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The role of Nano-sized Alumina tri-hydrate and Fumed Silica on the Erosion of Silicone Rubber under DC Voltage

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***Abstract*- This paper aims to investigate the effect of nano-sized alumina tri-hydrate on the DC erosion resistance of silicone rubber, using the inclined plane tracking and erosion test. Silicone rubber composite containing nano-sized alumina tri-hydrate is comparatively analyzed with reference to silicone rubber filled with fumed silica at loading level of 5 wt%. Moreover, commercial silicone rubber composites that contain micro-sized alumina tri-hydrate at high loading levels are used for reference. Thermal characterization of silicone rubber composites is presented using simultaneous thermogravimetric and differential thermal analyses. The results obtained indicate a correlation between the erosion resistance determined using the inclined plane tracking and erosion test under DC voltages and the level of interaction between the filler and the silicone rubber tethering the siloxane chains, thereby suppressing the depolymerization and promoting crosslinking of silicone rubber. It also appears that the loading level of nano-sized alumina tri-hydrate is an essential factor that needs to be considered in order to obtain an evident erosion suppression effect for the water of hydration.**

***Keywords*- Erosion resistance, HVDC Insulation, Silicone Rubber, Nano Alumina tri-hydrate, Fumed Silica, Inclined Plane Test.**

I. INTRODUCTION

In light of the research efforts conducted towards installing green electricity links that interconnect renewable energy resources in the electric grid, research on the application of the unconventional HVDC mode of power transmission has become important. Such a mode of power transmission is more convenient, as compared to the conventional HVAC, for facilitating the interconnection of renewable energy sources supplying DC power [1]. Accordingly, HVDC outdoor insulators could be considered as backbone components that support the HVDC infrastructure in the future electricity grid. Relatively, limited studies have been conducted about developing housing materials specifically designed for HVDC insulation, as studies have been focusing more on improving the pollution performance by modifying the geometry of the insulator.

Due to its desirable hydrophobic property that hinders the development of leakage currents and subsequent dry-band arcing, silicone rubber (SiR) has been the preferable material candidate for use in outdoor AC insulation applications [2]. Considering the transition towards adding more DC topologies in the power grid, more attention has been drawn towards studying the applicability of using the existing SiR material formulations for outdoor HVDC applications. This attention has become more important since several reports have indicated an inferior erosion performance for SiR outdoor insulation composites under DC (particularly +DC) as compared to AC voltages, using the standard inclined plane tracking and erosion test (IPT) [3-5]. This inferior erosion performance under DC as compared to AC voltages has also suggested the demand for more improvements to be made on the SiR composite material design for use in the HVDC infrastructure of the power grid. Achieving this objective would require a thorough understanding of the role of inorganic fillers as erosion suppressants during the DC dry-band arcing induced in outdoor polluted conditions.

As indicated in several reported studies, the DC erosion resistance of SiR composite could be improved using inorganic fillers as flame retardants. Filler such as silica and alumina tri-hydrate (ATH) were shown to give rise to the erosion resistance of SiR by improving the thermal conductivity and the heat capacity of the composite in the condensed phase and diluting the gas phase [6, 7]. A similar observation was reported in [8] by Du and Xu using Boron Nitride (BN) filler, by correlating the improvement in the DC erosion performance with the enhanced SiR-filler interactions giving rise to the overall thermal conductivity of the composite [8]. Comparable DC erosion resistance was obtained for SiR filled with micro ATH at 30 wt% and SiR containing nano alumina filler at much lower level about 4 wt% [9]. It was concluded that reducing the size of the alumina filler would result in enhancing the erosion resistance of SiR.

However, there is still a need for more elucidation on the erosion suppression mechanism of nano-sized fillers in SiR under DC voltages. Micro-sized ATH has been a commonly employed filler in order to improve the tracking and erosion performance of outdoor SiR insulators. Therefore, it would be also important to investigate the erosion suppression mechanisms of nano-sized ATH as compared to other nano-

sized fillers, such fumed silica, under DC voltages. In this paper the effect of nano-sized ATH filler on the erosion resistance of SiR is compared to other commonly used nano-sized fillers in SiR such as fumed silica.

II. Materials and Methods

The composites used in this study were prepared in the laboratory using a two-part (Parts A and B) room temperature vulcanized (RTV) SiR, with vinyl-polydimethylsiloxane as part A and a crosslinking agent as part B. A Silverson® high shear mixer was used to gradually disperse weighted proportions the filler into Part A of the SiR until the entire filler weight was added to the mixture. Once the filler agglomerates were unobservable, the curing agent (Part B) was added and mixed for 2 minutes. It is important to note that the weight ratio between parts A and B was attained as 10:1. The resulting mixture was degassed in a vacuum chamber and then poured into the IPT sample mold. The mold dimensions were set as per the specifications indicated in the IEC 60587 standard for the IPT samples [10]. The prepared mixture was left to cure at room temperature for 24 hours and then was post-cured for 4 hours at 87 °C. Table I describes the prepared composites. Commercial samples containing micro-sized ATH were also used in the study.

TABLE I
SiR Composite Samples Used in the Study and Asscoiated Filler Properties

Inorganic Fillers	Filler Sample Code	Filler (Median) Particle Size (nm)	Specific Surface Area (m^2/g)	Filler wt% in samples prepared
Alumina Trihydrate	NA10	10	650	5
Fumed Silica	NS07	7	390±40	5

Fig. 1 shows the circuit diagram and setup for the DC IPT used in the study. The most severe voltage polarity leading to deep erosion, i.e +DC, was applied during the IPT in order to ensure that the effects of the fillers during erosion could be investigated [3-5]. As per the DC IPT test procedure outlined in [4], the constant voltage method was carried out with the test voltage being set to 70% of the standard critical $4.5kV_{rms}$ AC test voltage [10]. The contaminant flow rate was set at 0.6 ml/min with a conductivity of 2.5 mS/cm. Accordingly, a +DC voltage of 3.5 kV was applied across the testing samples for test duration of 6 hours. As outlined in [10], a failing sample would either have the leakage current exceeding 60 mA or have an erosion path exceeding 1 inch in depth.

The tested composites were also analyzed using a simultaneous thermogravimetric and differential thermal analysis (TGA-DTA) in both air and nitrogen (N_2) atmosphere. The heating rate was set at 25 °C/min for a temperature span between 80 to 800 °C and the samples used weighted about 20 mg.

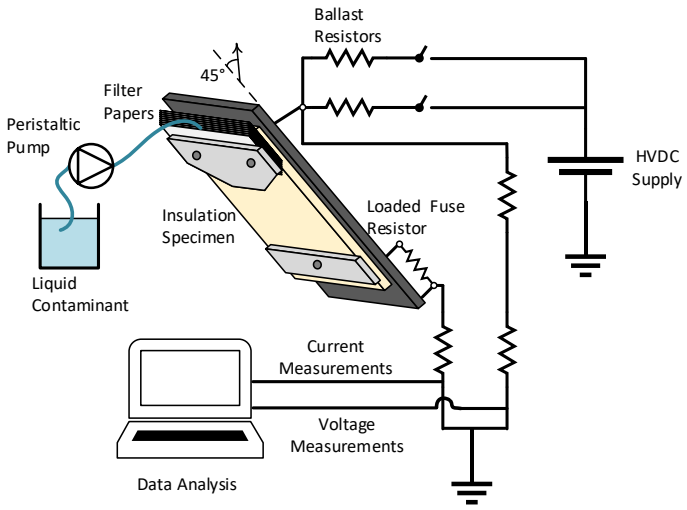

Fig. 1. DC IPT circuit diagram and setup

III. Results and Discussion

Fig. 2 shows the TGA performed in nitrogen atmosphere for the prepared composites. The initial weight loss took place for both composites at approximately 400 °C. According to Hamadani et al. in [11], SiR decomposes in nitrogen atmosphere due to random scission of the Si-O bonds at about 400 °C. The scission of Si-O bond results in shorter siloxane chains and the volatilization of cyclic SiR oligomers [12]. Similar results were also reported for the ATH –filled SiR by Kumagai et al. in [13].

However, ATH was shown to dehydrate at about 220 °C, thus initiating another weight loss stage in the TGA before the decomposition of SiR [13]. The dehydration of ATH was obtained for the commercial composites used in this study, leading to an endothermic dent in the corresponding DTA curve shown in Fig. 3. On the other hand, the dehydration dent was not evident in Fig. 3 for the SiR filled with nano-sized ATH (NA10). Instead, an exothermic hump was obtained, indicating the combustion of the volatile SiR oligomers as by product of SiR depolymerization. No exothermic hump was evident in Fig. 3 for the commercial composites. Commercial SiR composites typically contain ATH at about 60 wt%. Therefore, it appeared that, although nano-sized ATH was used, a critical ATH level was still needed in order to dilute the SiR the gas phase and suppress the combustion of volatile SiR.

The corresponding differential TGA (DTGA) curves in Fig. 4 showed that each weight loss stage for each of the composites analyzed was associated somehow with two peaks. Such a finding could be attributed to two different mechanisms taking place during the weight loss stage [11]. The first peak initiated at about 400 °C was already shown to correspond to depolymerization of SiR. The second peak in the DTGA curves occurred approximately at 650 °C and accompanied the depolymerization peak, thereby indicating a radical-based crosslinking of SiR. Camino et al. reported radical-based crosslinking initiated through Si-C bond scission as a competing mechanism taking place at higher temperatures than the depolymerization in SiR [12].

Two notable features were distinctly obtained for the composites containing nano-sized alumina tri-hydrate (NA10) and fumed silica (NS07) during their first weight loss stage, namely the rate of weight loss corresponding to the rate of depolymerization and the remnant residue level by the end of the TGA corresponding to the level of crosslinking. Faster weight loss rate was obtained for the SiR filled with NA10 as compared to NS07. In addition, higher remnant residue was obtained at the end of the TGA for the SiR containing NS07 as compared to NA10. The rate at which depolymerization of SiR occurs was shown to be predominantly governed by the mobility and flexibility of the siloxane chains [11]. Therefore, the interaction between the fumed silica and the SiR tethering the siloxane chains would be expected to suppress the Si-O bond scission, thus the depolymerization and volatilization of SiR. This interaction between the SiR and fumed silica was shown already shown to be taking place as a result of the silanol groups on the surface of the fumed silica [14].

Similarly the increase in the amount of the final residue obtained in the TGA conducted for the SiR filled with NS07 as compared to NA10 could be attributed to the interactions between the fumed silica and the SiR promoting radical-based crosslinking while suppressing depolymerization. The results obtained in Fig. 5 showing the DTA performed in air atmosphere confirmed the findings obtained with the TGA and the DTGA. An exothermic hump was obtained for both composite indicating the combustion of volatile SiR. The lower exothermic peak indicating the suppression of volatilization and thus depolymerization of SiR was evident for the SiR containing NS07 as compared to NA10. This suppression obtained in the combustion of the volatile SiR could also be attributed to the interaction between the fumed silica and the SiR. This interaction either suppressed depolymerization and thus volatilization or promoted radical-based crosslinking that gave rise to inert gases such as methane diluting SiR in the gas phase [12].

Fig. 6 shows the IPT outcomes in this study. The average eroded depth determined was lower indicating better erosion resistance for the SiR containing NS07 as compared to NA10. This finding could be confirmed visually in Fig. 7 showing more damage on the surface of the SiR containing NA10 as compared to NS07. Therefore, the IPT outcomes appeared to be correlated with the outcomes of the thermal analysis performed using TGA-DTA.

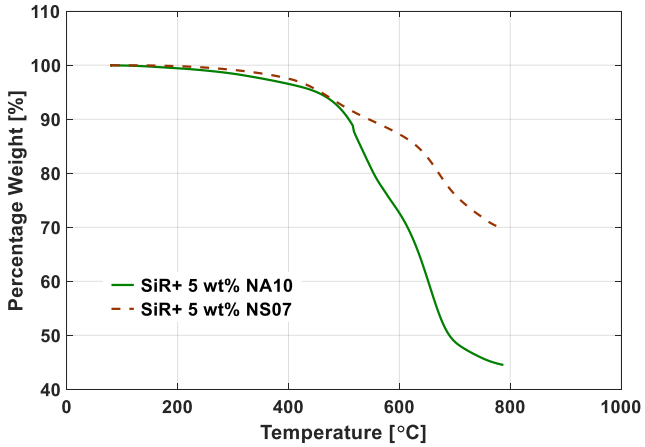

Fig. 2. TGA for the prepared NA and NS filled composites in N_2 atmosphere

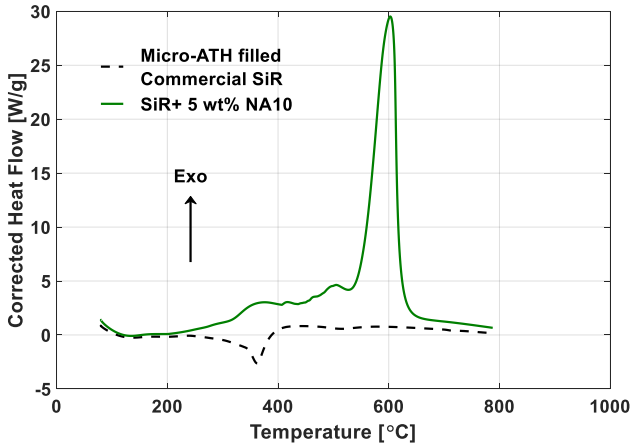

Fig. 3. DTA for the prepared NA-SiR composite and micro-ATH SiR commercial composite in air atmosphere

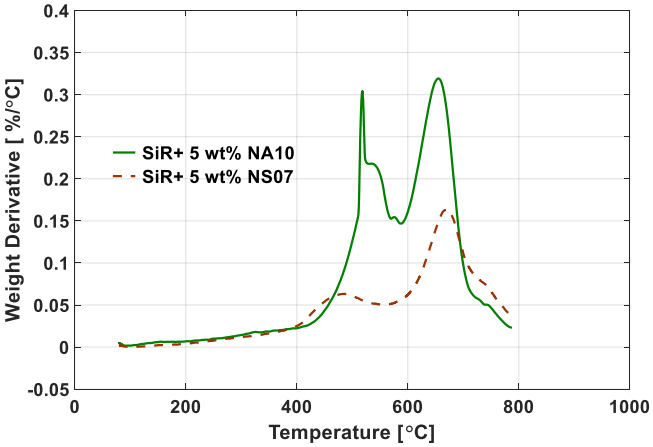

Fig. 4. DTGA for the prepared NA and NS filled composites in N_2 atmosphere

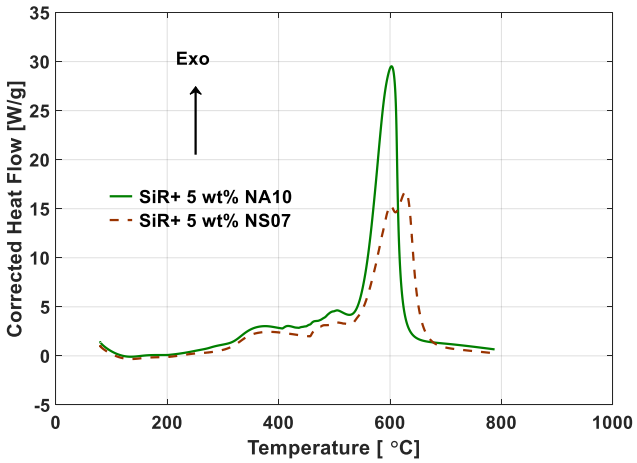

Fig. 5. DTA for the prepared NA and NS filled composites in air atmosphere

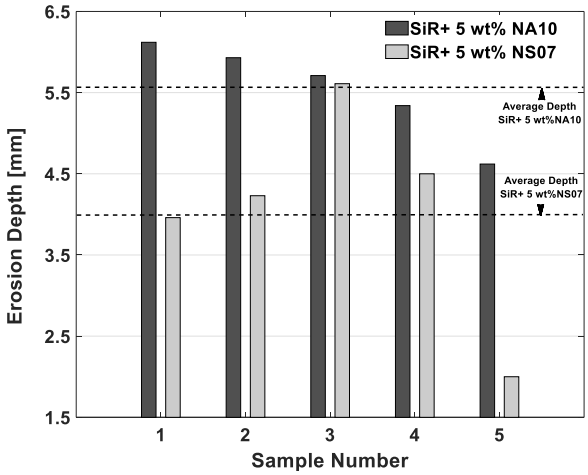

Fig. 6. Erosion Depth measurement outcomes for the prepared NA and NS filled composite samples after running the +DC IPT.

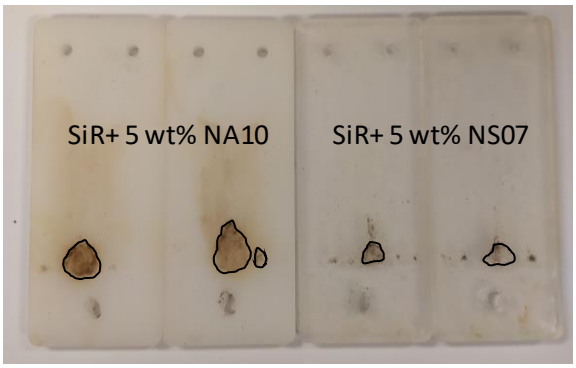

Fig. 7. Selected NA and NS-filled composite samples from the +DC IPT test

CONCLUSION

The presented paper investigated the use of nano-sized ATH fillers in outdoor SiR DC insulating materials. Fumed silica was used as a reference filler in the study and commercial SiR outdoor insulating materials that contained micro-sized ATH at high loading levels were also analyzed in order to investigate the water of hydration in ATH. The interaction between the nano-sized filler and the SiR was shown to have a significant effect in the suppression of depolymerization and the promotion of crosslinking of SiR. Higher level than 5 wt% of ATH was needed, even though with nano-sized particles, in order to obtain an effect for the released water of hydration diluting the gas phase of SiR. The outcomes of the IPT performed under DC voltages were successfully correlated with the outcomes of the simultaneous TGA-DTA performed for the tested composites in nitrogen and air atmospheres. Therefore, simultaneous TGA-DTA seemed to be a useful tool in the investigation of the effect of nano-sized fillers on the erosion of SiR under DC voltages.

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