

Tracking and Erosion Resistance of Nano-Filled Silicone Rubber for use in High Voltage Outdoor Insulators

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Abstract- Tracking and erosion (T&E) resistance of the weathersheds of polymeric insulators can directly influence the reliability of the power system where such insulators are being used. Usually the weathershed material is compounded with flame retardants (additives) to enhance its T&E resistance. It is necessary to compound with suitable filler for obtaining a satisfactory performance of the insulator. This paper deals with the studies related to the comparison of the erosion resistance of unfilled silicone rubber (SR) as well as SR filled with nano-sized alumina (ALU) and precipitated silica (SIL) particles. Tracking and erosion resistance studies of samples were carried out using an inclined plane (IP) T&E resistance test apparatus. Results show that the T&E performance of the ALU filled (up to 4 wt %) SR was much better than the SIL filled (up to 4 wt %) SR. Many of the SIL filled samples failed in the IP tests whereas ALU filled samples performed exceptionally well due to the higher thermal stability of the nanoalumina composites.

I. INTRODUCTION

Composite polymeric insulators are emerging as promising and reliable candidates for the transmission and distribution of electrical power. They offer attractive advantages like light weight, easy transportation and installation and also they exhibit good resistance to vandalism. They also provide much better performance under contaminated environments during the initial period of service as compared to that of conventional insulators. If the weathersheds do not have adequate T&E resistance, then the polymeric insulators cannot provide satisfactory long term performance especially under polluted wet conditions. The T&E occurs on the weathersheds due to the dry band arc taking place on its surface. The different steps leading to the dry band arcing are as follows. It is possible that during service, considerable leakage current can flow on the contaminated wet surface of an insulator. Leakage current produces ohmic heating resulting in the formation of dry bands. The sharp and subsequent increase in local field gradients across dry bands results in arcing (also called scintillations) across them. Temperature generated (1200 °C) due to repeated dry band arcing can be beyond safe limits ($\approx 400^\circ\text{C}$) of organic material (SR) [1-2]. If the rise in temperature is beyond the safe limit that the polymeric material can handle, then it can lead to tracking and/or erosion. To mitigate the deleterious effect of the high temperature generated during scintillations, flame retardants (micron-sized fillers) are added to the base polymer in varying concentrations. Hence, even though SR is considered as a better material for outdoor insulator application, it has become necessary to add flame retardants to improve its performance

with respect to T&E resistance. To improve the different properties of the base polymer, it is compounded with various fillers depending upon the property to be achieved. Highly loaded SR performed better than SR with lower filler content in terms of T&E resistance [2-4]. Common practice to improve T&E resistance is by loading heavily (50 to 60 %) with micron-sized ATH filler in outdoor insulators. The processability and flexibility of the end product may get affected by such high loadings of the micron sized filler. It has been reported that higher loadings of the hydroxide filler for targeted flame retardancy can often lead to poor mechanical properties such as lower tensile strength and elongation at break [5]. It has been reported that insulators in the field failed due to T&E on the surface of the polymeric weathersheds in spite of improving the T&E resistance by such heavy loading. Hence the current level of improved T&E resistance at this heavy loading is also seems not adequate.

Addition of a few wt % of nano-fillers has a profound impact on the electrical, mechanical, physical and thermal properties of the polymer [6-7]. Alumina nanocomposites showed very different dielectric properties as compared to the unfilled polymer [8]. An improvement in the erosion resistance performance has been observed in SR nanocomposite at low wt % of silica filler loading as compared to the microcomposites [9-11]. It is also reported that oxide nano-fillers improved the thermal stability and flammability properties of the composites [12]. Hence the performance of the nanocomposites is highly promising even at low filler wt % loadings.

The electrical performance of the weathershed depends upon the type and size of the filler that is compounded with the weathershed material. Hence it is necessary to identify a suitable nanofiller for obtaining satisfactory performance of the insulator. Silica (SIL) has been used as an additive by various manufacturers for the outdoor polymeric insulator. There are different forms of the silica filler available such as fumed and precipitated and hence all the forms may not provide the same T&E performance when they are compounded with SR. This underscores the need to carry out experimental studies with various types of fillers. Literature on studies with nanoalumina and precipitated nanosilica in SR is scarce as this field is still at its infancy. The present paper deals with the comparison of the erosion resistances of unfilled SR as well as 4 wt % of ALU and SIL filled SR. Studies have been carried out using an IP test apparatus built in house specifically for the studies. An attempt has been made to elucidate the possible reasons for the better performance of nanoalumina filled SR as compared to the precipitated nanosilica filled SR.

II. EXPERIMENTAL DETAILS

A. Material

Two component Room Temperature Vulcanised Silicone Rubber (RTV SR) supplied by Wacker Chemie, Germany was used for making the samples. As per the manufacturers data it does not contain any added fillers. Also, its performance is as good as the high temperature vulcanised SR used for outdoor insulators [13]. Nanoalumina and precipitated silica of sizes < 45 nm and < 20 nm respectively supplied by Sigma Aldrich have been used for making the nanocomposites.

B. Sample Preparation

The fillers were dried in an oven at 130°C for at least 10 h before their usage. Similarly RTV A and B components were kept under vacuum for few hours in order to remove trapped air and moisture. For making nanocomposites, first mechanical mixing followed by ultrasonication has been used. Ratio of RTV components A : B for the composite developed is 3 : 1. Sample has been cured in the oven at about 130°C . More processing details have been given in a recent publication by the authors [14]. Rectangular samples of sizes 130 mm (L) X 60 mm (B) X 5 mm (H) were cast for the studies. SR samples filled with 4 wt% of nanoalumina (4 ALU) and nanosilica (4 SIL) have been made for the studies.

C. Inclined Plane Tracking and Erosion Test

The test has been conducted conforming to the ASTM standard 2303. Voltage has been fixed at 2.5 kV (r.m.s) as it creates average electric stress (50 V/mm) which is close to the field levels (30 to 40 V/mm) that exist on the insulators used for power transmission [14]. Also it was noticed that scintillations at higher voltages (say 4.5 kV) has been very aggressive and highly random w.r.t time and location on the surface of the sample. Conductivity of NH_4Cl solution used is 2.5 mS/cm. Samples were tested at 2.5 kV for 7 h. The experimental set up used is shown in Fig. 1. The measurement details of the eroded material from the sample are given in an earlier publication [14].

D. Scanning Electron Microscopy (SEM) Studies

The eroded areas were observed using microscope to understand the physical role played by the particles in the matrix in enhancing the erosion performance of the material. SEM machine (FEI make ESEM Quanta) at different accelerating voltages has been used to obtain the images.

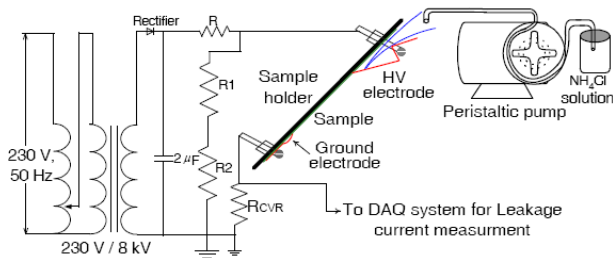


Fig. 1. Inclined Plane Tracking and Erosion Test Setup

E. Thermo Gravimetric Analysis (TGA)

This study helps to understand the thermal stability of the material. Perkin Elmer Pyris Diamond TG/DTA instrument has been used and the temperature was raised to 720°C from room temperature at a constant heating rate of 10°C .

III. RESULTS

A. SEM Studies

Figure 2 shows the SEM image of the eroded region of the ALU SR composite. SEM image of the eroded region of the SIL SR composite has not been provided as most of the tested samples failed during the IP test. It is very interesting to see the physical shape and unique structure formed on the eroded regions of the ALU nanocomposites. A honey comb type of structure has been found on the ALU nanocomposite. This type of structure was present on all the ALU nanocomposites and was much more evident at higher voltages (4.5 kV) of the inclined plane testing. Honey comb structure is very strong and it is also tightly bound to the ALU nanocomposite samples. If the degraded material is bound tightly, it forms a strong ceramic barrier to the subsequent erosion due to the discharges and it can resist further degradation to a greater extent. This type of honey comb structure formation can be due to the stronger forces of interaction between hydroxyl groups on the ALU nanofiller and the SR matrix [14] as compared to the SIL nanoparticles and the SR matrix (see

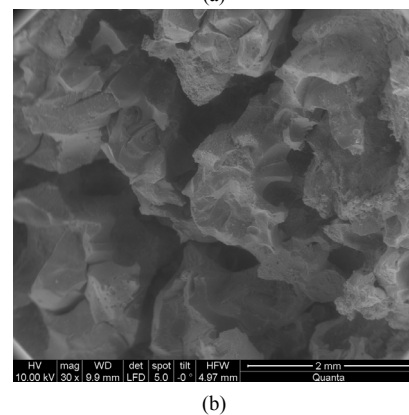
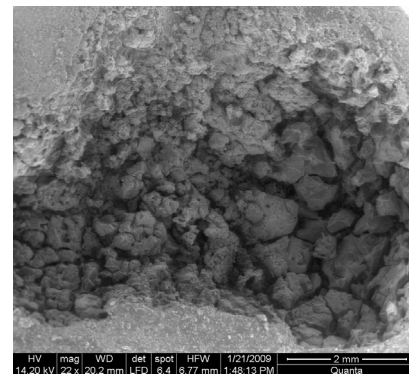


Fig. 2. SEM pictures of the eroded regions of the nanocomposite sample (4 ALU) after IP test at test voltages (a) 2.5 kV (b) 4.5 kV

section IV for more details). This can lead to better reinforcement between the fillers and the silicone rubber matrix. This improved physical bonding can help to hold the polymeric material intact and can facilitate the structure formation. At this point of time it is not very clear about the behaviour of the nanocomposites as the understandings in this particular SR nanocomposite are not fully mature. Various reasons for the better performance of the ALU nanocomposite have been given in section IV based on the various results obtained in this study.

B. Physical Studies

Figure 3 shows the photographs of the samples after the IP test has been conducted. Table 1 shows the erosion performance of the samples studied. From Figure 3 and Table 1, it is observed that the performance of unfilled SR (UnF) is inferior to ALU SR nanocomposites in terms of the eroded mass. The performance of the ALU SR at 4 wt % is much better as compared to the UnF samples. But the SIL nanocomposites performance deteriorated with the filler addition. It is also observed that most of the SIL SR samples

failed during the IP test whereas none of the ALU SR samples failed during the test. Hence the SIL composites performance is inferior to the UnF SR performance. The poor performance of the SIL composites has been attributed to the poor thermal stability of the SIL composites and poor interaction between the filler and the polymer matrix as compared to the UnF and ALU composites (see section IV for more details).

C. TGA Studies

Figure 4 shows that TGA of the samples studied. It is clear that the whole TGA curve of the SIL lies below the TGA curve of the UnF and ALU samples which indicates that the rate of degradation (the tangents drawn on TGA gives the rate of degradation) of the SIL samples is higher than the UnF samples and much higher than the ALU samples. The wt % of the sample after the TGA test gives the residual weight which is also an indicator of the thermal stability apart from the rate of degradation during TGA. After the TGA test, the residual wt % of the SIL sample is also almost zero like the UnF sample. Hence the thermal stability of the SIL is poorer as compared to the UnF and ALU composites. Hence most of the

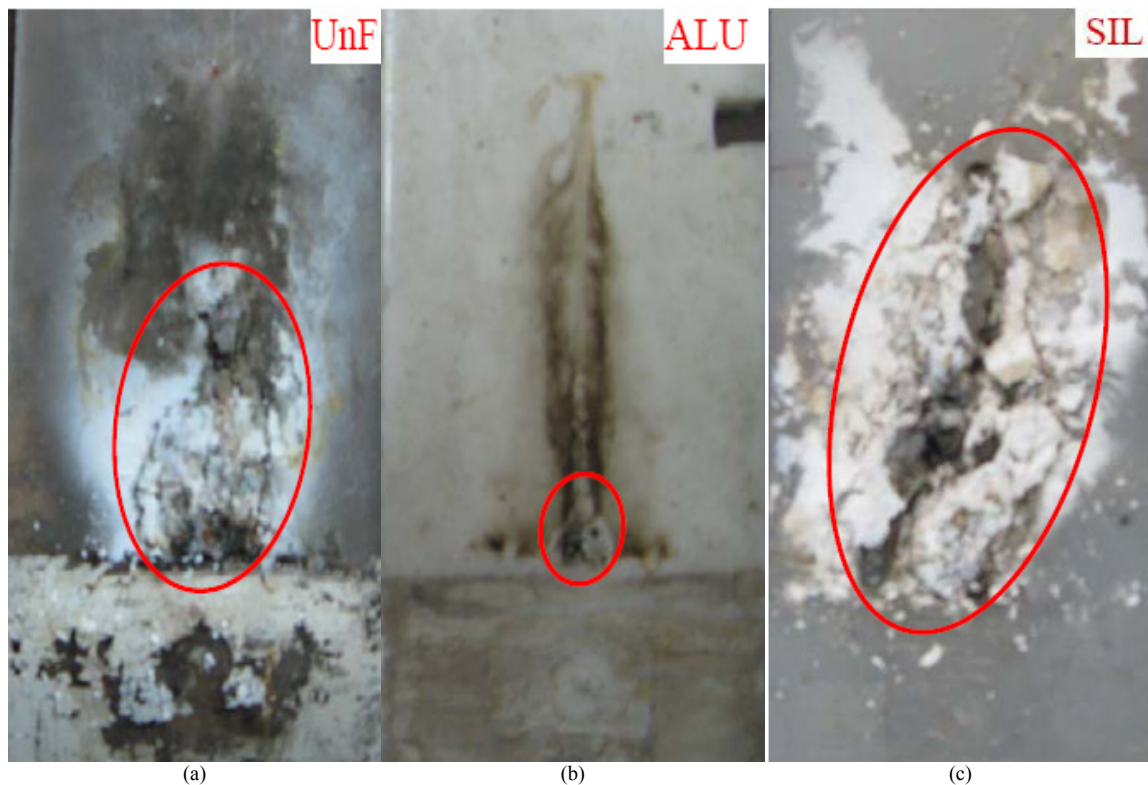


Fig. 3. Photographs of silicone rubber samples after the IP test (a) Unfilled, (b) 4 wt % filled ALU and (c) 4 wt % filled SIL.

Table 1. Eroded mass of different representative samples tested under ac and dc

S.No	Eroded mass (g)					
	AC			DC		
1	UnF	4 ALU	4 SIL	UnF	4 ALU	4 SIL
1	0.50	0.05	0.16	0.65	0.20	0.94
2	0.41	0.07	F*	0.44	0.53	F*
3	0.21	0.06	F*	0.55	0.44	F*
4	0.60	0.05	--	0.50	0.40	--

F*- Failed

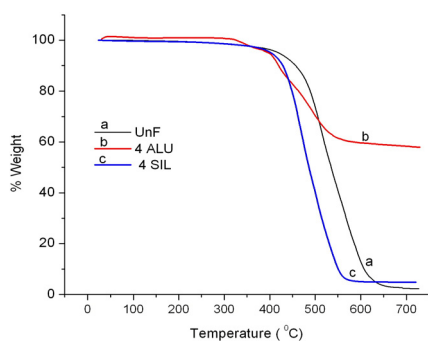


Fig. 4. TGA of the various samples studied

SIL samples failed during the IP test. The thermal behaviour (TGA curves in the tested temperature range) of the samples is not fully understood at this moment. More explanation for this kind of behaviour has been given in the next section. From Figure 4 it is concluded that small wt % of ALU filler added to the SR enhanced its thermal stability significantly and hence the erosion performance of the ALU is quite encouraging as compared to the UnF samples or even the higher wt % of ATH filled microcomposite as reported in detail by the authors in an earlier publication [14].

IV. DISCUSSIONS

The studies indicate that not all the fillers will have positive influence on the electrical properties such as erosion resistance with the increase in filler concentration. Again for the same filler, depending upon the chemical structure and morphology (e.g. fumed and precipitated silica), the final properties of the compound are decided. Hence it is required to carefully investigate experimentally the properties of the final compounded material for the suitability of the filler (material) for outdoor applications. The ac and dc erosion resistance of the UnF, ALU and SIL composites have been studied using IP tests. Majority of the tested SIL samples failed in the IP tests. The erosion performance of the SIL samples was found to be poorer than the UnF and ALU filled samples. The poor performance of SIL has been attributed to the poor thermal stability and poor interaction between the nanoparticles and the polymer matrix as given below.

It has been reported that due to the interaction of the nanoparticles with the polymer in the host matrix, the thermal properties of the polymer around the nanoparticles are modified [16-17]. The thermal properties of the polymer nanocomposite were observed to be significantly enhanced due to the interaction zones around the nanoparticles [17]. As explained in section IIIC, the thermal stability of the SIL has been observed to be poorer than the UnF and ALU filled SR. Erosion due to electrical discharges is a thermal phenomenon and hence the thermal stability will directly influence the erosion resistance of the samples during the IP tests. The poor thermal stability could be because of the poor physical bonding between the filler and polymer matrix [13]. The physical bonding is significantly influenced by the degree of

the interaction between the filler and the polymer. Since the interaction in SR is believed to be due to the hydrogen bonding, it will not be reflected in the FTIR spectra [18] of the SR composite. Hence an indirect study has been conducted where FTIR spectra of fillers are obtained and knowing the SR chemical structure, the hydrogen bonding can be assessed. The presence of the hydroxyl groups on the nanofiller surface leads to the hydrogen bonding [19]. Hence the relative intensity of the OH functional groups has been ascertained from the FTIR spectra. From Figures 5a and 5b and Table 2, it can be observed that the relative intensity of the OH functional groups is significantly less which can lead to poor physical

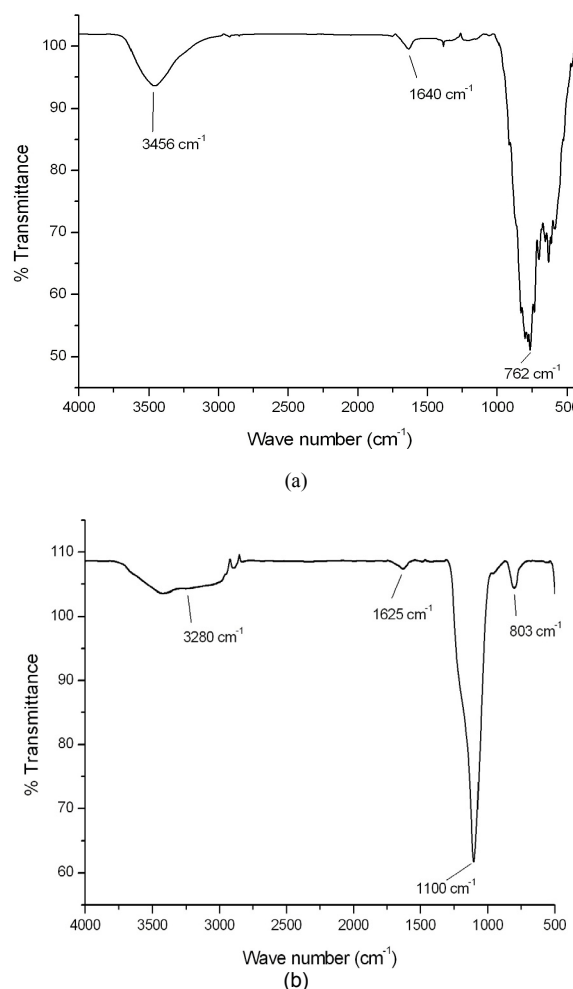


Fig. 5. FTIR spectra of the nano-alumina and silica fillers respectively

Table 2. Analysis of the OH functional groups on the surface of the nanoparticles using IR spectra.

S. No	Combination of OH groups (corresponds to 3300 cm^{-1} to 3400 cm^{-1}) on the surface of nanoparticle and absorbed water in % (relative to max. peak in its IR spectrum)	
	Nanoalumina	Nanosilica
1	17 %	10 %

bonding. If the bonding between the fillers and polymer matrix is poor they can act as defects and hence poor erosion performance.

V. CONCLUSIONS

The erosion resistances of nanoalumina and precipitated nano silica filled silicone rubber samples have been studied in the IP test. It was found that nanoalumina filled SR performed exceptionally well even at low wt % of the filler loading as compared to the unfilled SR. However, nanosilica filled SR samples failed in the IP tests and hence their erosion performance is poorer than even the unfilled SR. So precipitated nanosilica filled SR samples may not give satisfactory performance with respect to the erosion (up to the wt % of the filler studied). This infers that erosion performance not only depends upon the type and size of the fillers but also on its chemical structure. The poor performance of the silica nanocomposites has been attributed to the poor thermal stability and poor interaction between the fillers and the SR matrix. Alumina nanocomposite is promising in terms of the erosion resistance even at low wt % of filler loading for the outdoor applications. Use of lower loadings of filler as in the case of the ALU nanocomposite may lead to better flexibility, ease of processing during the product manufacturing and at the same time better electrical performance.

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