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Characteristics of Electrical Insulation in PDMS-ATH Composite for High Voltage Insulators

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Summary

The electrical insulation properties and the tracking and erosion resistances of high-temperature vulcanized silicone rubber were investigated as to the concentration of alumina trihydrate (ATH) therein for the fabrication of silicone rubber with optimum ATH content. Controlling the ATH concentration has been found to be an important factor in the enhancement of the tracking and erosion resistances of silicone rubber. In addition, the silicone rubber showed constant electrical resistivity and dielectric breakdown voltage without any decrease due to the interfacial problems with the addition of ATH to the silicone rubber. Therefore, this fabricated silicone rubber that contains an optimum ATH concentration can be applied to outdoor high-voltage insulators.

Introduction

Since silicone rubber was introduced for use in outdoor high-voltage insulators in the 1960s, its applications have been rapidly growing worldwide. Composite insulators are utilized in new power lines as replacements of traditional glass and porcelain insulators.[1-5] Reduced weight, better contamination performance, easy handling, vandal resistance, and reduced cost of composite insulators with silicone rubber housings constitute their important characteristics. Here, silicone rubber allows improved electrical performance under wet and contaminated environments over porcelain and glass because of its excellent hydrophobicity. Other important characteristics of silicone rubber include thermal and oxidative stability, a high degree of chemical inertness, resistance to weathering, and temperature-insensitive physical properties. These outstanding properties have been found to be related to the unique molecular structure of silicone rubber.[6-13]
In general, traditional porcelain and glass insulators have poor electrical performance in wet conditions due to their mainly hydrophilic surface. In contrast, composite insulators with silicone rubber housings exhibit superior electrical properties due to their hydrophobic surface. The hydrophobicity of the housings can be temporarily lost, however, due to corona discharges, contamination and dry band arcing, which

make the housings subject to tracking and erosion. Tracking and erosion are irreversible serious degradations of composite insulators, considerably reducing their electrical insulation properties and mechanical strength.[14-16] Typically, an alumina trihydrate (ATH, $Al(OH)^3$) filler is added to the silicone rubber as an anti-tracking agent and flame retardant. The mechanism of the tracking and erosion of silicone rubber and the suppression mechanism of ATH have been reported.[17] ATH allows an endothermic reaction that results in the release of water vapor when it is heated above 200°C. The water vapor liberated from ATH at 200°C oxidizes the carbonaceous species to form electrically nonconductive materials such as CH_4 and CO_2. In addition, the water vapor from the second-step dehydration of ATH (at 470~560°C) sweeps off harmful residues produced during the thermal degradation on the surface of silicone rubber housings.

Therefore, it is important to determine the optimum ATH content needed in high-temperature vulcanized silicone rubber to maintain the rubber's electrical insulation properties. In this study, we provide a correlation between the ATH content and the electrical insulation properties of silicone rubber. The tracking and erosion resistances of silicone rubber at various ATH contents were measured using the IEC 60587 inclined plane method. In addition, we studied how the ATH content of silicone rubber affected its electrical insulation properties such as its electrical resistance, dielectric strength, and arc resistance.

Experimental

Specimen Preparation

The silicone rubber housings prepared for this study were composed of polydimethylsiloxane as a basic polymer, a silane-treated silica reinforcer, ATH as an anti-tracking agent and a peroxide curing agent. The weight-average molecular weight of polydimethylsiloxane was 800,000 and its vinyl content was 0.12 mol%. The contents of the ATH filler were varied from 90 to 150 phr (parts per hundred rubber). The ATH was silane-treated and its average diameter was 1.0 μm. These were cured at 170°C for 10 minutes under a hydraulically operated press (Tetrahedron, USA) to form various virgin specimens.

Arc Resistance

The ASTM D495 was used to evaluate the arc resistance under a high voltage, low current, and dry condition. The arc resistance is a measure of an electrical breakdown condition on an insulation surface, caused by the formation of a conductive path on the surface. Higher values indicate greater resistance to breakdown on the surface due to arcing or tracking conditions. This test method is useful in the preliminary evaluation of changes in structure and composition without the complicating influence of environmental conditions, especially dirt and moisture. The end point of failure was defined as the arc disappeared into the material.

Tracking and Erosion Resistance

The IEC 60587 inclined plane method was used to evaluate the resistance to tracking and erosion. Here, tracking is defined as the progressive degradation of the surface of a solid insulation material by local discharges to form a conducting or partially conducting path. Electrical erosion is defined as the wearing away of a solid insulation material by the action of electrical discharges without the formation of tracks. The inclined plane method is commonly used to evaluate the tracking and erosion resistance of polymeric insulation materials. Figure 1 shows a typical instrument setup. The samples used were 120×50×6 mm^3 and were set up with an inclination of 45°. The contaminant was an NH_4Cl solution with a nonionic surfactant of 0.02 g/*l* at a conductivity of 2,500 μS/cm at 23°C. This contaminant flowed from the top to the bottom electrode at a rate of 0.6 ml/min. The distance between the top and the bottom electrodes was 50 mm. The applied voltage was 4.5 kV AC and the resistance of the series resistor was 33 kΩ. The tests were carried out 10 times. The samples were subjected for 24 hours because no tracking failure occurred in 6 hours. The other conditions were the same as IEC 60587.

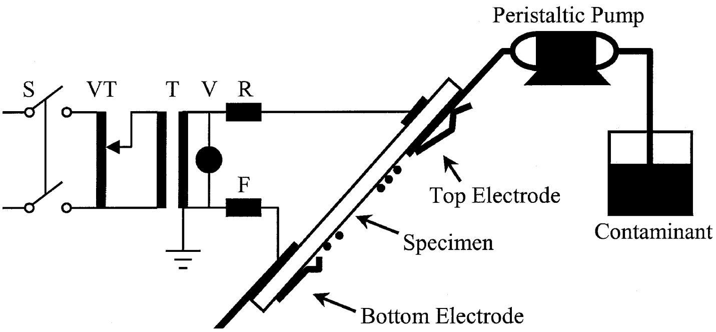


Figure 1. Schematic diagram of the inclined plane tracking and erosion test.

Dielectric Strength

All insulation materials show failure phenomena at some level of applied voltage for a given set of operating conditions. The dielectric strength, normally expressed in voltage gradient terms, such as volts per mil, is the voltage that an insulation material can withstand before a dielectric breakdown occurs. The dielectric strength of an electrical insulation material is a property of interest in any application where an electrical field will be present. In many cases, the dielectric strength of a material will be the determining factor in the design of the apparatus in which it is to be used. To

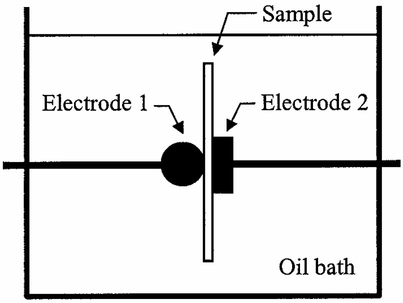


Figure 2. Schematic diagram of the experiment on the dielectric strength.

avoid flashovers, the entire arrangement of the electrodes and the silicone rubber sample was put into a test cell with insulation oil. The 60 Hz AC voltage was increased at a rate of 500 V/sec until a breakdown took place. To measure the dielectric strength, the flat samples used were 100×100×2 mm^3. A schematic diagram of the experiment on the dielectric strength is shown in Figure 2.

Results and Discussion

The arc resistance of the silicone rubber with various ATH contents is shown in Figure 3. The arc resistance increased with increasing filler content. A significant increase in the arc resistance of the silicone rubber was observed at above 130 phr of the ATH filler in the silicone rubber, and increase at under 130 phr of the ATH seemed obtuse. These results imply that 130 phr of ATH in silicone rubber is a critical level for withstanding dry band arcing.

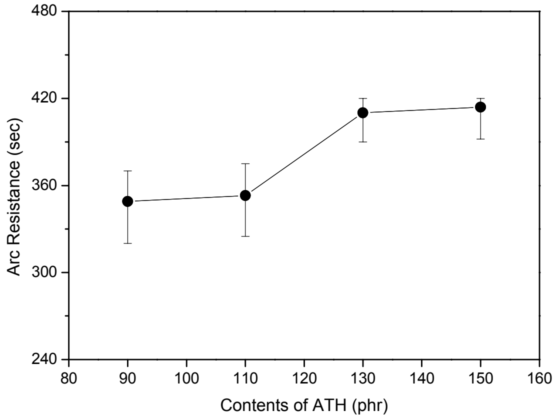


Figure 3. Experimental relationship between arc resistance and ATH content.

It has been well known that polymeric insulation materials used in outdoor high voltage applications exhibit aging phenomena with not only dry band arcing but also environmental stresses such as UV radiation. Once polymeric insulation materials are subjected to tracking and erosion, they do not recover their reduced electrical insulation properties and mechanical strength. Tracking and erosion of polymer occur with thermal degradation as a result of high temperatures caused by dry band arcing. Figure 4 shows the tracking and erosion resistance as expressed by the weight loss of the silicone rubber after its exposure to the inclined plane test for 24 hours at 4.5 kV. The weight loss caused by the tracking and erosion decreased with increasing ATH content, that is, the high-filled silicone rubber withstood the tracking and erosion. A significant increase in the tracking and erosion resistance ability of the silicone rubber was observed at above 130 phr of the ATH. These results suggest that 130 phr of ATH in silicone rubber enables the rubber to withstand arcing. The rubber's tolerance to tracking and erosion was in agreement with its arc resistance. It is very important for silicone rubber to have a certain ATH content for it to be properly protected.

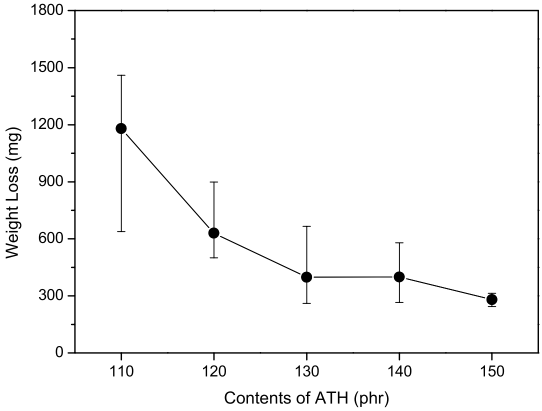


Figure 4. Experimental relationship between weight loss and ATH content after the inclined plane test for 24 hours at 4.5 kV.

Figure 5 shows the changes in the surface after its exposure to the inclined plane test for 24 hours at 4.5 kV. Figure 5a~e show that the rubber's tolerance to tracking and erosion is strongly dependent on its ATH content. It was found that Figure 5a and e show the highest and lowest degrees of tracking and erosion, respectively. These results indicate that the degree of tracking and erosion decreases with increasing ATH content. It was also observed that the area close to the bottom electrode had the highest degree of tracking and erosion. Due to dry band arcing, two modes of degradation are possible. One is the formation of a conductive path (tracking), and the other is progressive material loss (erosion). High-temperature vulcanized silicone rubber is mainly allowed to erosion mode. This phenomenon of silicone rubber is related to its unique molecular structure with a siloxane bond (Si-O-Si) in its main chain. Polydimethylsiloxane is produced mainly as a nonconductive silica during thermal degradation. Also, the water vapor from the dehydration of ATH would sweep off the electrically conductive residues produced during the thermal degradation.

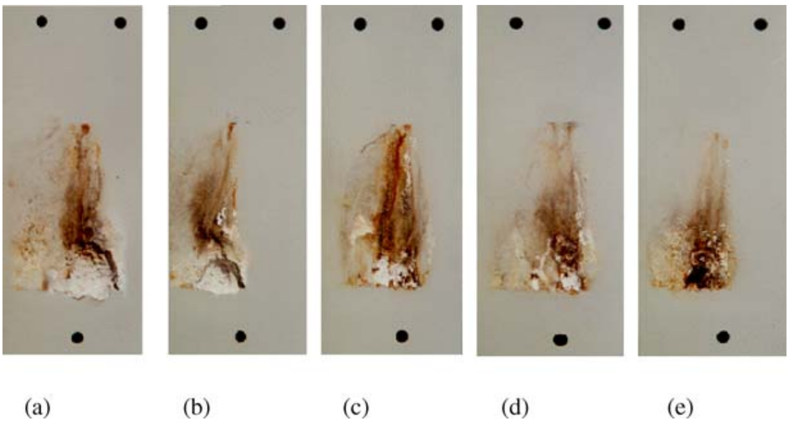
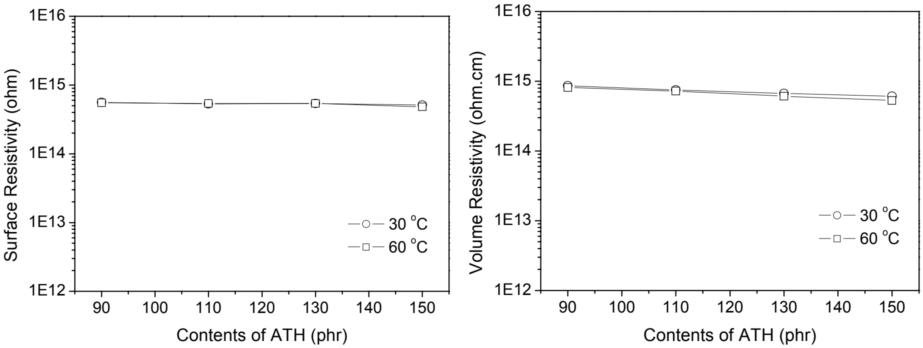


Figure 5. Photographs of the physical changes in the silicone rubber surfaces after the inclined plane test for 24 hours at 4.5 kV. The ATH contents of the silicone rubber were (a) 110, (b) 120, (c) 130, (d) 140 and (e) 150 phr.

Figure 6 shows the electrical resistivity (Figure 6 (a) surface resistivity and (b) volume resistivity) as a function of the ATH content and temperature. The electrical resistivity was constant with increasing ATH content and temperature in the silicone rubber. These imply that interfacial defects between the silicone rubber and the ATH filler did not appear with increasing the ATH content.



(a) surface resistivity (b) volume resistivity

Figure 6. Experimental relationship between electrical resistivity and the ATH content.

Figure 7 shows the dielectric strength as a function of the ATH content of silicone rubber. It was found that the dielectric strength was also constant with increasing filler content. This suggests that interfacial defects between the silicone rubber and the filler did not occur with increasing filler content. The change in the dielectric strength had a tendency similar to that of the electrical resistivity, as shown in Figure 6.

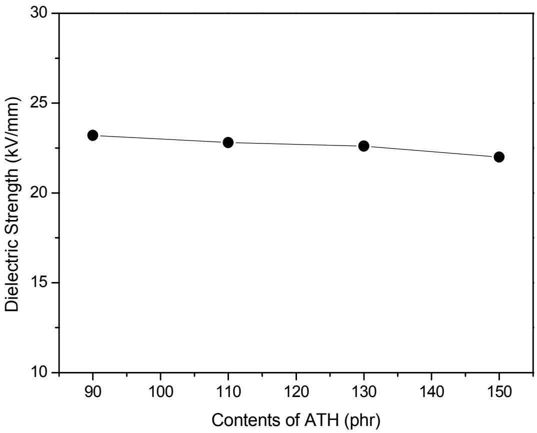


Figure 7. Experimental relationship between dielectric strength and the ATH content.

Conclusions

We investigated the influence of the ATH content of high temperature vulcanized silicone rubber on its electrical insulation properties and tracking and erosion resistance. We found that its electrical resistivity was constant with both increasing

ATH content and temperature. We also observed that the dielectric strength was also maintained with increasing ATH content. In the arc and inclined plane tests, a significant increase in the arc resistance and the tracking and erosion resistance of the silicone rubber was clearly observed at an ATH content of above 130 phr. These results show that silicone rubber with 130 phr of ATH can be used as a housing material for high-voltage insulators.

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