Three-Dimensional Computed Tomography and Composition Analysis of Porcelain Insulators for 154 kV Power Transmission Lines

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ABSTRACT

Porcelain insulators were removed from 154 kV power transmission lines from three locations that were installed between 1969 and 1977. Visual inspection, three-dimensional computed tomography (3D-CT), and X-ray fluorescence (XRF) analyses were carried out. The 3D-CT analysis shows the presence of a number of pores. It was found that the insulating resistance of the porcelain insulators decreases with increasing number of pores and total pore area. Since most of the pores are located in the cement area, it is expected that the decrease in insulating resistance is related to the deterioration of the cement. The XRF analysis reveals that a high percentage of Fe exists in the cap. The Fe_2O_3 content, which indicates corrosion, is the highest at 95.7% in Region C (48 years), followed by 88.4% in Region A (40 years), and 81.65% in Region B (38 years). High levels of Al_2O_3 and SiO_2 were detected in Regions B and C where the number of yellow dust days is high. In the case of the cement, the water-absorbing CaO component is 62.87% on average. In Region C where the insulators are the oldest, higher CaO is detected. This shows water absorbion greatly affected the insulation deterioration of the porcelain insulator. It was found that the Al content of the porcelain insulator from Region C, for which the main material is cristobalite, is lower than that from other areas using alumina. The components found by XRF analysis are dependent on the age, the main materials, and the environmental conditions where the insulators were installed.

Index Terms — **3D CT analysis, porcelain insulator, XRD, XRF**

1 INTRODUCTION

INSULATORS are used to mechanically support and electrically insulate bare conductors on steel towers or poles. They play a role in securing the insulation between the working transmission line and the electric pole.

The characteristics required for the material used in the insulator are as follows: (1) high mechanical strength; (2) high electrical insulation; (3) smooth surface; (4) low number of defects in the material; (5) the coefficient of thermal expansion should be similar to that of the bonding material; (6) good chemical resistance and durability; and (7) the material characteristics; (6) good chemical resistance and durability; and (7) the material characteristics should independent of heat and discharge during use [1,2].

The mechanical load is determined by the weight of the conductor and the tension on the conductor, which can vary depending on the weather conditions, such as wind, snow, and ice. Insulators should have insulation characteristics to withstand overvoltages caused by the voltage of the transmission system, lightning strikes, and switching operations [3, 4].

Insulators are a small portion (5% to 8%) of the installation cost of overhead transmission lines, but they account for ~70% of transmission line failures and more than 50% of maintenance costs, and play an important role in determining the reliability of the lines [5].

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The lifetime of porcelain insulators is very long, 30 to 60 years. Insulators are subject to mechanical and electrical stress. It is inevitable that they are exposed to some degree of pollutants depending on the environment (urban area, industrial area, coastal). Owing to age deterioration by various factors, the period during which the porcelain insulators can be used without causing a problem is an important factor. Periodic replacement of insulators is required. Power failures due to insulator-related problems can be accompanied by human and material damage as well as enormous economic losses. Thus, the prediction of lifetime expectancy is very important [6]. Porcelain insulators, including the 154 kV porcelain insulators used for transmission, are made of clay, feldspar, quartz, and corundum (Al_2O_3). The stable phase of SiO_2 at room temperature is quartz. A phase change occurs in cristobalite at high temperature. Cristobalite, which is a high-temperature phase, may remain at room temperature when cooled from high temperature to room temperature. A large amount of SiO_2 is contained in the 154 kV porcelain insulators made prior to 1980, and it is expected that many changes in electrical/mechanical characteristics occurred owing to the change in external environment and aging compared to those made after 1980 which contain alumina instead of SiO_2. For porcelain insulators, the relative amounts of alumina and SiO_2 crystal phases, particle size, and amount of amorphous phase have a decisive influence on the density and mechanical/electrical properties of the product [7-10].

In this study, samples of 154 kV porcelain insulators installed between 1969 and 1977 were removed from three different locations. Visual inspection, 3D-CT, and XRF analysis were carried out.

2 EVALUATED PORCELAIN INSULATOR FOR 154 KV TRANSMISSION LINE

The porcelain insulator is composed of an iron cap, porcelain, cement, and iron pin as shown in Figure. 1. There is bituminous coating on the interface between the metal part and the cement, and a sand bond between the porcelain and cement. Such an insulator has been in use since 1950 [11]. This study analyzes a porcelain insulator with a porcelain diameter of 250 mm for 154 kV power transmissions.

In most porcelain insulators, the iron cap and iron pin are rusted, predominantly owing to aging, and the inner cement part is deteriorated by shrinkage and expansion due to moisture penetration. The cement used is predominantly Portland cement. Porcelain has a different content of alumina and cristobalite depending on the year of production. The higher the alumina content, the higher the mechanical strength; the higher the cristobalite content of, the lower the mechanical strength [12].

According to USASI (USASI) 2935 9.4.5, the order of mechanical risk is considered to be the iron pin, cap, and porcelain [13]. However, the deterioration analysis of cement is also very important because of continuing electrical/mechanical stress and environmental stress.

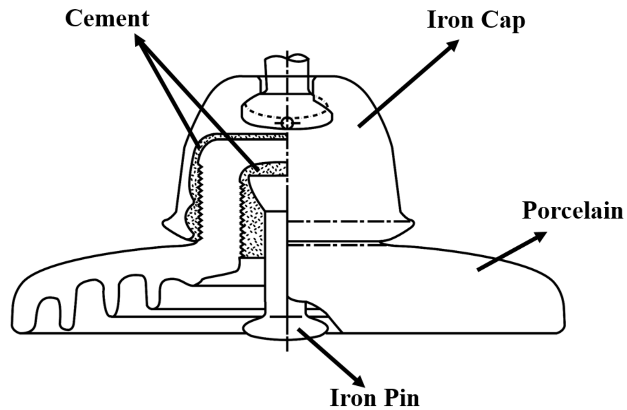

Figure 1. Sectional view of porcelain insulator.

Table 1 shows the porcelain insulators, numbered B-1 to B-6, used in this study. They have an identical capacity of 110 kN (25,000 lbs) and were placed in three different regions. The period of use differs in each area. The main components of the porcelain insulators from Region C and the other insulators is cristobalite and alumina, respectively.

Table 1. Details of analyzed porcelain insulators.

Sample	Installed year	Age	Region	Component	Resistance [MΩ]	Capacity [lb]
B-1	1977	40	A	Alumina	1,010	25,000
B-2					1,180	
B-3	1979	38	B	Alumina	172	
B-4					84	
B-5	1969	48	C	Cristoballite	83,000	
B-6					14,600	

As of 2017, insulators in Region A, Region B, and Region C have been in use since 1977 (40 years), 1979 (38 years), and 1969 (48 years), respectively. In Regions A and B, where the insulators are composed of alumina, the resistance values of B-1 and B-2 for Region A are more than 1,000 MΩ; however, those of B-3 and B-4 are 172 and 82 MΩ, which cannot be used because they are below the reference value of 1,000 MΩ. Despite having the longest service period of the porcelain insulators, B-5 and B-6, which are composed of cristobalite, have excellent insulation resistance characteristics. It is considered that they are used in applications with insensitivity to the voltage and load distribution [14,15]. The B-6 insulators failed the power arc tests.

3 ANALYSIS OF PORCELAIN INSULATOR USING X-RAY – 3D-CT, XRF, XRD

An arc test was performed by connecting three units of porcelain insulators, as shown in Figure 2. For the arc test, either an rms current of 12 kA flows for 0.1 s or an rms current of 6 kA flows for 0.2 s. If any part of the component is broken after the test including separation of the porcelain, cap or pin, or breakage of the porcelain shell, fails to meet the regulation requirements and cannot be used. However, as long as they do not hinder the usage, flashover marks on the surface of the insulator, peeling of shells, melting of the glaze, are acceptable.

Figure 2. Porcelain shell broken owing to the arc test (Sample B-6).

In this experiment, 12 kA flows for 0.1 s. Materials with low resistance, such as silver, copper, and aluminum, are used for the initiation of the arc. Copper was used in this experiment. A wire with a cross-section of less than 1 mm^2 is used, and the cap at the top is connected to the pin at the bottom. The current flowed and during the arc test, all parts of the porcelain part were damaged owing to thermal damage, and the insulation resistance reduced from 14,600 to less than 400 MΩ.

This means that the insulation resistance reduced by more than 97%. It is considered that cracks are increased in the cement part owing to the electric stress and thermal damage caused by the arc test.

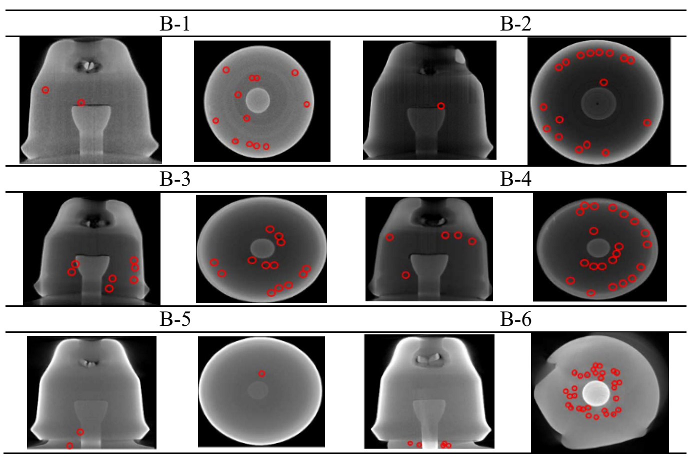

Figure 3. 3D-CT single-layer analysis of porcelain insulators.

Since the characteristics of insulation resistance are not good, numerous pores are visible inside the B-1 to B-4 insulators. There are 14 and 18 pores in B-1 and B-2, respectively. B-3 has 20 pores, but the size of the pores is twice that of B-1 and B-2. B-4, which has the lowest insulation resistance at 84 MΩ, has 26 pores. B-5 has an insulation resistance of 83,000 MΩ, which is very good. B-6 has an insulation resistance of 14,600 MΩ, but 35 pores were counted in the 3D-CT analysis after the arc test. In the arc test, a current of 12 kA is applied for 0.1 s. It seems that the arc test causes internal damage. This has a detrimental effect on the insulation resistance and the mechanical properties [16].

Figure 4 shows the number pores in the porcelain insulators observed in the 3D-CT analysis. A total of 14 and 18 pores were found in B-1 and B-2, respectively, with an insulation resistance of more than 1,000 MΩ, and 20 and 26 pores for B-3 and B-4, respectively, with an insulation resistance of 1,000 MΩ or less. B-5 with the insulation resistance of 83,000 MΩ shows very few pores, only three.

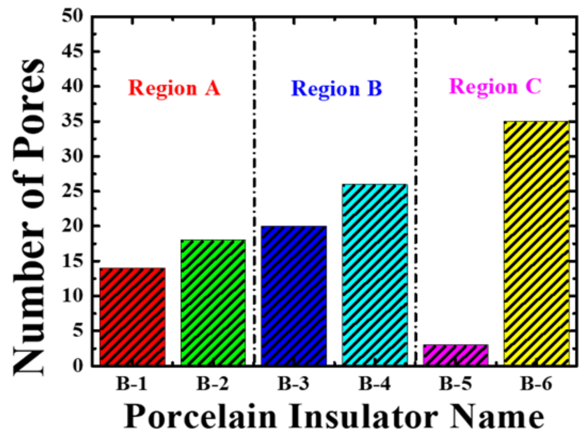

Figure 4. Number of pores inside porcelain insulators.

However, the 3D-CT analysis after the arc test on B-6 with an initial insulation resistance of 14,600 MΩ, shows up to 35 pores. It is assumed that more internal pores are generated owing to thermal shock during the 12 kA arc test. In comparison with other porcelain insulators, B-6 has excellent insulation resistance characteristics. However, B-6 has 35 internal pores in the arc test. This means that the internal compressive stress of the cement part is reduced owing to electrical stress and heat damage during the arc test, which indicates that the mechanical properties have deteriorated [15].

Figure 5 shows the XRF analysis data of the iron cap and porcelain of B-1 ~ B-6. Figure 5a shows the Fe_2O_3 and ZnO content in the iron cap. Fe_2O_3 increased from 80% to 96% over the transmission line service period. In the case of ZnO coated on the iron cap, it is observed that 0 to 6% of the coating was removed, depending on the service period of the transmission line. The reason for the increase in Fe_2O_3 is that the corrosion of the iron cap started after the transmission line was installed. Therefore, with time, both the corrosion and the content of Fe_2O_3 increased. ZnO decreased as it was dissolved during the corrosion. Although Fe_2O_3 increased as the iron corrosion progressed, a rapid decrease in the insulation resistance is not seen. It seems that the corrosion of the metal portion is not the critical point for the insulators.

The SiO_2 (cristobalite) and Al_2O_3 (alumina) contents of the porcelain are observed as shown in Figure a5b. The initial porcelain insulator was fabricated using cristobalite, which has a cheaper manufacturing process. However, it was found that the physical properties of the porcelain insulator are improved by adding an alumina component which improves the electrical/mechanical properties of the porcelain insulator. Many studies have shown that when the amount of SiO_2 increases, the mechanical properties and the insulation level degrades [18].

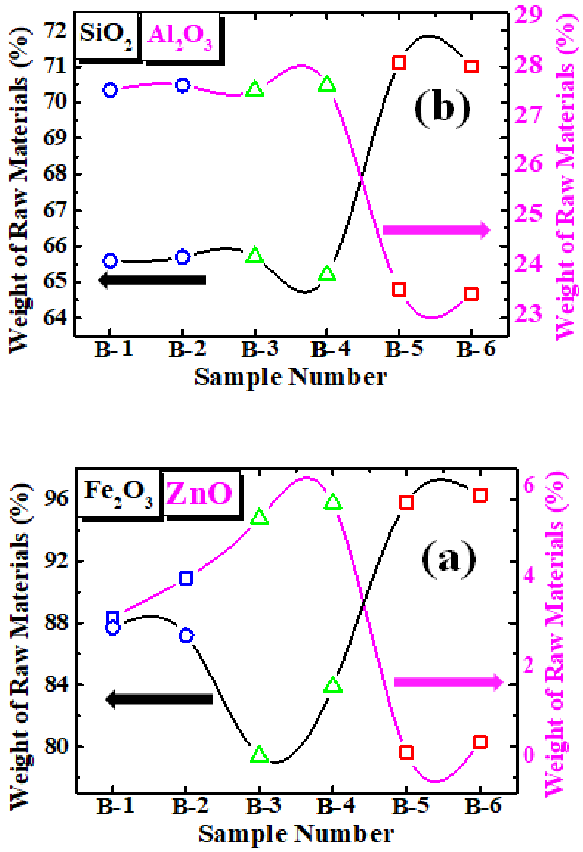

Figure 5. Composition analysis by X-ray fluorescence of (a) cap, (b) porcelain.

Figure 6 shows the XRD analysis data of porcelain, indicating the constituents of porcelain insulators of B-1 to B-6. The components consist mainly of mullite ($3Al_2O_3{\cdot}2SiO_2$), Al_2O_3, and SiO_2 (quartz, cristobalite), where mullite a mixed phase of SiO_2 and Al_2O_3. In Figure 6a, Al_2O_3 is strong, and the content is also large in the porcelain in Region A and Region B. Figure 6b shows the result of analyzing the porcelain in Region C. The intensity of mullite is prominent and the content of SiO_2 is high.

If the amount of SiO_2 in the porcelain is large, the insulating property deteriorates and the mechanical strength is also lowered. It appears that Al_2O_3 is added to prove the insulation and mechanical properties [19, 20]. However, for the samples used in this study, the porcelain insulators with SiO_2 exhibited a better insulation resistance, despite being used for a longer time. When the arc test was carried out for the insulators with SiO_2 and Al_2O_3, only the insulator with SiO_2 failed the test. The actual service period is also important, but it can be seen that the service environment is also a very important factor

4 CONCLUSIONS

3D-CT analysis of porcelain insulators for 154 kV transmission lines showed that there were numerous pores in the cement and that the internal porosity of the cement increased with use in the transmission line. The numbers of internal pores was low for high resistance, and increased for poor resistance. The arc tests conducted on the insulator with good resistance resulted in cracking of the porcelain part, and deterioration of the internal cement owing to thermal expansion was confirmed by the 3D-CT.

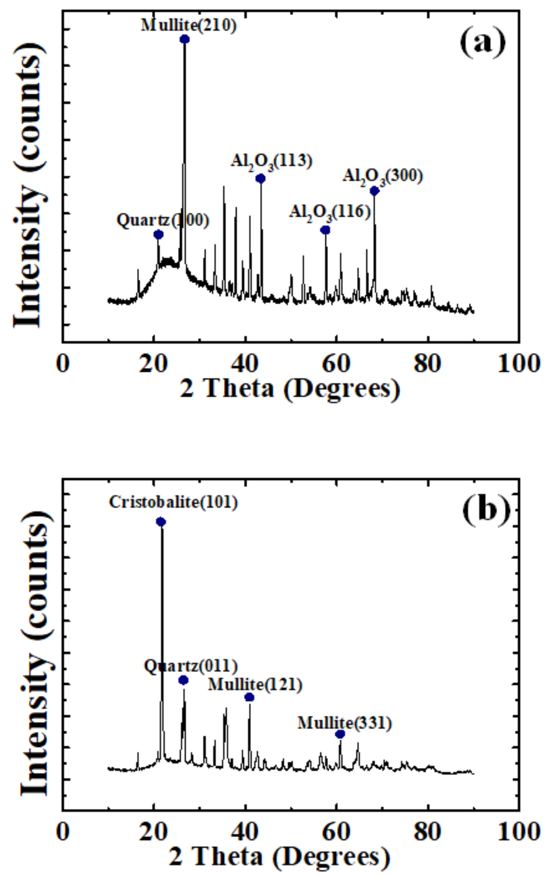

Figure 6. Analysis of component peaks of porcelain by X-ray diffraction.

The results of XRF analysis showed that Fe_2O_3 increased and ZnO decreased with service time owing to the corrosion of the iron cap. The alumina content increased with the year of production of the porcelain insulators. Alumina is known to improve the mechanical properties of porcelain insulators. Although the resistance of the cristobalite porcelain insulator was high, it failed the arc test, whereas the alumina one passed.

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