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Analysis of Thermal Sensitivity by High Voltage Insulator Materials

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ABSTRACT Insulators serve bi-fold objectives of holding the conductor and electrical segregation from the grounded structure. For reliable operation of utility, electrical and mechanical strength of insulators are equally significant. The mechanical load is governed by weight of conductor, tension and environmental conditions like wind, snow, rain and typhoons etc. However, electrical strength is determined by survival of insulators against system voltage and transient over-voltages. A simulated power arc test was conducted on porcelain insulator samples by passing 72 kA/cycle surge current to evaluate for sudden lightning conditions after conducting insulation measurement of insulator samples. All cristobalite samples broke during power arc test. Power arc test revealed the thermal expansion coefficient of cristobalite samples were1.6 times higher as compared to alumina samples. Followed to arc test, X-Ray Diffraction (XRD), and Scanning Electron Microscope (SEM) were performed on insulator samples to evaluate consequences of power arc test on both cristobalite and alumina insulators. XRD reveals doubling of peak of cristobalite phase of fractured cristobalite insulators due to flow of high surge current through insulator body. X-Ray Fluorescence (XRF) was performed to investigate the elemental composition of Alumina and cristobalite porcelain insulators. Results of XRF show 5% increased Al_2O_3 in alumina samples as compared to cristobalite samples. Finally SEM was carried to study microstructure of samples before and after power arc test. SEM analysis depicts the maximum pore size in cristobalite porcelain insulators were increased to 200 μm unlike alumina insulators. This article outline layout of research strategy to study behavior of alumina and cristobalite porcelain insulators.

INDEX TERMS Cristobalite insulators, Alumina insulators, Power arc test, XRF, XRD, SEM.

I. INTRODUCTION

The concept of insulators has been come into existence before 1942. Since the inception, it has been strictly managed as international standards like ANSI and IEC [1], [2]. These standards are globally acceptable [3]. Insulators must be verified to meet these international standards before installation. Recent days polymeric insulators are more popular as compared to porcelain due to hydrophobicity characteristics of polymer insulators. In Korea 1,223,538 porcelain insulators are in active state. The lifespan of porcelain insulators are approximately 30 years. However, 65.19% of the existing insulators had already completed 30 years [4]. For long time, insulators were exposed to continuous electrical and mechanical stresses such as lightning, wind, rain, ice etc. This kind of strain could lead to generation of defects, degradation of electrical and mechanical performances and finally could lead to insulator failure. Thus evaluation of aged insulator samples is significant.

Detection of damaged insulators prior to failure is critical from reliability point of view. Thus, proper prediction of lifetime of aged insulators was required. Accurate methods to determine and access extent of degradation are required to predict rest over lifetime. Visual detection of damage is not possible in all cases in insulators. Literatures reported several devices such as UV and IR cameras have been excessively used to detect damaged insulators [5]–[7]. However, such techniques are highly dependent on illumination and quite costly.

In case of cracks or micro-cracks present in the interface or inside the porcelain insulators, SEM could be used to investigate the micro-structural defect. The SEM studies

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could generate high resolution, three dimensional images which provide topographical, morphological and compositional analysis of sample. In past research were conducted to determine electrical and mechanical tests and characterization of samples to estimate lifespan [6].

There are various factors which affect lifetime of insulators such as direction and speed of wind, ice, rainfall, temperature and location of installation of insulators. This is the reason due to which more investigations are required regarding this concern [7]–[9]. The nature of insulators is classified into electrical and mechanical characteristics. The electrical and mechanical strength degradation which is main reason for failure was analyzed by simulating surge conditions. The failure of insulators could occur due to degradation in cement, metal or shell of insulators. In this article porcelain insulators of various materials such as cristobalite and alumina were studied and compared. Experiments such as power arc test were conducted to simulate lightning surge condition. Power arc test simulate thermal sock, surge current as well as high mechanical stress conditions of natural lightning condition. Mechanical and electrical strength as well as thermal expansion coefficient were analyzed with the help of power arc test. Due to difference in weight of material components the behavior of both alumina and Cristobalite insulators would be different [10]. XRF was carried out to understand the reason of different behavior of both alumina and cristobalite insulators. Consequently SEM was performed for micro-structural analysis of alumina and cristobalite insulators [11], [12]. This article basically outlines a scientific study to compare behavior of alumina and cristobalite insulators.

II. EXPERIMENTS

Porcelain insulator Samples were collected from different utilities in South-Korea. These were removed for laboratory evaluation from different utilities. First of all insulation resistance was measured with the help of FLUKE 1507 Insulation tester to analyze the integrity of insulator.

In addition, 10 insulator samples were randomly chosen for Power arc test. This test is performed on insulators as per IEC 61467:2008 standard to ensure mechanical and electrical strength of insulators after a power arc was applied. Set-up for power arc test was arranged as depicted in Figure 1.

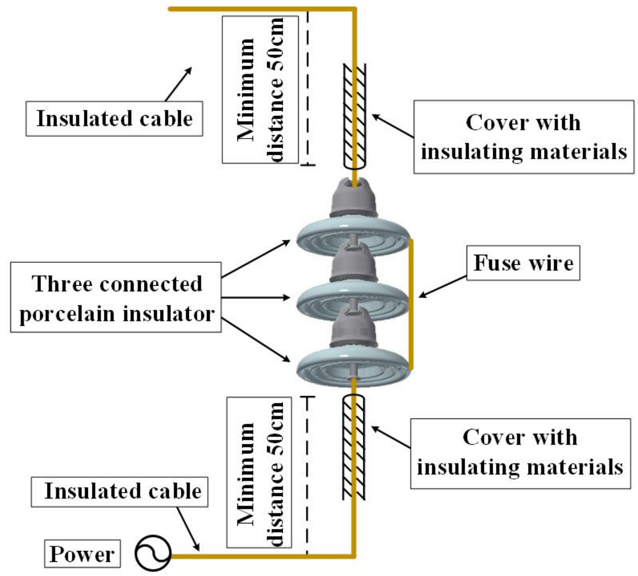

FIGURE 1. Schematic diagram of arc test for attaching test porcelain insulator.

Power arc test is a simulation of natural lightning flashover condition. Power arc test imitate thermal sock, surge current as well as high mechanical stress conditions of natural lightning. Mechanical and electrical strength as well as thermal expansion coefficient were analyzed with the help of power arc test. Test current supplied was single phase alternating current 45-65 Hz and asymmetry was limited to 30% initially. Surge current, 12 kA was supplied for 0.1 second or 6 kA for 0.2 second.

The product of arc current and duration were 72 kA/ cycle ± 10%. The arc was initiated by single or multiple strands of fusible wire made with low resistance material and cross-sectional area lower than 1 mm^2. Due to high current, peeling of glaze and burning of glaze were seen in samples evaluated. It was accepted till it does not affect the function of insulators. Temperature was varied from −40 °C to 500 °C by increasing 5°C in every step. Coefficient of thermal expansion could be measured from changes in length due to thermal shock by using Seiko Ecstar6000 (TMA6100). In case of cristobalite $\delta L = 7.6\ \mu m$ (average), $L_0 = 5mm$, $\alpha = 8 \times 10^{-6}$ (/K) however in case of alumina insulators $\delta L = 4.9\ \mu m$ (average), $L_0 = 5mm$ and $\alpha = 4.78 \times 10^{-6}$ (/K).

The Thermal expansion coefficient could explain the fractional change in size of device with varying temperature. Especially, it estimates the fractional change in size per degree change in temperature under non varying, same pressure. Following to Power arc test, XRD studies were carried out for investigating the consequences of power-arc test on crystalline phases of porcelain. Results of XRD analysis could be used to analyze change in crystalline phases of alumina and cristobalite material before and after power arc test. D8 Discover Gadds model with 10mm diameter of X-Ray beam was used for XRD analysis. For studying normal and aftershock affect of microstructure of porcelain insulators SEM studies were performed by using Hitachi &Horiba / S4800 device. Resolution used was 1nm at 15kV, with higher and lower magnification 20∼2000X and 100∼800,000X respectively. For proceeding with SEM, samples were prepared by cutting sample into a cube shape with volume of $1cm^3$ with the help of water jet. To avoid charging effect and making surface smooth, porcelain samples were polished with SiC paper and dipped into aqueous solution of hydrofluoric acid for at most 60 sec. A 15nm layer of Pt was deposited over polished sample to make surface conductive. Finally XRF was performed by using same D8 Discover Gadds model and 10mm diameter of X-Ray beam. It was performed to investigate the elemental composition of Alumina and

TABLE 1. Specifications of evaluated porcelain insulators.

Sample ID	Resistance [MΩ]	Used period	Materials	Remarks
A	84	40	Al	Degraded I.R
B	172	38	Al	Degraded I.R
C	630	48	Cb	Degraded I.R
D	950	48	Cb	Degraded I.R
E	13,300	40	Cb	Damaged
F	14.600	48	Cb	Damaged

cristobalite porcelain insulators to understand the difference in cristobalite and alumina insulators.

III. RESULTS AND DISCUSSIONS

The insulators evaluated were removed from utilities operated at 154 kV. This article focused on comparing 6 Alumina and 4 cristobalite insulators starting from A to F having mass 25000 lbs respectively. The insulation resistance was measured before the power arc tests. Both alumina (A, B) and cristobalite insulators (C, D) depicted decrease in insulation resistance. After the power arc test, all of the cristobalite insulators show high damage unlike alumina insulators. Higher degree of degradation due to aging could be possible reason for failure of cristobalite insulators. Table1 summarizes specifications and relevant observations during measurement of insulation resistance and power arc testing on insulators under evaluation. I.R represents insulation resistance and damaged refers damaged after power arc test. Three kind of damages could be observed in evaluated insulators after power arc test represented in Figure 2. During Power arc test surge current flows through pin to metal cap of insulator. Thus, fracture occurred closest to the centre as represented by Figure 2(a). Six insulators among 18 represented such kind of damage.

Due to surge current, higher electrical and mechanical forces were applied simultaneously on insulators. As a result detachment of metal part and shell occurred as represented in Figure 2(b). In case of Figure 2(c) failure caused due to weak porcelain-cement interface resulting in detachment of shell and metal parts [5], [13], [14]. Among all insulators evaluated 4 of the samples shown lower insulation resistance. Alumina insulators with very lower insulation resistance such as 172 MΩ and 84 MΩ did not fail power arc test. However all cristobalite insulators failed power arc tests. Power arc test is basically a simulation of lightning process. When lightning, thunderstorm or any such kind of disaster take place. Outdoor insulators which include both cristobalite and alumina insulators undergo a thermal shock due to flashover besides electrical and mechanical thrust.

During conduction of power arc test due to flow of surge current the lower most insulator was fractured. The surface of middle and topmost insulator was burnt as depicted

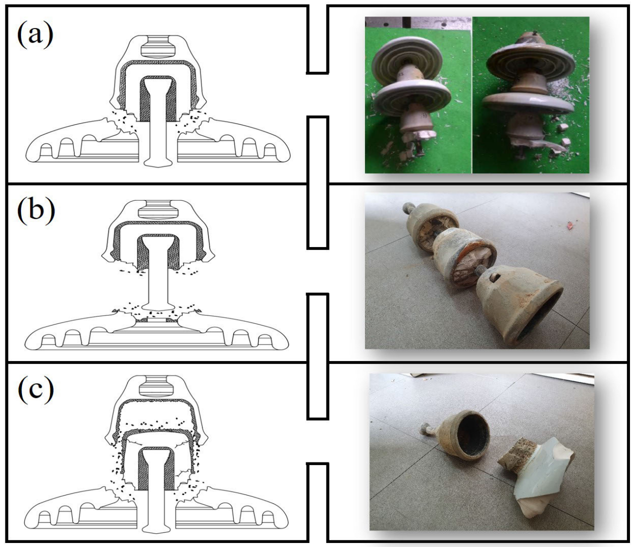

FIGURE 2. Difference in thermal expansion coefficient depending on materials.

FIGURE 3. Difference in thermal expansion coefficient depending on materials.

in Figure 3. Due to it, the dielectric part of insulator expanded thermally and damaged. This situation may cause detachment of porcelain insulators from transmission lines. Thermal expansion coefficient measurement was carried out to further analyze causes of damage Figure 4 represented observations for the coefficient of thermal expansion. The average coefficient of thermal expansion of alumina and cristobalite material was calculated as 4.78×10^{-6}/K and 8×10^{-6}/K respectively. It was observed that Cristobalite insulators were almost 1.6 times more sensitive to thermal shock as compared to alumina insulators [15], [16]. The observations regarding thermal expansion coefficient is represented in Figure 4. In case of cristobalite insulators there is difference between

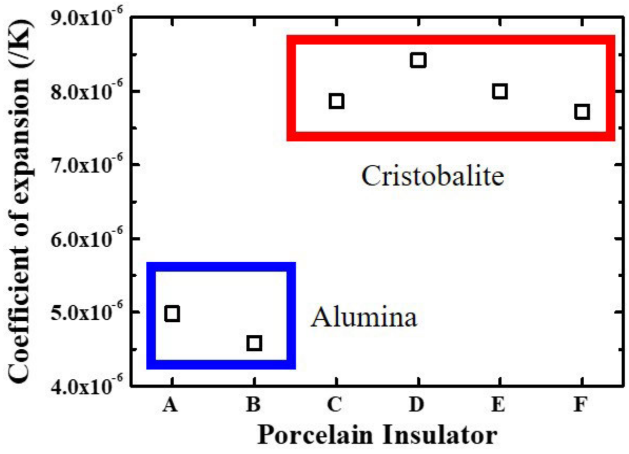

FIGURE 4. Difference in thermal expansion coefficient based on materials.

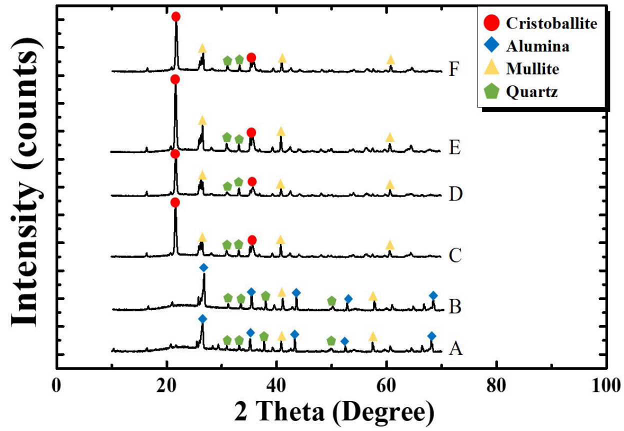

FIGURE 5. Analysis of component peaks of porcelain by X-ray diffraction from sample A to F.

TABLE 2. X-ray fluorescence (XRF) analysis of porcelain samples.

Chemical composition	Elemental concentrations (wt%)					
	A	B	C	D	E	F
SiO_2	65.4	65.1	71.8	71.7	71.9	71.5
Al_2O_3	28.2	28.4	23.4	23.2	23.2	23.4
K_2O	4.09	4.1	1.89	1.95	1.71	1.84
Fe_2O_3	1.08	1.03	1.18	1.17	1.22	1.28
Na_2O	0.608	0.775	1.06	1.18	1.23	1.24
TiO_2	0.383	0.37	0.48	0.59	0.56	0.58
MgO	0.192	0.181	0.154	0.169	0.141	0.129
Rb_2O	0.033	0.029	0.011	0.014	0.012	0.012
P_2O_5	0.014	0.015	0.025	0.027	0.027	0.019

thermal expansion coefficients of quartz grains and matrix surrounding them.

This difference in the value develops tensile stress in the quartz grains and compressive grains surrounding the body led to intensify stress during temperature variation of device. This leads to generation of micro-cracks. Consequently, XRF was performed for investigating elemental composition analysis of cristobalite and alumina porcelain insulators to study the reason of better performance of alumina insulators.

Table 2 depicts results for XRF analysis. XRF analysis revealed elemental composition of materials. All porcelain insulators both cristobalite and alumina revealed presence of oxides such as SiO_2, Al_2O_3, K_2O, Fe_2O_3, Na_2O, TiO_2, MgO, Rb_2O and P_2O_5. It could be observed from XRF studies that samples A, B (alumina insulators) showed 5% additional increase in Al_2O_3 and 6.48% drop in amount of SiO_2 in average. XRF also revealed average weight (%) of Fe_2O_3 in the samples A, B, C, D were 1.08% and 1.12% in E, F respectively. Fe_2O_3 acted as an impurity in the shell. Other components except Al_2O_3 and SiO_2 are not directly responsible for mechanical strength of porcelain insulators. The rise in weight (%) of Al_2O_3 could be considered as reason for better mechanical and thermal performance in alumina insulators [17], [18]. Following the elemental analysis with the help of XRF analysis, XRD was performed to determine difference in crystalline phases of insulator samples.

XRD results were presented in Figure 5. The diffraction pattern reported the existence of alumina (Al_2O_3), Quartz (SiO_2), β-cristobalite and mullite. Peaks were recognized with the help of JCPDS database. When amount of silica was increased and alumina decreased the sharp peaks related to alumina was decreased because of dissolution of alumina in glassy phase.

With increasing Silica in the composition of porcelain insulators, β-cristobalite phase began to generate and caused major peak intensity in sample C and D as represented in Figure 5. Intensity of crystalline phases of insulators with different materials was observed by varying 2 Theta (degree) from 21 to 70 degree. In case of samples A and B crystalline peaks of alumina was highest. Mullite and Quartz were also found in samples A and B with Al_2O_3 [19]. In case of sample C and D large amount of Al_2O_3 was added to increase the mechanical strength. Therefore, peak of alumina was highest in case of A and B. In case of sample C and D peak of the cristobalite peak was highest unlike alumina [20]. When current of 72 kA/cycle passed through E and F insulators, peak of crystal phase of fractured cristobalite insulators doubled as compared to C and D. The microstructure of insulator samples A, B, C, D, E and F were shown in Figure 6. Sample A and B are alumina porcelain insulators, contained with higher amount of Al_2O_3. Due to higher amount of Al_2O_3, voids were very small. Electrical characteristics of the alumina samples

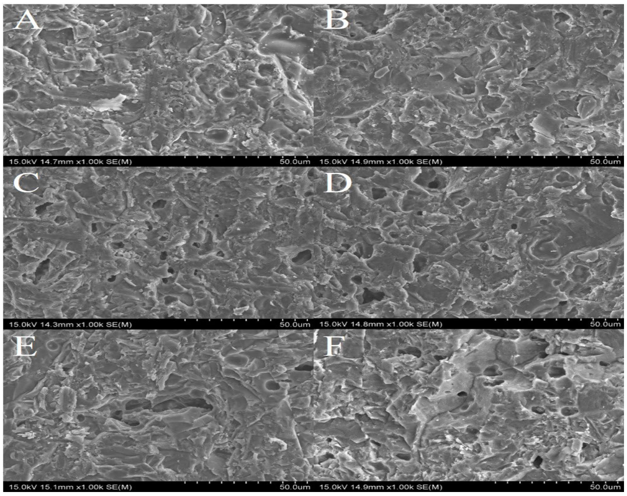

FIGURE 6. Analysis of component peaks of porcelain by X-ray diffraction from sample A to F.

were excellent. Thus it did not get affected with high surge current. In case of C and D intensity and depth of pores increases with aging. Most of the pores found in insulator samples C and D were approximately 50 μm in diameter. Microstructure of C and D were more porous as compared to A and B. However E and F gained higher porosity with larger pores of 100μm-200μm and degraded microstructure as compared to C and D. The reason could be passage of surge current, 72 kA/cycle through E and F [21], [22]. Increasing porosity in the micro-structure decreases bulk density and increases the chance of moisture or water accumulation in insulators. Thus from the above experiments it could be confirmed that with increasing Al_2O_3 in the microstructure, the mechanical and electrical properties as well as bulk density enhanced.

IV. CONCLUSION

Insulator samples with alumina and cristobalite were studied to understand the difference in electrical and mechanical properties. During power arc test all cristobalite insulators were damaged due to large thermal expansion coefficient, 8×10^{-6} (/K) which is almost 1.6 times more than alumina insulators. All Alumina insulators passed power arc test. This power arc and high surge current were responsible to increase the porosity of shell as depicted by SEM which could lead to dielectric breakdown of cristobalite insulator samples. Alumina insulators did not get affected by power arc test due to superb mechanical strength and lower thermal expansion coefficient of alumina, 4.78×10^{-6}. Thus it is evident that during lightning condition possibility of failure of cristobalite insulators were quite higher than alumina. XRF revealed cristobalite insulators had 5% lesser Al_2O_3 and as compared to alumina insulators. Whereas alumina insulators revealed 6.42% lower SiO_2 as compared to cristobalite insulators. XRF also revealed average weight (%) of Fe_2O_3 in the samples A, B, C, D were 1.08% and 1.12% in E, F respectively. However, Fe_2O_3 acted as an impurity in the shell and affect lifespan of insulator in very long run. Thus, the rise in weight (%) of Al_2O_3 could be considered as reason for better mechanical and thermal performance in alumina insulators. XRD depict in case of samples A and B crystalline peaks of alumina was highest, for sample C and D peak of the cristobalite peak was highest and for E and F (fractured insulators) peak of cristobalite phase doubled due to flow of high surge current through insulator body. SEM suggested pore size found in insulator samples A and B were minute, C and D were approximately 50 μm in diameter. However E and F depicted larger pores of 100 to 200 μm in SEM analysis. Thus, the rise in weight (%) of Al_2O_3 could be considered as reason for better mechanical and thermal.

REFERENCES

[1] B. Mills, "Porcelain insulators and how they grew," in *Electric Insulators and Insulation*, vol. 78. Washington, DC, USA: Library of Congress, 1970, pp. 146–302.

[2] E. Rosenthal, "Insulator glazes," *Nature*, vol. 150, pp. 771–772, May 1942.

[3] J. Li, C. Sun, W. Sima, Q. Yang, and J. Hu, "Contamination level prediction of insulators based on the characteristics of leakage current," *IEEE Trans. Power Del.*, vol. 25, no. 1, pp. 417–424, Jan. 2010.

[4] J. Duncan Glover, S. Mulukutla Sama, and T. Overbye, *Power-System Analysis and Design*. 5th ed. Stamford, CA, USA: Cengage Learn, 1987, p. 853.

[5] A. Mishra, R. Gorur, and S. Venkataraman, "Evaluation of porcelain and toughened glass suspension insulators removed from service," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 15, no. 2, pp. 467–475, Apr. 2008.

[6] A. Rawat and R. Gorur, "Microstructure based evaluation of field aged and new porcelain suspension insulators," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 16, no. 1, pp. 107–115, Feb. 2009.

[7] X. Jiang, J. Yuan, L. Shu, Z. Zhang, J. Hu, and F. Mao, "Comparison of DC pollution flashover performances of various types of porcelain, glass, and composite insulators," *IEEE Trans. Power Del.*, vol. 23, no. 2, pp. 1183–1190, Apr. 2008.

[8] X. Jiang, L. Chen, Z. Zhang, C. Sun, and J. Hu, "Equivalence of influence of pollution simulating methods on DC flashover stress of ice-covered insulators," *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 2113–2120, Oct. 2010.

[9] *American National Standard for Electrical Power Insulators—Test Methods*, ANSI, New York, NY, USA, 1996.

[10] A. Ilhan Aksay, A. Joseph Pask, and F. Robert Davis, "Densities of SiO_2-Al_2O_3 Melts," *J. Am. Ceram. Soc.*, vol. 62, pp. 332–336, May 1979.

[11] C. E. Brackbill, H. A. McKINSTRY, and F. A. Hummel, "Thermal expansion of some glasses in the system Li2O-Al2O3-SiO2," *J. Amer. Ceram. Soc.*, vol. 34, no. 4, pp. 107–109, Apr. 1951.

[12] E. Demirkesen, Z. E. Erkmen, and N. Yildiz, "Effect of Al_2O_3 additions on the thermal expansion behavior of a Li2O-ZnO-SiO2 glass-ceramic," *J. Amer. Ceram. Soc.*, vol. 82, no. 12, pp. 3619–3621, 1999.

[13] E. A. Cherney, A. C. Baker, J. Kuffel, Z. Lodi, A. Phillips, D. G. Powell, and G. A. Stewart, "Evaluation of and replacement strategies for aged high voltage porcelain suspension-type insulators," *IEEE Trans. Power Del.*, vol. 29, no. 1, pp. 275–282, Feb. 2014.

[14] T. Kim, S. Jeon, Y.-J. Lee, J. Yi, I.-H. Choi, J.-A. Son, and C.-W. Choi, "Three-dimensional computed tomography and composition analysis of porcelain insulators for 154 kV power transmission lines," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 26, no. 1, pp. 115–119, Feb. 2019.

[15] S. P. Singh, K. Pal, A. Tarafder, T. Hazra, and B. Karmakar, "Influence of SiO2and Al2O3Fillers on thermal and dielectric properties of barium zinc borate glass microcomposites for barrier rib of plasma display panels (PDPs)," *Trans. Indian Ceram. Soc.*, vol. 69, no. 2, pp. 75–82, Apr. 2010.

[16] H. Torkamani, S. Raygan, C. Mateo, J. Rassizadehghani, J. Vivas, Y. Palizdar, and D. San-Martin, "The influence of la and ce addition on inclusion modification in cast niobium microalloyed steels," *Metals*, vol. 7, no. 9, p. 377, 2017.

[17] J. J. Liang, Q. H. Lin, X. Zhang, T. Jin, Y. Z. Zhou, X. F. Sun, B. G. Choi, I. S. Kim, J. H. Do, and C. Y. Jo, "Effect of alumina on cristobalite crystallization and properties of silica-based ceramic cores," *J. Mater. Sci. Technol.*, vol. 33, pp. 204–209, 2017.

[18] A. Kazemi, M. A. Faghihi-Sani, and H. R. Alizadeh, "Investigation on cristobalite crystallization in silica-based ceramic cores for investment casting," *J. Eur. Ceram. Soc.*, vol. 33, nos. 15–16, pp. 3397–3402, Dec. 2013.

[19] M. M. S. Wahsh, "The effect of microsilica and aluminum metal powder on the densification parameters, mechanical properties and microstructure of alumina–mullite ceramic composites," *Adv. Mater.*, vol. 4, no. 4, pp. 80–84, 2015.

[20] Munasir, M. Zainuri, Triwikantoro, and Darminto, "Synthesis of SiO_2 nanopowders containing quartz and cristobalite phases from silica sands," *Mater. Sci. Poland*, vol. 33, no. 1, pp. 47–55, Mar. 2015.

[21] N. Riahi Noori, R. Sarraf Mamoory, and S. Mehraeen, "Effect of Materials Design on Properties of Porcelain Insulators," *Amer. Ceram. Soc. Bull.*, vol. 86, pp. 9201–9205, 2007.

[22] S. I. Warshaw and R. Seider, "Comparison of strength of triaxial porcelains containing alumina and silica," *J. Amer. Ceram. Soc.*, vol. 50, no. 7, pp. 337–343, Jul. 1967.

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