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A Study on the Effect of Inorganic Fillers on the Dry-Band Arcing Erosion of Silicone Rubber Composites

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Abstract - **This paper investigates the erosion of silicone rubber composites filled with various fillers. The fillers under study are alumina tri-hydrate, magnesium hydroxide and silica in a liquid silicone rubber. The inclined plane tracking and erosion test was used to compare the erosion of the composite materials at 50 wt% filler level and at 4.5 kV. Simultaneous thermogravimetric and differential thermal analyses are reported which shows various mechanisms by which the fillers can suppress the dry-band arcing erosion. The effect of water of hydration in the alumina tri-hydrate and magnesium hydroxide is investigated and its effect on the suppression of the dry-band arcing erosion is reported for the composites filled with alumina tri-hydrate and magnesium hydroxide.**

I. INTRODUCTION

Silicone rubber insulation of various types is being used extensively on the electrical power system due to its excellent performance under wet and polluted conditions. The silicone materials in use are filled with alumina tri-hydrate (ATH), silica, combinations of both, or no filler at all [1]. Generally, no differences in performance have been reported between the various compositions which can be attributed to the characteristic property of silicone rubber and that is its hydrophobicity [2]. Hydrophobicity prevents leakage current from developing which inevitably leads to dry band arcing and subsequent material erosion [1]. It is for this reason that fillers are not really required. However, fillers do lower the cost of the silicone materials and in the event of a temporary loss of hydrophobicity along the entire creeepage path of an insulator, fillers will reduce the rate of erosion.

In highly polluted environments, for example in coastal regions, composite insulators with silicone rubber housings have failed. The failures have been attributed to material erosion exposing the fiberglass core and tracking of the core [1]. These insulators were all filled with ATH filler. In many cases these insulators have been replaced by room temperature vulcanizing (RTV) coated conventional insulators. Allthough some erosion of RTV coatings has been observed, no failures have been reported and the reason for this is that the underlying material is a ceramic, not prone to tracking [3].

Normally, the addition of alumina tri-hydrate to 50 wt% has been the usual practice for composite insulators and RTV coatings. For high temperature vulcanized silicone rubber, this level is about the maximum that can be mixed in an industrial plant and for RTV coatings, the viscosity for spray application is the limitation. However, these materials are tested for erosion resistance using the inclined plane tracking and erosion test (IPT) as per ASTM D2303 or IEC 60587 meeting the usual test requirement of class 1A 4.5 in IEC 60587.

As the significant other advantages of silicone rubber composite insulators are of great interest to electrical power utilities, improved resistance to erosion of silicone rubber is a desirable goal. To this end, it is still important to understand the mechanism(s) of inorganic fillers in suppressing dry-band arcing erosion to be able improve silicone rubber compositions for heavily polluted environments and that is for this reason this research.

Meyer et al. investigated different filler parameters such as size, level and type using the step-voltage method in the IPT with a starting voltage of 2 kV. Insignificant difference was reported between alumina tri-hydrae (ATH) as compared to silica in improving the erosion resistance of silicone rubber in the IPT [4]. Thermal conductivity was accordingly the main property of the composites reported to govern the erosion resistance, and water of hydration was shown to play a secondary role [4]. Secondary effect for the water of hydration was also reported by Ghunem et al. in the DC IPT [5]. In particular dilution effect was shown for the water of hydration in both the solid and the gas phase of the filler [5]. However, Kumagai et al. showed the water of hydration in ATH to play a major role in suppressing tracking of silicone rubber in the IPT under the critical test voltage of the IPT [6]. The importance of using the critical test voltage in the IPT was highlighted by Krivda et al. [7].

The water of hydration was shown using thermal analysis to promote an internal oxidation mechanism with the released dimethyl groups from the decomposed silicone rubber [5], [6]. Chemical analysis showed hydrogen and carbon dioxide in the gas phase as byproducts of this mechanism rather than carbon residue leading to tracking [6]. This was confirmed by reporting carbon to be no more than 1wt% of the solid reside formed on the aged silicone rubber in the IPT [8].

Ramirez et al. reported insignificant difference between ATH- and Silica-filled silicone rubber composites tested under critical test voltage in the IPT [9]. Ansorge et al. reported silicone rubber with high volumes of surface modified ATH to pass the IPT even under higher voltage than the critical test voltage, at 6 kV. As such, 6kV test voltage was suggested to be applied as an alternative to the critical test voltage for more reliable IPT outcomes [10]. Significant influence for the type and particle size of the added ATH was also shown [10]. Schmidt et al. raised the importance of having good dispersion of the filler in the polymer matrix and good

bonding between the filler and the polymer matrix in improving the erosion resistance of ATH-free silicone rubber composites in the IPT [11].

In this paper the effect of water of hydration in silicone rubber composites filled with ATH or magnesium hydroxide (MH) is investigated. As erosion of silicone rubber is considered to be a thermal process, thermogravimetric (TGA) and differential thermal (DTA) analyses were conducted in order to elucidate the mechanisms by which the incorporated fillers in this study impart erosion to silicone rubber.

II. Materials and Methods

Unfilled liquid silicone rubber (LSR), supplied as part A (vinylpolydimethylsiloxane), was used as the base polymer for the composites in the study. Part B, which is a curing agent, was added in a ratio of 1:10 with respect to part A. Three different fillers, i.e. silica, ATH and MH were added in a level of 50 wt% in order to prepare three different composites. All the composites were mixed using a Ross® high shear mixer and then degassed in a vacuum oven. The IPT samples were cured in molds and heated at 85°C after curing for stabilization. All the fillers were reported to possess an average particles size of 1μm. Five samples each with surface area of 5 cm ×10 cm and thickness of 1cm as per ASTM D2303 were used. The IPT was conducted as per ASTM D2303/IEC 60587 at the critical test voltage of 4.5 kV. Such a voltage level is necessary in order to ensure that the test conditions are severe enough to induce an eroding dry-band arcing (DBA), thereby obtaining reliable results that correlate well with field experience [6], [7], [8]. In addition, the critical test voltage facilitates a well-established, stable and continuous DBA activity on the bottom electrode. Figure 1 depicts schematic circuit diagram of the IPT used in the study. The IPT started with the flow of an aqueous solution of ammonium chloride (the liquid contaminant) at a rate of 0.6 ml/min, applied by a peristaltic pump.

The test voltage is applied once a continuous rivulet channel of the liquid contaminant can be clearly observed on the surface of the test sample. Such a channel can be obtained with the help of a wetting agent, Tritton X100, added as per IEC 60587 in order to destroy the hydrophobicity of the tested surface. It is therefore important to note the IPT is strictly a test for the erosion resistance and its outcomes cannot be correlated to hydrophobicity. Higher voltage applied will increase the length of the arc and induce random and scattered DBA activity. As a result the arc hitting the surface will not be sufficient enough to cause damage and the test will be somewhat like a flashover test. On the other hand lower test voltage will not drive enough DBA power that leads to erosion. Erosion path with a length of 1-inch or measuring 60 mA or more leakage current on the samples were adapted as the failure criteria during the test. For the samples that passed the test, erosion volume was measured to evaluate the erosion resistance.

In addition, simultaneous TGA and DTA analyses were conducted for thermal analysis of the tested composites. The TGA-DTA were performed on samples that weighted less than 10 mg under a ramping temperature raise between 80 °C and 800 °C at a rate of 10°C/minute in Nitrogen atmosphere.

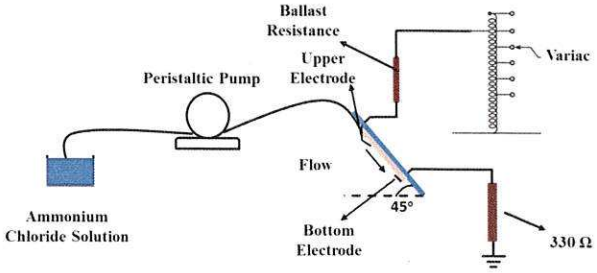

Fig. 1. Circuit diagram of the IPT.

III. Results and Discussion

Figures 2-4 show the failure patterns obtained on the tested composites. All the silica samples failed the IPT; whereas, only one sample failed from the ATH- and the MH-filled composites. No signs of tracking could be reported on the failed surfaces as no traces of carbon were visually evident on the eroded paths. The erosion paths were not found to promote leakage current as measured during the test. In particular, the silica-filled composites did not show any sign of tracking, despite the silica is not hydrated. Silica is not expected to promote an internal oxidation mechanism with the released dimethyl group that suppresses the formation of carbon residue leading to tracking. Such a finding suggests that the volume effect of the filler; i.e the filler level, replacing the combusted fuel polymer during DBA and eventually imparting the formation of carbon reside leading to tracking is the governing factor for the suppression of silicone rubber tracking, rather than the water of hydration. As such, the water of hydration can be reported as an additional influential factor on the tracking suppression.

However, a clear superior erosion performance was evident on the composites contained hydrated fillers, i.e ATH and MH, as compared to silica, suggesting a major role for the water of hydration to suppress erosion during the IPT. Figure 5 compares the eroded volume from the ATH-filled and the MH-filled composites that passed the IPT. Initially, in significant difference in the erosion resistance could be reported for the ATH-filled as compared to the MH-filled composites.

Figure 6 shows the TGA and the differential TGA (DTGA) curves for the unfilled silicone rubber which could be used in the thermal analysis part of the study as a reference. The unfilled silicone rubber experienced a weight loss indicating a decomposition of silicone rubber at a starting temperature around 400 °C. No char formation could be reported as the wt% of residue at the end of the TGA approached zero (Fig. 6). Figure 7 depicts the TGA curves for the tested composites in the study. Similar to the unfilled silicone rubber, weight loss started in the silica-filled composites at around 400 °C, indicating the decomposition of silicone rubber. The effect of silica in reducing the rate of weight loss and thus rate of decomposition of the composite

could be clearly observed in the differential TGA (DTGA) curve of the silica-filled composite shown in Fig. 8 as compared to the DTGA curve of the unfilled silicone rubber shown in Fig. 6.

The ATH-filled composites experienced an additional weight loss stage that started around 210 °C. This first weight loss was associated with an endothermic dent as shown in Fig. 9 of the DTGA curves obtained for the tested composites, showing the dehydration of ATH to be responsible for this stage of weight loss. The enthalpy of dehydration could be expected to raise the heat capacity of the tested composites during the IPT and thus suppress temperature rise leading to erosion. In addition the dehydration of ATH can promote the formation of char or a layered structure that can act as a heat shield on the DBA hitting the surface [12]. Similar erosion suppression mechanisms could be speculated for the MH as an endothermic dent for the dehydration of MH was obtained in the DTA curve shown in Fig. 9. However, unlike the ATH-filled composites, the MH-filled composites did not experience a two-stage weight loss during the TGA. MH dehydrated around 350 °C, which is a close temperature value to the decomposition temperature of silicone rubber, as could be seen in the corresponding TGA-DTA curves.

The silica filled composites showed the most inferior performance in the IPT, despite forming largest char wt% as compared to the ATH- and the MH-filled composites. Such a finding might indicate that the amount of char acting as a heat shield has a secondary effect on suppressing the DBA erosion. In significant difference in the dehydration enthalpy of ATH and MH could be reported as comparable areas under the endothermic dents were observed in the corresponding DTA curves. Such a finding might elucidate one of the main reasons for obtaining similar erosion performance between the ATH- and the MH-filled composites. However, it is important to note than more samples need to be tested to verify the findings obtained and to add more statistical significant to the results obtained [7], [10].

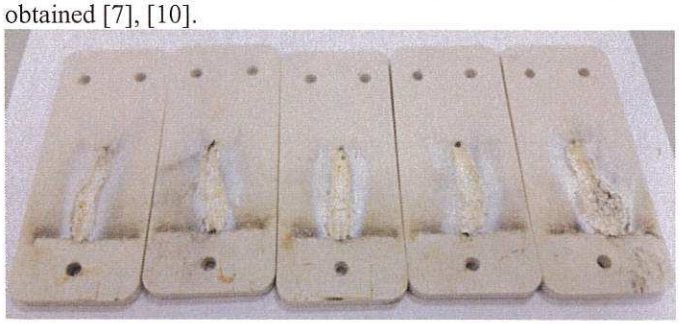

Fig. 2. Failed silica-filled silicone rubber composites in the IPT.

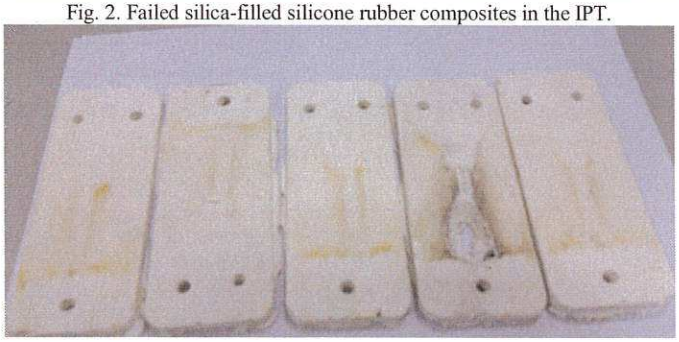

Fig. 3. Tested ATH-filled silicone rubber composites in the IPT.

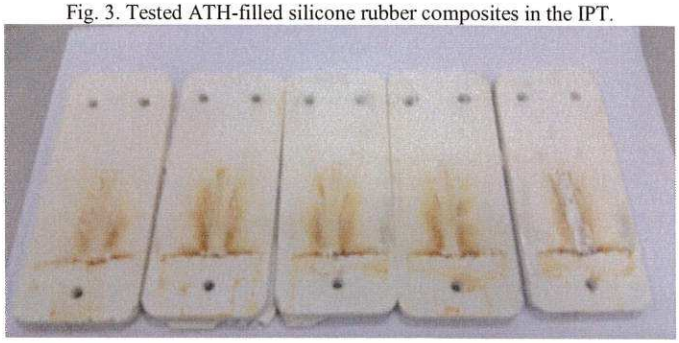

Fig. 4. Tested MH-filled silicone rubber composites in the IPT.

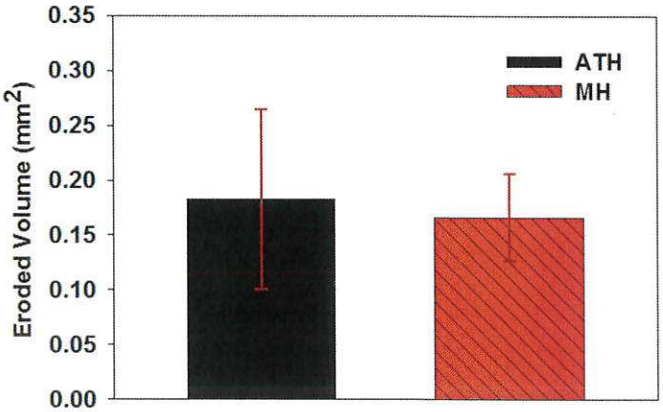

Fig. 5. The eroded volume measured for the ATH- and MH-filled silicone rubber samples after the IPT.

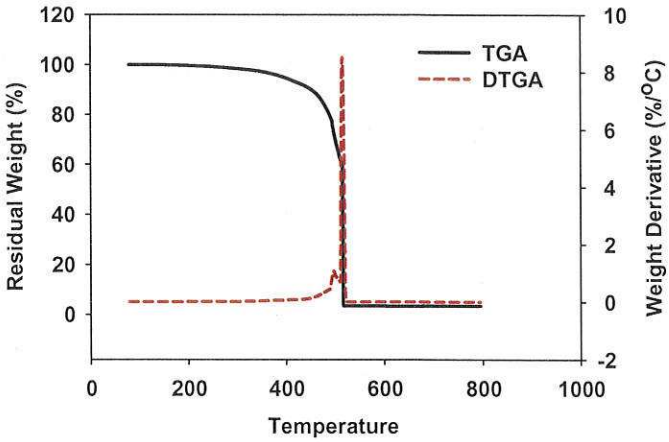

Fig. 6. Typical TGA and DTGA curves obtained for the unfilled silicone rubber used in the study.

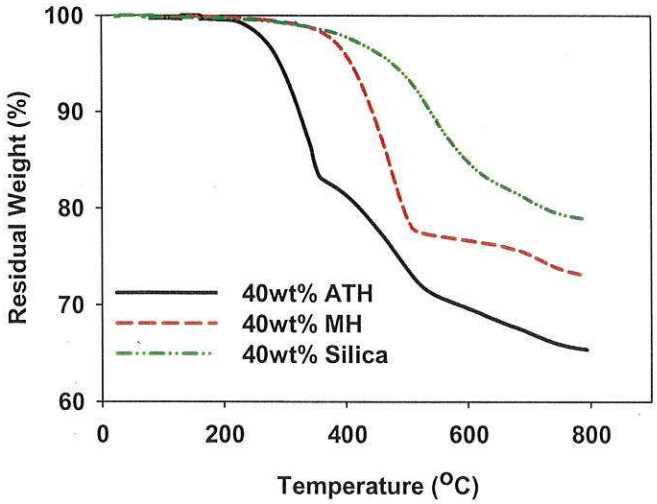

Fig. 7. Typical TGA curves obtained for the tested materials.

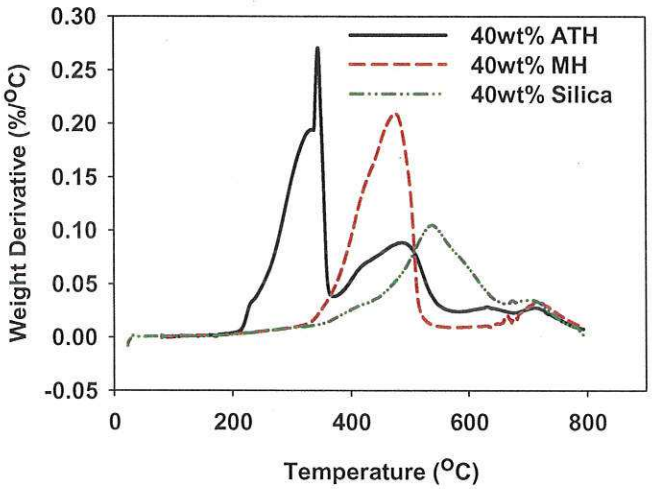

Fig. 8. Typical DTGA curves obtained for the tested materials.

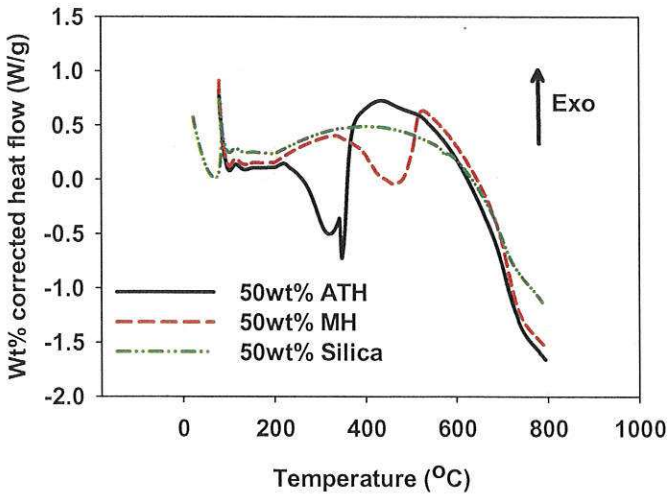

Fig. 9. Typical DTA curves obtained for the tested materials.

IV. Conclusions

A correlation is established between the IPT outcomes and thermal analysis of the composites using simultaneous TGA and DTA. Water of hydration in hydrated fillers such as ATH and MH seems to play a major role in improving the erosion performance of silicone rubber in the IPT. Selection of critical test conditions is essential for obtaining reliable outcomes in the IPT. It is important to quantify the erosion suppression effect of inorganic fillers for achieving optimum composite designs of silicone rubber outdoor insulation.

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