Effect of chemical composition and alumina content on structure and properties of ceramic insulators

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MS received 23 April 2012; revised 17 October 2012

Abstract. In the present work, six electrical porcelain compositions with different amount of alumina and silica have been prepared and fired in an industrial furnace at 1300 °C. Density, porosity, bending strength and electrical strength were measured in the samples. In order to find a relationship between properties and sample microstructures, samples were analyzed by scanning electron microscope (SEM) and x-ray diffraction (XRD) techniques. The results showed that, with chemical composition of 53.5 wt.% SiO₂ and 37.5 wt.% alumina, highest electrical strength of 21.97 kV/mm was achieved in fabricated electrical porcelains. Increasing amount of alumina up to 30 wt.% decreases quartz and cristobalite phases, but increases corundum phase 3 to 5 times. SEM observation revealed that dense particles and uniform distribution of long and thin needle shaped mullite are predominant in sample microstructures with highest electrical strength.

Keywords. Porcelain insulators; bending strength; dielectric strength; phase structure; mullite structure.

1. Introduction

Electrical porcelains are widely used in transportation and distribution of electricity. The main responsibility of these porcelains is insulating of electrical lines from support structure. These porcelains must have good mechanical and electrical properties and must retain these properties for more than 30 years (Ramaswamy *et al* 2005). In high voltage insulators, the main objective in recent decades is to increase the mechanical and electrical strength properties. These are achieved through the development of materials from hard porcelain to quartz and alumina porcelain based materials (Gobur *et al* 1999). In IEC672-2 standard, these porcelains are classified into five groups:

- (I) Steatite porcelains (class C-220).
- (II) Quartz porcelains (class C-110).
- (III) Alumina porcelains (class C-120 with 30–50 wt.% alumina and class C-130 with more than 50 wt.% alumina).
- (IV) Cristobalite porcelain (class C-112).
- (V) High alumina porcelains (class C-780 with 80–86 wt.% alumina and class C-786 with 86–94.5 wt.% alumina) (IEC 672-2 1980).

In these groups, bending strength increased from 70 MPa in steatite porcelains to 250 MPa in high alumina porcelains (Gorur *et al* 1999). In addition to high strength of this group,

high alumina porcelain has been used widely in fabrication of high voltage insulators because of their low electrical conductivity, stability in oxidative and corrosive environments and good resistance to aging (Holtzhausen 1992).

Silicate and alumina porcelains have highest application among electrical porcelains, but increase of glass phase in silicate porcelains lead to decrease in electrical strength in these materials. In silicate based porcelains, presence of undissolved quartz lead to initiation of non-coherent interface in structure, micro crack formation and decrease of mechanical properties (Amig and Serrano 2005). Cooling the insulator sample (573 °C) results in quartz grain volume decrease of 2%. This can produce sufficient strain to cause cracking of the glassy matrix and the quartz grains. The cracking severity is dictated by the quartz particle size and the cooling rate (Carty and Senapati 1998). On the other hand, alumina based porcelains do not have any phase transformation. They do not have any affinity for crack formation during cooling and are, therefore, usually stronger than quartz porcelains. This behaviour is related to corundum phase formation in these porcelain types (Morrell 1985; Vazquez and Mejia Velasquez 1998). By increasing alumina content in these porcelains up to 15%, mechanical strength is increased to 44% and quartz to mullite ratio decreased in comparison to porcelain samples without alumina (Vazquez and Mejia Velasquez 1998). It is reported in a research work that the replacement of filler material by alumina increases the mechanical strength and, if its volume fraction is increased to 36% by weight, the bending strength of porcelain increases by 200% (Khandelwal and Cook 1970).

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Microstructure has major effect on strength and reliability of high alumina porcelains. The main factors influencing physical and mechanical properties of porcelains are grain size, amount and distribution of produced phases in the production process (Khandelwal and Cook 1970). Orlova *et al* found that, in alumina porcelains, optimum mechanical properties are achieved by using a corundum microstructure with less than 3 μm diameter well distributed particles (Vazquez and Mejia Velasquez 1998). On the other study strength of alumina porcelains are related to acicular mullite interlocking as well as mullite amount and size (Ebrahimi *et al* 2000). Otherwise, the glassy phase and unresolved quartz particles are the two major parameters of porcelain material. Because of high mobility of ions, acceptable electrical performance may be achieved with decrease in the glassy phase (Vazquez and Mejia Velasquez 1998).

In this research programme, changes in the chemical composition, especially the alumina content on the mechanical and electrical properties as well as the microstructure of porcelains, have been investigated. This study is mainly focused on the development of the chemical composition of high voltage porcelains.

2. Experimental

The materials used in this research are: Quartz (Setabran Mine, Esfahan, Iran), Alumina (Nabaltec Company, Germany), Potassium Feldspar (Chghai Mine, Hamedan, Iran), Zenuz Kaolin (Marnd Mine, Ardebil, Iran), Abadeh Ball clay (Abadeh Mine, Shiraz, Iran) and Kerman Ball clay (Kerman Mine). The results of chemical analysis of raw materials are shown in table 1.

The start point and reference base of this study is an electrical insulator, fabricated in Iran Insulators Company production line. This body is named TN1. Alumina content of this commercial product was increased and amount of SiO_2 was decreased based on it in each sample and five samples were fabricated (table 1).

For fabrication of samples, powders were mixed by wet grinding for 6 h until their particle size was reduced to less than 45 microns and then filter pressed by industrial filter press. To shape samples, the mixture was extruded by Netzsch (ID-8672SELB) extruder and different diameter (11, 30 and 50 mm) test samples were produced. The samples were held for 4–8 h at ambient temperature and then dried for 2 h at 50 °C followed by drying at 110 °C for 4 h in an industrial furnace. The total firing cycle involved was 48 h at maximum temperature of 1300 °C. Bulk density of samples was calculated according to ASTM-C373-88 and shrinkage was determined by measuring diameter and length of samples in each stage. Bending strength was determined by three points bending test, as per IIC 672-2 standards, using Stavebi-B167 bending strength equipment. Electrical strength test was done in an isolated chamber

with one spherical and one flat brass electrode. Chamber was filled with liquid dielectric with an electrical resistance of 10^{10} – 10^{12} $\Omega\cdot\text{cm}$.

To identify phase structure, samples were powdered to a size of less than 75 microns and analyzed by x-ray diffractometer (BRUKER) with Cu target. Diffraction curves were analyzed by comparison with JCPDS cards 15-776A (mullite), 10-173 (corundum) 5-0490 (quartz) 11-695 (cristobalite).

For microstructural observation, the samples were polished mechanically and by diamond paste (1 μm). Then, they were etched by 10 wt.% HF acids for 3–4 min. Sample morphologies were studied by XL30 Phillips scanning electron microscope (SEM).

3. Results and discussion

The density and porosity of fabricated samples is shown in table 2.

Based on table 2, when silica was replaced with alumina in the main composition of body insulators, the density of bodies increased. This was because of the higher density of alumina compared to that of silica. Also porosities of TN1 to TN4 decreased. This may be related to decrease of micro cracks around silica grains. As Vazquez and Mejia Velasquez (1998) have reported, by decreasing silica content in porcelain body and replacing it by alumina, micro cracks around silica particles decrease and, by using suitable sintering temperature, the highest density and the least porosity are achieved. The bending strength of TN1–TN6 bodies is plotted in figure 1.

Table 1. Amounts of raw materials in the fabricated samples (wt.%).

Body no.	TN1	TN2	TN3	TN4	TN5	TN6
Quartz	25	20	15	10	5	0
Alumina	0	5	10	15	20	25
Feldspar	15	15	15	15	15	15
Ball clay	25	25	25	25	25	25
Kaolin	35	35	35	35	35	35

Table 2. Density and porosity of samples.

Body no.	Average of density (kg/m^3)	Average of porosity (%)
TN1	2300	3.32
TN2	2320	2.73
TN3	2360	1.54
TN4	2430	0.09
TN5	2520	0.28
TN6	2570	1.35

As observed from figure 1, there is no appreciable change in the bending strength of TN1 to TN3, but there is a significant increase in the value of bending strength for the samples TN3 to TN6. Perhaps, the compositional change has resulted in the increase in the bending strength of TN6 compared to that of TN3. Islam *et al* (2004) have reported that the increase in the alumina content in porcelain material increases the mullite phase which, in turn, increases the bending strength. Thus, the present finding gets good support from the reported work (Islam *et al* 2004) in respect of the increase of bending strength.

Electrical strength of fired samples was measured and is shown in figure 2. Based on this figure, electrical strength was increased from 18.5 kV/mm in TN1 sample to 21.9 kV/mm in TN4 sample and then decreased in TN5

and TN6 samples. It can occur because of low temperature of sintering. Low temperature of sintering is unsuitable for high alumina samples and also lack of liquid phase for filling open pores may be responsible for decrease of electrical strength in high alumina samples (TN5 and TN6 samples). Capillary cracks around the unsolved quartz phase are one of the reasons for low electrical strength. In the research by Islam *et al* (2004), sintering temperature of high alumina porcelain bodies were optimized up to 1350 °C which is higher than the temperature of our industrial sintering furnace.

XRD results in figure 3 show that, by increasing alumina content, intensities of (1 0 1) plane of quartz phase, (1 0 1) and (2 0 0) planes of cristobalite phase are reduced by about 5–65%, intensity of (2 3 0) and (2 2 0) planes of mullite increased by 100% and intensity of (1 0 4), (1 1 3), (0 2 4)

Figure 1. Bending strength variation in fired samples with different chemical composition.

Figure 2. Electrical strength variation in fired samples with different chemical composition.

Figure 3. Comparison of x-ray diffraction of samples.

Figure 4. SEM of TN1 body etched by 10% HF for 4 min.

Figure 6. SEM of TN3 body etched by 10% HF for 4 min.

Figure 5. SEM of TN2 body etched by 10% HF for 4 min.

Figure 7. SEM of TN4 body etched by 10% HF for 4 min.

and (1 1 6) planes of corundum peaks increased by about 300 to 500%.

XRD results of TN1 and TN6 samples show the presence of silica and cristobalite phases (figure 3) leads to low electrical strength in these samples.

As per figure 3, quartz and cristobalite peak are decreased with increasing alumina content. Thus, increase of corundum and mullite phases and decrease of silica phase has resulted in increase of the bending strength from TN1 to TN6.

As explained, the electrical strength was reduced from TN4 to TN6. According to figure 3 it is understood that there was an increase in corundum phase in these samples. The increase in corundum phase concentrations requires higher firing temperature, but in the present case, insufficient firing temperature of 1300 °C would have lead to higher porosity levels and defects in these samples.

Scanning electron microscope images of TN1 to TN6 samples are shown in figures 4 to 9. Figure 4 shows thick and small needles of mullite surrounded by unsolvable quartz particles. Ramaswamy *et al* (2005) have reported that low electrical and mechanical strength in porcelain body is due to small and thick needle shaped mullite and unsolved quartz in microstructure. The loss in electric strength is attributed

Figure 8. SEM of TN5 body etched by 10% HF for 4 min.

to the micro cracks formation adjacent to 1–5 nm diameter quartz particles (Ramaswamy *et al* 2005).

Figure 9 shows longer and thinner mullite needles in TN6 sample. Corundum phase has a compressed bulky feature. Change of mullite and corundum morphology (length and thickness) varies with increase of alumina and decrease of

Figure 9. SEM of TN6 body etched by 10% HF for 4 min.

silica in insulator samples. This change in mechanical and physical properties of insulators is similar to the results reported by Ramaswamy *et al* (2005) but some features are observed which need to be studied further.

4. Conclusions

In this study, different results were obtained as follows:

- (I) Replacement the silica with alumina is suggested in order to high voltage porcelain insulators manufacturing.
- (II) The amount of porosity decreases with increase in alumina content up to 15%, but the porosity increases with further increase in alumina content to 25%.
- (III) Bending strength of porcelain insulator bodies increases up to 132 MPa when alumina content is increased in suggested porcelain bodies.

(IV) The electrical strength increases to 21.3 kV/mm, with increase in the alumina content up to 15%, but with further increase in alumina content up to 25%, the electrical strength drops down which may be attributed to the high porosity observed in these samples.

(V) The TN4 composition seems to be the best choice having good morphology of alumina with highest electrical strength.

Acknowledgement

This research was supported by Iran Insulator Company.

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