high voltage insulators is to increase the mechanical and electrical strength properties. They may achieve this by developing materials from hard porcelain to quartz and alumina-based materials [3]. In the IEC672-2 standard, these porcelains are classified into five groups such as (a) Steatite porcelains (class C-220), (b) Quartz porcelains (class C-110), (c) Alumina Porcelains (class C-120 with 30-50 wt. % Alumina and class C- 130 with more than 50 wt. % Alumina), (d) Cristobalite Porcelain (class C-112) and (e) High Alumina porcelains (class C – 780 with 80-86 wt. % Alumina and class C-786 with 86-94.5 wt. % Alumina) [4]. In these above groups, the bending strength of steatite porcelains increased from 70-250 MPa in high alumina porcelains [3]. In addition, the high strength of this group, high alumina porcelain, has been used widely in fabricating high voltage insulators because of their low electrical conductivity, stability in oxidative and corrosive environments, and good resistance to aging. Silicate and Alumina porcelains have the highest application among electrical porcelains, but the increased glass phase in Silicate porcelains leads to decreased electrical strength in these materials. In addition, in Silicate-based porcelains, the presence of un-dissolved quartz leads to the initiation of a non-coherent interface in structure, micro-crack formation, and decreased mechanical properties [5]. It is reported that cooling the insulator sample results in a quartz grain volume decrease of 2%, which produces sufficient strain to cause cracking of the glassy matrix and the quartz grains. The quartz particle size and the cooling rate dictate the cracking severity [6].

On the other hand, alumina-based porcelain does not have any phase transformation. Therefore, they do not have any affinity for crack formation during cooling and are usually stronger than quartz porcelains. This behavior relates to corundum phase formation in these porcelain types 7-8. Increased Alumina content in these porcelains by up to 15%, increases mechanical strength to 44%, and the quartz-to-mullite ratio decreases compared to porcelain samples without Alumina 8. In addition, researchers reported that Alumina increases the mechanical strength by replacing filler material, and the bending strength of porcelain increases by 200% 9 if its volume fraction is increased to 36% by weight. The microstructure dramatically affects the strength and reliability of high alumina porcelains. The grain size, amount, and distribution of produced phases in the production process affect porcelain's physical and mechanical properties9. In Alumina porcelains, optimum mechanical properties can be achieved using a corundum microstructure with less than 3 µm diameter of well-distributed particles 9. In the other study, the strength of Alumina and porcelains is related to acicular mullite interlocking, mullite amount, and size 10. Two significant parameters are the porcelain material's glassy phase and unresolved quartz particles. Acceptable electrical performance may be achieved with a decrease in the glassy phase because of the high mobility of ions 8. This study aims to investigate the increase in mechanical and electrical properties and optimize the microstructure of porcelain insulators. In this article, changing the chemical composition of porcelains insulator has been optimized by varying especially wt% of Alumina and Silica content.

2. MATERIALS AND METHODS

2.1 Material Preparation:

A mixture of 25% of kaolin (w/w), 20% (w/w) of ball clay, and 10% (w/w) of Feldspar, a ceramic porcelain insulator, was prepared with varying % wt. of Alumina (Al2O3) and Silica (SiO_2). Due to their hygroscopic nature, Feldspar, ball clay and kaolin are heated in an oven at 105 ±5°C for 24 hours to remove their moisture content [11-13]. Later, the raw materials (Kaolin, Ball clay, and Feldspar) were passed through a 120 µm mesh sieve to obtain a uniform particle size. In the same way, the Silica and alumina contents were also passed through an 80-micrometer of meshed sieve to obtain a particle size of 80 micrometers. Three compositions (Table 1) of ceramic porcelain insulation were prepared using varying concentrations of Silica and Alumina. Below mentioned steps are used for the preparation of ceramic porcelain insulation.

- Raw materials are put into agate and completely handed. Later it was mixed for about 30 minutes with the help of a pestle.
- To reduce the particle size and get homogeneous. Mixing materials are kept for 30 minutes in a ball mill. The above procedures were repeated 8-10 times to obtain homogeneity in particle sizes.
- Four drops of 5% polyvinyl alcohol are used as a binder in the prepared composition and mixed up for 30 minutes.
- Using a hydraulic press machine, the composition was compacted and prepared with a pressure load of 160 MPa for making pellets (samples). Similarly, samples named A1, A2, and A3 were prepared.

Each prepared sample (A1, A2, A3) having different compositions was sintered at 1300°C as suggested. Detailed compositions of all the samples are shown in Table 1.

Table 1: Quantity of raw material in the fabricated sample

Code	Kaolin, % w/w	Ball clay, % w/w	Feldspar, % w/w	Sillica, % w/w	Alumina, % w/w
A1	25	20	10	0	45
A2	25	20	10	10	35
A3	25	20	10	20	25

2.2 Characterizations of Samples

All the samples were characterized by their physical, mechanical, and thermal properties. Physical behavior, such as the bulk density of the samples, was determined as per ASTM C20; a Universal Testing Machine was used to know the compressive and tensile strength of the sintered samples. In addition, X-ray diffraction (XRD) characterization was done to know the sample microstructures, and it was further examined with Scanning Electron Microscopy (SEM) (refer Fig. 1).

Fig. 1: Actual Image of Setup

3. RESULTS AND DISCUSSION:

The effect of Silica on the electro-mechanical properties of porcelain materials was evaluated. The coded samples (XRD patterns) A1, A2, and A3, sintered at 1300°C, are shown in Fig.2

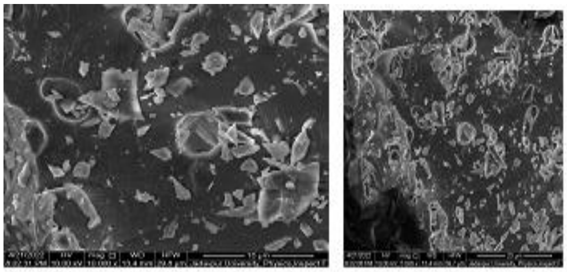


Fig. 2: XRD patterns of samples sintered at 1300 °C.

During sintering, the formation of different phases was identified by performing the X-ray diffraction analysis. The patterns achieved through this diffraction revealed the presence of Alumina (corundum), β-Cristobalite, and mullite phase (M) in the samples. As the concentration of Silica increased and Alumina decreased, the significant peak intensity decreased, corresponding to Alumina (A). It may be because, at high temperatures, the dissolution of the Alumina in the glassy phase might have taken place. With increasing the Silica concentration (0-20 % w/w.) in base composition, the β – Cristobalite phase starts to develop from 10 to 20% w/w of Silica (Fig. 2). The surface topographies confirmed the presence of little agglomeration and porosity in the samples. SEM micrograph analysis (Fig. 3) for the sintered sample at 1300°C shows no formation of phase separation in any compositions in the mullite phase (primary and secondary). At 1300°C, the presence of the particles in the material is more porous and agglomerated, slightly uniform, and homogeneous. Critical analysis of Fig. 3 reveals that as the Silica content was up by 10%, pores probably disappeared because of the glassy phase of Silica-filled pores. It may be the reason behind the increased density of the material, which increases mechanical strength. At 15% and above addition of Silica content, strength will decrease due to non-bonding additional free Silica content, resulting in close pores increases (Fig. 3)

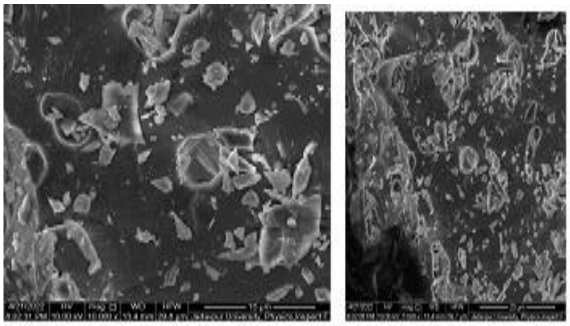


Fig. 3(a): SEM Micrograph of Sample A1 [Sillica: 0%, Alumina: 45%]

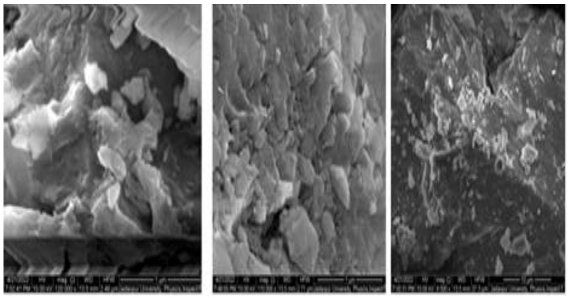
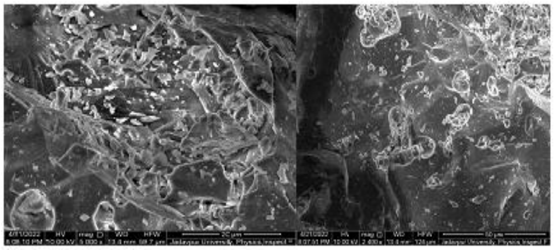


Fig. 3(b): SEM Micrograph of Sample A2 [Sillica: 10%, Alumina: 35%]

It may be noted that due to the excess Silica present in the composition (more than 10 % w/w), the β-Cristobalite phase begins to develop, resulting in a decrease in the strength of the sample. The sintering temperature directly affects the β-Cristobalite phase of Silica. Phase transformation occurs to α-Cristobalite from the β phase just after the cooling of the sample starts. The volume contraction occurs during this time, leading micro–crack generation in the sintered samples. Considering the mechanical strength and chemical stability, 10% w/w Silica composition can be considered more suitable for porcelain insulator bodies.

Table 3 summarizes the effect of different percentages of Silica at 1300˚C sintering temperature on samples' bulk density, linear shrinkage, and water absorption capacities. It is also presented graphically (Fig. 4) close look at the table and figure and table reveals that the water absorption capacity of the sample decrease with the addition of Silica up to 10% in the base composition. It indicates that water absorption should be minimal or zero for good high-voltage electrical porcelain. The water absorption dropped to a minimum by adding 10 %w/w/w SiO_2 with 35% w/w Al_2O_3 with a soaking period of 2 hours. It is also noted that with further addition of SiO2, the physical properties of samples start to decrease due to an excess amount of glassy Silica content dispersed on the surface of the porcelain body, increasing the closed pores in the porcelain body (Fig. 3).



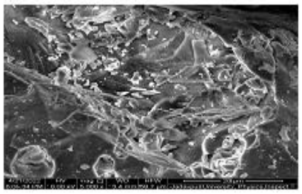


Fig. 3(c): SEM Micrograph of Sample A3 [Silica: 20%, Alumina: 25%]

Table 3: Effect on linear shrinkage, bulk density, and water absorptive at sintering temperature 1300˚C and different % w/w of Silica

% Silica content	0	10	20
Bulk density, gm/cc	2.44	2.5	2.4
Linear shrinkage, %	7.67	8.21	6.66
Water absorption, %	3.24	1.83	3.74

3.1 Bending, Compressive and Tensile Strength of Samples

A rectangular specimen (40 mm,10 mm, 10 mm) was used as the mold for the three-point bending test, and a cylindrical specimen with a dimension of 30 mm (diameter) was used for compressive strength measurement. For tensile strength measurement, samples prepared from different compositions and sintered at 1300°C with a soaking period of 2 hours were used. Samples with the specification of 25 mm gauge length, 7 mm width,10 mm thickness, and 40 mm overall length were considered and tested with a universal testing machine at a strain rate of 2 mm/min. The maximum mechanical strength was observed in sample A2 having bending strength (132 MPa), tensile Strength (37 MPa), and compressive Strength (203 MPa). The decrease in strength for samples A1 and A3 is due to increased porosity and decreased density. It is also proved from XRD; with more addition of Silica from 10 to 20%w/w developed a B-Cristo-barite phase at high temperatures.

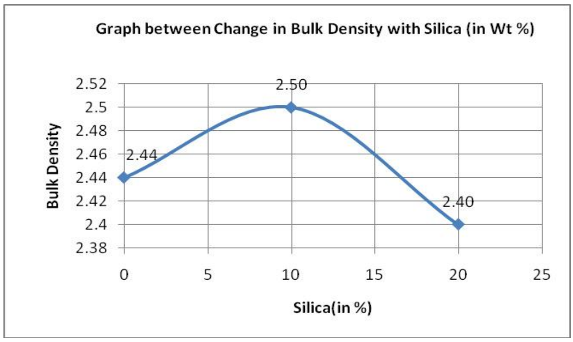


Fig. 4(a): Effect on Bulk Density with the different % w/w of Silica (0- 20%) at 1300°C sintered temperature.

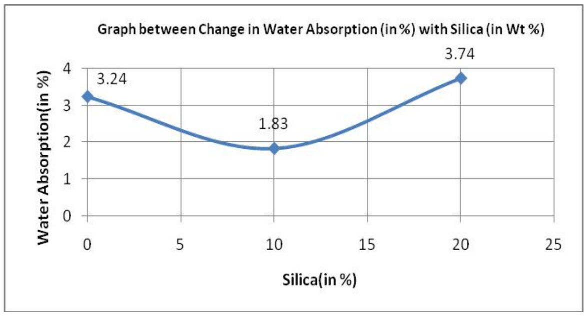


Fig.4(b): Effect on Water Absorption with the different % w/w of Silica (0- 20%) at 1300°C sintered temperature

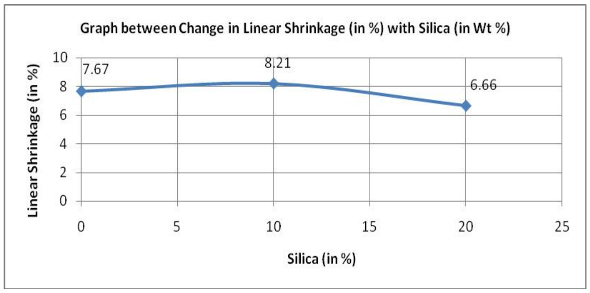


Fig.4(c): Effect on Linear Shrinkage with the different % w/w of Silica (0- 20%) at 1300°C sintered temperature

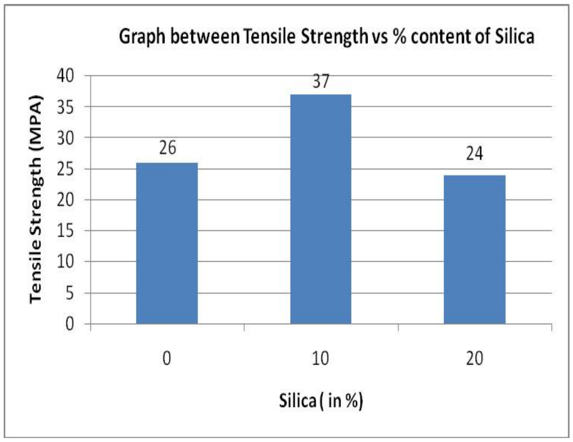


Fig: 5: Relation between Tensile Strength and % w/w of Silica

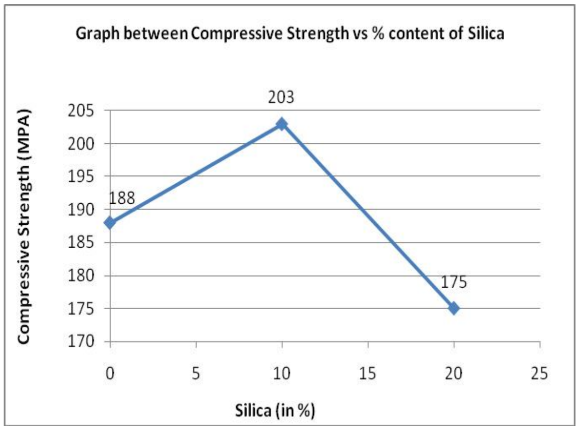


Fig: 6. Relation between compressive Strength and % w/w of Silica

3.2 Electrical Strength

The electrical strength of fired samples was measured. For this, one end of the test specimen is connected to a high-voltage terminal, and the other is connected to the ground. With the help of the control panel, the voltage was applied in steps (varied from 20.2 to 23.5kV), and it was increased until a breakdown in the unit occurred. Details results are tabulated in Table 4.

Table 4: Electrical strength of Sample

Sample Marked	Electrical strength
A1	21.8 KV
A2	23.1 KV
A3	23.5 KV

A close look at Table 4 shows sample A1 can tolerate Electrical Strength up to 21.8kV; however, sample A3 can tolerate electrical strength up to 23.5kV. It may be due to the low temperature of the sintering. The low sintering temperature is unsuitable for high alumina samples, and the lack of liquid phase for filling open pores may be responsible for the decrease of Electrical strength in high alumina samples (A1). Capillary cracks around the unsolved quartz phase are one of the reasons for low electrical strength.

4. CONCLUSIONS

A porcelain insulator having strong mechanical and electrical properties was prepared using a considerable amount of economical clay, Silica, and Alumina. The porcelain insulator with a composition of 10% w/w Silica and 35% w/w Alumina sintered at 1300°C is most suitable for mechanical and electrical applications. Water absorptive of the bodies was observed to decrease due to the non-availability of micro-cracks and pores filled with Silica with Alumina melted glassy content. Compressive strength, bending strength, and tensile strength of porcelain insulator A3 were observed as 203MPa, 132MPa, and 37MPa, respectively. Considering the mechanical strength and chemical stability, the 10 %w/w silica composition can be considered more suitable for porcelain insulator bodies.

Abbreviations
XRD: X-ray diffraction
SEM: Scanning Electron Microscopy
Nomenclature:
˚C: Degree Celsius
wt. %: Weight percentage
MPa: Mega Paskal
µm: Micron

w/w: Weight per weight
gm/cc: Gram per cubic centimeter
kV/mm: Kilo Volt per millimeter

Declaration

- The authors have no relevant financial or non-financial interests to disclose.
- All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.
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- All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.
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Data Availability Statement : Data sharing not applicable to this review article as no datasets were generated or analysed during the current study.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by R.N. Singh, K.P. Tiwari and S. Gangopadhyay The first draft of the manuscript was written by R.N. Singh and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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