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Tracking and Erosion of Silicone Rubber and EPDM Insulation in the DC Inclined Plane Test

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ABSTRACT

This paper investigates the tracking and erosion of silicone rubber and EPDM insulation in the DC inclined plane tracking and erosion test. Silicone rubber filled with alumina tri-hydrate fails due to combustion in the gas phase or erosion paths, but with no evidence of tracking. EPDM fails due to tracking and surface capturing fire, from dry-band arcing leaving a black residue while impinging the surface. Carbonaceous residue on EPDM gives rise to leakage current magnitude; whereas, fused silica-based residue on silicone rubber is shown to promote combustion. A high amount of alumina tri-hydrate replacing the polymeric fuel in the composite is shown as a primary factor preventing failure and changing the nature of the residue in the DC inclined plane tracking and erosion test. Depolymerization is the main degradation mechanism reported for silicone rubber and EPDM, with notable degrees of crosslinking reported only for silicone rubber. Crosslinking reduces the amount of silicone rubber undergoing depolymerization, thus the amount of fuel prone to combustion is reported to promote a coherent residue shield against the eroding dry-band arcing.

Index Terms — **tracking, erosion, silicone rubber, EPDM, outdoor insulation, ATH, inorganic fillers, residue, residue**

1 INTRODUCTION

INSULATORS with polymeric housing materials are replacing insulators made from toughened glass and porcelain, for many reasons including: cost reduction, improvement in pollution performance and resistance to vandalism. Silicone rubber insulators are widely employed as low-molecular-weight siloxane fluids diffuses from the bulk to the surface of the housing material, thereby maintaining a hydrophobic insulator surface. Concerns remain about degradation in the long term causing erosion of the housing material. Insulator housing materials based on ethylene propylene diene monomer (EPDM) are also employed, for further reduction in cost in comparison to silicones [1]. In addition, EPDM offers better mechanical properties than silicones – stimulating the development of hybrid blends of both silicone rubber and EPDM [2]. Field experience demonstrates superior hydrophobicity, and thus pollution performance, for silicone rubber as compared to EPDM insulators [1, 3].

Little attention has been given to the tracking and erosion resistance of silicone rubber as compared to EPDM insulators. Ramirez *et al* reported insignificant difference in erosion resistance between silicone rubber and EPDM, containing alumina tri-hydrate (ATH) or silica and tested in the inclined plane tracking and erosion test (IPT) [4]. The study conducted with IPT by Heger *et al* showed inferior erosion performance for EPDM as compared to silicone rubber under AC voltages; whereas, a superior erosion performance was reported for EPDM as compared to silicone rubber under DC voltages [5]. Gorur *et al* reported better tracking and erosion performance for EPDM than silicone rubber under a high-conductivity salt-fog, but the contrary was obtained under a low-conductivity salt fog [6].

A clear variation in outcomes could be noted for studies comparing the tracking and erosion performances of silicone rubber and EPDM, which highlights the need for further investigation. With greater interest in DC composite insulators, it is also important to conduct this investigation under DC voltages. There is a need to understand the mechanisms of tracking and erosion, and not to only limit the investigation to comparing the tracking and erosion of silicone rubber and EPDM using different tests and under different types of voltages. Therefore, this paper reports on the tracking and erosion mechanisms of EPDM and silicone rubber using the IPT, and thermal behaviour using simultaneous thermal thermogravimetric analysis (TGA) and differential thermal analysis (DTA).

2 MATERIALS AND METHODS

Table 1 describes the high temperature vulcanized silicone rubber and EPDM materials used in the study. Slabs of composites

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were tested in the DC IPT as illustrated in Table 1 using both the initial tracking voltage (ITV) and the constant voltage (CV) test methods in most parts as per ASTM D2303. The dimension of the composites were 125 x 50 mm with 5 mm thickness.

The S25 and E25 composites contain a lower ATH level as compared to the typical 60 wt% amount for outdoor insulation applications as in S60 and E60 composites. The S25 and E25 composites were expected to fail or track during the IPT and therefore investigating the failure mechanism of these composites would be a useful task to perform. On the other hand, the S60 and E60 composites are highly filled with ATH at 60 wt%, which is typical of commercial grade insulators, and therefore they would tend to erode rather than fail or track in the IPT. Highly filled composites may still fail typically due to erosion paths or combustion in the IPT under the critical voltage, i.e. 4.5 kV. This approach is useful when viability of the composite is tested for outdoor insulation applications. However, since the failure mechanism would already been investigated for the E25 and the S25 composites, it is useful to compare the erosion resistance for the S60 and E60 composites using the constant voltage (CV) method without burning them by applying a lower or critical voltage.

The DC voltages applied during the IPT were selected to be equivalent (not equal) to the corresponding standard AC voltages at a specific liquid-contaminant flow rate of 0.3 ml/min and with a specific ballast resistance value of 50 kΩ. The following steps were conducted in order to determine DC voltages of the ITV and CV methods of the IPT.

1. The AC_{rms} ITV was determined as per ASTM D2303 to be 3.25 kV.
2. The recommended ratios for determining the equivalent +DC and –DC inclined plane voltages were respectively reported as 67% and 84% on average [9]. These ratios were determined using the power approach by measuring the relative initial tracking and the dry-band arcing inception voltages as discussed in details in [9].
3. Accordingly the equivalent +DC and –DC voltages in the ITV method would be about +2kV and -2.5 kV.
4. The S60 and E60 composites are highly filled with ATH at 60 wt% and therefore would be expected to pass the 3-3.75 kV AC_{rms} range in the IPT but with erosion to a certain extent. Accordingly, the preferred AC_{rms} voltage of IPT would be in the middle of the range at 3.5 kV.
5. Similarly, the equivalent +DC and –DC voltages of the CV method can be determined respectively using the 67% and 84% ratios to be about +2.25 kV and -3.0 kV.

At least five samples were tested for each composite and under each voltage polarity. The eroded area on the tested materials was approximated by multiplying the maximum two dimensions of the ablation region after the test. Simultaneous leakage current (LC) and surface temperature measurements were monitored and some of the tested surfaces were video recorded during the test. The LC waveform was acquired using Labview® software at a sampling frequency of 7.68 kHz, and only a window of 512 samples was stored for analysis. The infrared camera facilitated two manually selected temperature measurement ranges between room temperature and 500 °C and between 350 and 1200 °C; with an accuracy of ± 2 °C. Specifically, the maximum hot spot temperature on the surface was acquired every second. The surface emissivity was assumed to be 0.98 for the temperature measurement. Figure 1 shows the schematic diagram of the IPT setup used in the study. The liquid contaminant constituted of a 0.1 wt% aqueous solution of NH_4Cl with Triton X100 added as a wetting agent at 0.02 wt%. The three failure criteria applied in this study were (1) erosion path of 2.54 cm, (2) severe erosion depth of exceeding 2.5 half the thickness and (3) sample ignition of flaming. Details describing the experimental setup can be found in [7] and [8].

Simultaneous TGA-DTA was conducted using TA SDTQ600®, with 10–15 mg samples taken from the composites. Measurements were performed in both nitrogen (inert) and air atmospheres and in a temperature range between 80 and 800 °C while increasing the temperature at a rate of 10 °C/minute.

It should be noted that it was not the intent in this study to compare the tracking and erosion resistances of the material samples under +DC and –DC voltages. The intent was rather to elucidate the tracking and erosion mechanisms for each type of material and the protective mechanism of the ATH filler. Details about the effect of voltage polarity on the tracking and erosion of the materials used in the study can be found in [8].

Table 1. Samples used in the study.

Material	Inorganic Fillers	I.D	Approximate Filler (wt%)	Test Method
Silicone Rubber	ATH	S25	25	ITV
		S60	60	CV
EPDM		E25	25	ITV
		E60	60	CV

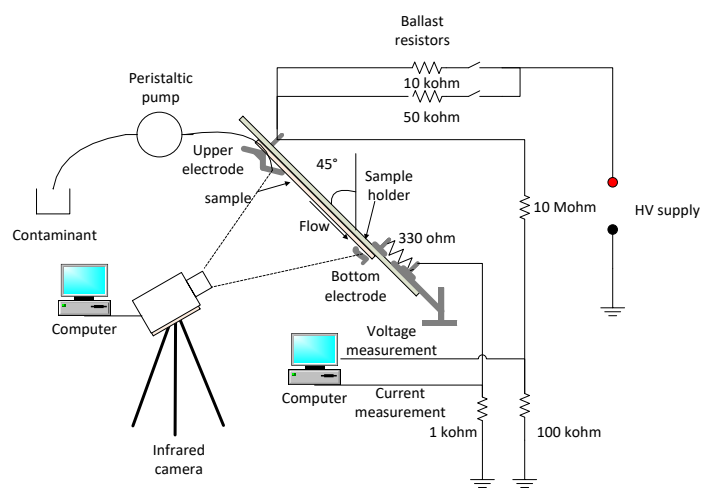

Figure 1. Schematic of the inclined plane test (IPT).

3 RESULTS AND DISCUSSION

3.1 COMBUSTION OF SILICONE RUBBER

Residue was observed, indicating surface decomposition of the S25 samples at an early stage of the IPT, which led to a stable dry-band arcing [9]. Consequently, the S25 composites failed due to what appeared as smolder, as illustrated in Figure 2. Smolder is a slow, flameless form of combustion, sustained by the heat produced when oxygen comes in contact with the

material. Therefore, S25 behaved somewhat like a low-fuel polymer impinged by dry-band arcing.

Failure to smolder was reported soon after stable dry-band arcing became intense. The intense dry-band arcing was associated with supplementary current pulses detected to be superimposed on the main DC LC waveform (Figure 3). This observation has been discussed in detail in [9], and is summarized here to explain the failure mechanism of the S25 composite. The supplementary pulses, which appear as spikes superimposed on the main flattop of the DC leakage current waveform, only began once the dry-band arcing was stable and intense. When the dry-band arcing was intermittent, i.e., not severe, no supplementary pulses were detected. Therefore, there is an additional fast mechanism giving rise to leakage current magnitude in the form of supplementary pulses and intensity observed for dry-band arcing, i.e., likely additional ionizations. The supplementary current pulses could be remarkably extracted with wavelet-based multi-resolution analysis and were found to occur at elevated frequency bands as compared to the main DC leakage current waveform, which confirms that supplementary ionizations are different in nature than main DC dry-band arcing plasma [9].

In addition, a strong correlation was established between supplementary ionizations as detected by the wavelet-based analysis and hot spot temperature on the surface, which suggests that temperature is involved. Kumagai *et al* in [10] with the aid of simultaneous TGA-DTA and gas spectrometry, also attributed enhanced intensity of the dry-band arcing under AC voltage during the IPT to ionizations. These ionizations taking place in the dry-band arcing plasma were shown, by Kumagai *et al* as a result of the dielectric breakdown of silicone rubber oligomers in the gas phase [10]. The depolymerization of silicone rubber initiated at a temperature exceeding 400 °C was shown to result in these oligomers in the gas phase [10]. Therefore, the detected ionizations in the gas phase promoted a more intense dry-band arcing [9, 10].

The layered structure shown in Figure 2 in proximity to the bottom electrode was also formed as soon as the intense dry-band arcing was initiated. This structure progressed with erosion paths towards the standard failure benchmark of 2.54 cm distance away from the bottom electrode. A similar observation was reported in [10, 11], as the intense dry-band arcing was also shown to cause progressive dielectric breakdown in the gas phase, which led to failure under critical voltages of the AC IPT and left a layered structure of silicates or silica-alumina networks, i.e., mullite [10, 11].

Mullite with a small amount of carbonaceous residue forms from the high temperature fusion of alumina and silica; the latter forms from the decomposition of silicone at temperatures exceeding 1200 °C [11]. It should be noted here that although the carbonaceous paths did not appear as conventional black/carbonaceous tracks, erosion paths on silicone rubber may be mistakenly perceived as tracking. It is important to report observations shown in Figure 2 as combustion failure or erosion path failure rather than tracking. This difference in failure mode needs to be clearly addressed when specifying the IPT test methods or the failure criteria, especially when a tracking-resistant material such as silicone rubber is tested in the IPT.

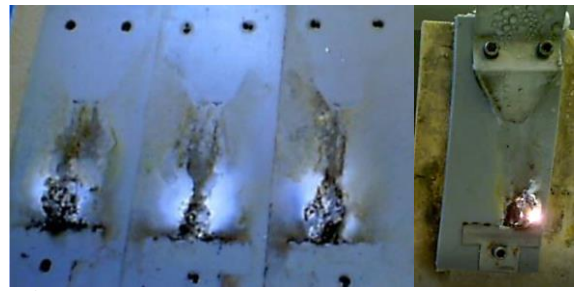

Figure 2. Failed silicone rubber composites containing 25 wt% ATH under DC voltages due to combustion/erosion paths.

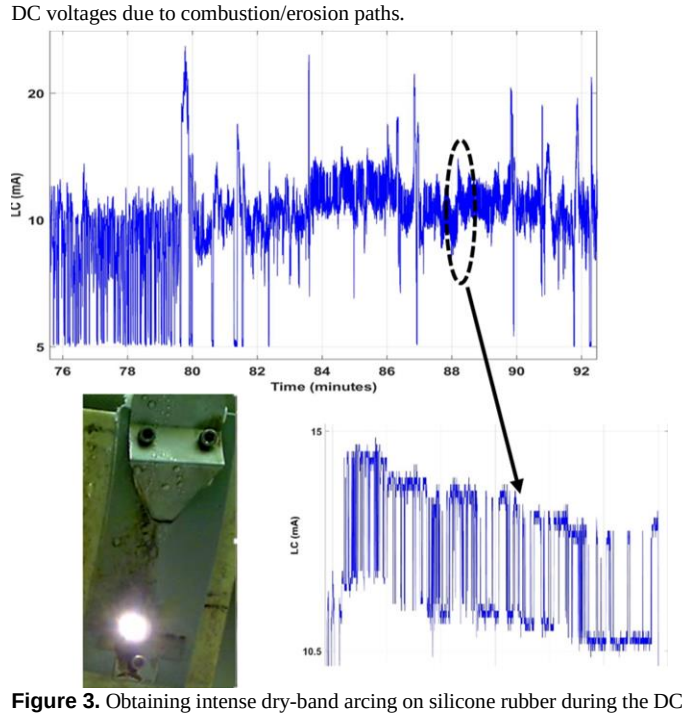

Figure 3. Obtaining intense dry-band arcing on silicone rubber during the DC IPT while ionizations taking place in the gas phase were detected as superimposed pulses in the main dry-band arcing waveform. Details about characteristics of the DC dry-band arcing waveform can be found in [9].

3.2 TRACKING OF EPDM

E25 composites failed during the IPT due to tracking. Tracking is not associated with erosion until the surface flames causing some mild heat ablation (Figure 4). Flames started as soon as an extensive amount of black residue was formed on the surface. Insignificant evidence of supplementary ionizations superimposed on the LC waveform was obtained for E25 as compared to S25, which clearly suggests that tracking was mainly progressing on the surface (or the condensed phase) of EDM rather than the gas phase. Figure 5 shows a clear trend of increase in the LC magnitude, possibly as a result of the carbonaceous nature of the residue giving rise to the surface conductivity. On the other hand, this increase in the LC magnitude was not as evident for the tested S25 composites (Figure 3). The shape of the LC waveform in Figure 3 reflects more of a stable dry-band arcing, featuring a reduction in the degree of intermittency as the S25 test progressed [8].

Obtaining flame with combustion indicates that E25 is more prone to the duffision of oxygen as compared to S25, thus EPDM is considered to fuel dry-band arcing as compared to silicone rubber. Figure 6 shows the DTA obtained for S25 and

E25 in air. A more evident exothermic peak for E25 as compared to S25 could be observed, confirming sigificant oxidation for E25 as comapred to S25.

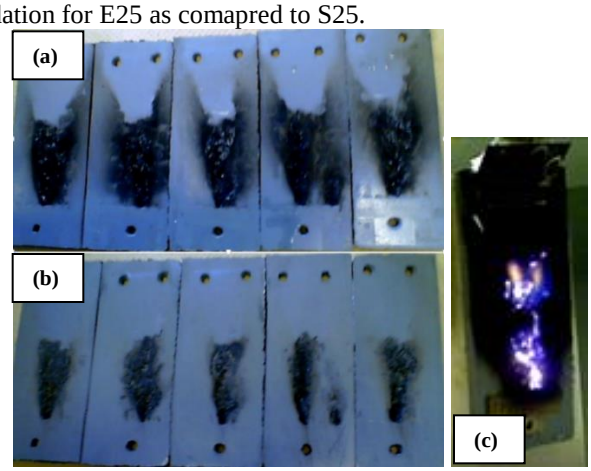

Figure 4. Failure of E25 composites: (a) typical appearance of five E25 samples tested in the DC IPT and failed due to tracking (this example was for –DC), (b) appearance of samples in (a) after washing off the carbonaceous residue from the surface, which confirmed that failure was mainly due to tracking and erosion was mild on the surface, and (c) typical appearance of flame on the surface of the E25 during the DC IPTs. Same observations were reported from the +DC IPT.

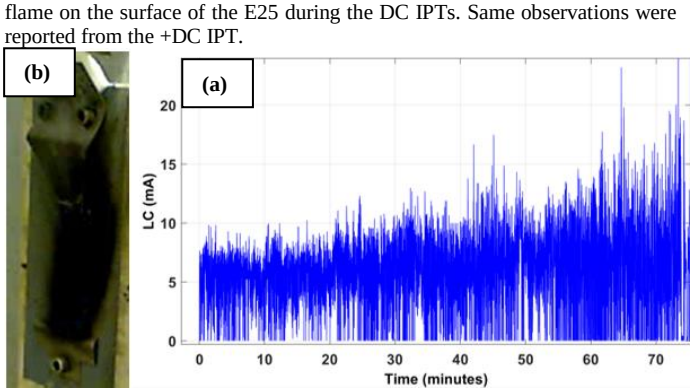

Figure 5. (a) Typical appearance of leakage current obtained during the DC IPT on EPDM. The waveform clearly shows a trend of increase in the leakage current magnitude and the corresponding surface on (b) only shows tracking without erosion.

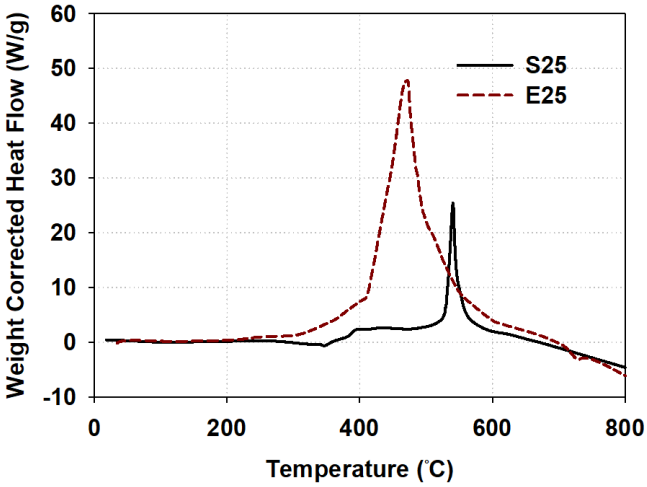

Figure 6. DTA of S25 and E25 composites in air.

3.3 PROTECTIVE MECHANISMS OF ATH IN SILICONE RUBBER AND EPDM

Although different failure modes have been reported for silicone rubber and EPDM with the ATH filler level of 25 wt%, the relative time to failure is comparable [8]. It could be that the carbonaceous residue leading to tracking of E25 and the silica-based residue leading to combustion of S25 were forming at a similar rate on the surface, thus similar time to failure was obtained. Unlike the S25 and E25 composites filled with 25 wt% ATH, the S60 and E60 composites filled with 60 wt% ATH did not fail the constant +2.25 and -3.0 kV inclined plane voltages. Such a finding highlights the filler loading level as a primary factor that must be taken into account when using ATH to suppress failure of the insulator housing material in the DC IPT. However, a noticeable difference in erosion resistance was still observed between S60 and E60. Specifically, the erosion area reveals a higher erosion resistance for S60 as compared to E60 as shown in Figure 7, suggesting additional protective mechanisms suppressing erosion on silicone rubber as compared to EPDM.

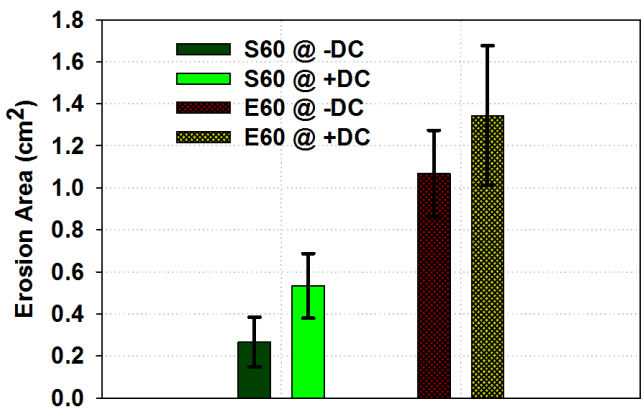

Figure 7. Erosion area of S60 and E60 composites after the DC IPT.

Figure 8 shows the TGA curves obtained for S60 in air and nitrogen. Both curves appear to match each other, which indicates that oxygen in air does not significantly alter the degradation of S60. The corresponding DTA in Figure 9 confirms the suppression of oxidation as no distinct exothermic hump was obtained in the DTA performed for S60 in air as compared to nitrogen. On the other hand, oxygen in air appears to influence degradation of EPDM, as suggested by the difference in corresponding TGA curves obtained for E60 in air as compared to nitrogen (Figure 10). In particular, the difference was detected as reaching the depolymerization temperature of EPDM at 300 °C [12]. An exothermic hump was also detected in the corresponding DTA in air as exceeding 300 °C (Figure 11), but not in nitrogen, confirming E60 is prone to oxidation as compared to S60. These findings coincide with outcomes shown in Figure 6 for S25 as compared to E25. This strong evident effect for oxidation in EPDM as compared to silicone rubber however needs to be evaluated for its significance by estimating the consequence on the degree of

depolymerization for both types of samples.

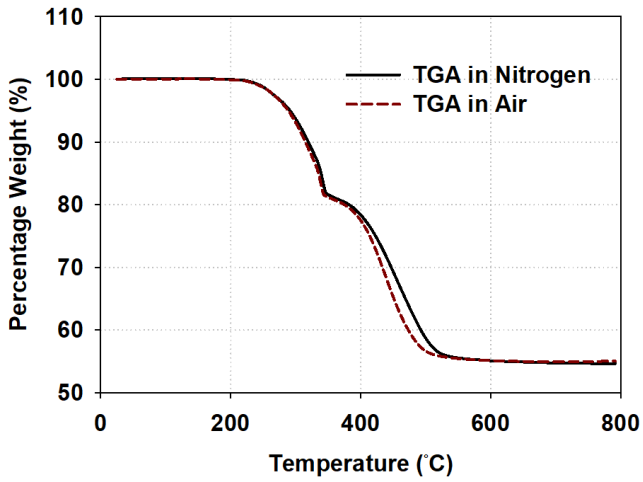

Figure 8. TGA of S60 composites in nitrogen and air.

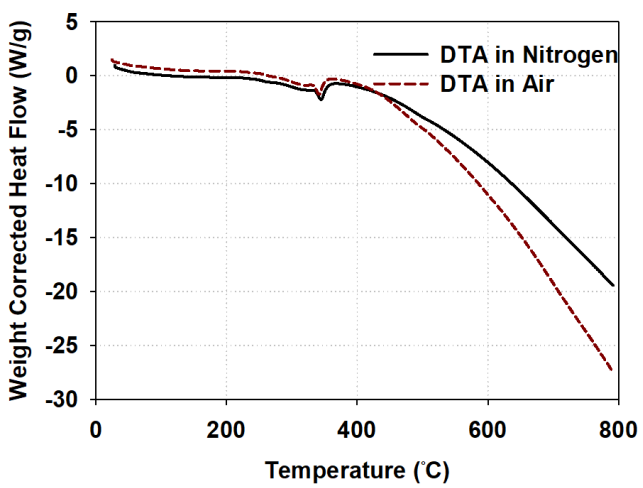

Figure 9. DTA of S60 composites in nitrogen and air.

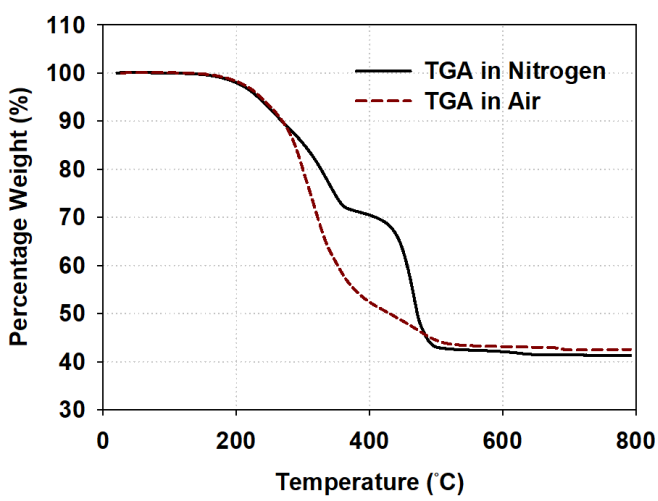

Figure 10. TGA of E60 composites in nitrogen and air.

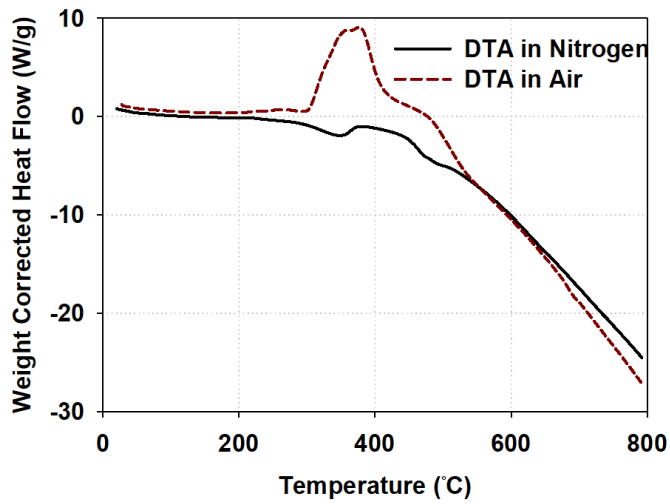

Figure 11. DTA of E60 composites in nitrogen and air.

ATH has been shown to dehydrate releasing about 35 wt% water of hydration during TGA [13]. Therefore, the remaining alumina particles in both composites after TGA could be estimated by:

$$\%\,Alumina = \%ATH \times 65\%. \quad (1)$$

Accordingly, the amount of the additional residue (AR) after depolymerization of silicone rubber or EPDM could be estimated as:

$$\%AR = \%\,Final\ TGA\ Residue - \%Alumina\ [14]. \quad (2)$$

The degree of depolymerization (DDP) in the polymer could accordingly be estimated based on Equations (1) and (2) as:

$$\%\,DDP = 100\% - \%ATH - \%AR. \quad (3)$$

Note this method considers that ATH and silicone rubber are the main constituents of the material compositions, with negligible amounts for other constituents in the residue level such as fumed silica, colourants, antioxidants or the char of combustion. In order to determine the level of uncertainty of this estimation method, reference should be made to the main dehydration temperature range of ATH in TGA. The main dehydration temperature range of ATH in silicone rubber is known to be between 200 and 350 °C, releasing about 30 wt% water of hydration. Also, it has been widely established that silicone rubber depolymerization may not start during TGA conducted in nitrogen before 350 °C [13]. Accordingly, the weight loss determined for silicone rubber at 350 °C in TGA is likely a result from released water of hydration. In addition, negligible amounts of silicone rubber depolymerization should be determined during TGA conducted in ntrogen at 350 °C. Table 2 shows the estimated level of silicone rubber depolymerization during TGA conducted in nitrogen at 350 °C and the uncertainty level reported for the estimation method in equations (1) to (3).

Table 2. Estimating the uncertainty using the method of equations (1) to (3).

Material	ATH Level (wt%)	Water Dehydrated at 350 °C (wt %)	Expected wt% at 350 °C	Measured wt% at 350 °C	Uncertainty
S25	25	7.5	92.5	91.5	1%
S60	58	17.5	82.5	81.5	1%

Table 3 shows the estimated residue and depolymerization levels of the tested composites using equations (1) to (3). Although, better oxidation suppression is shown with the TGA and DTA of S60 as compared to E60, insignificant difference is determined in the DDP between tests in nitrogen and air for both silicone rubber and EPDM. Such a finding suggests an insignificant effect for oxidation on depolymerization of E60. However, Table 3 clearly shows an additional thermal degradation mechanism giving rise to a noticeable amount of additional residue for S60, i.e., radical-base crosslinking. Whereas, the EPDM appears to mainly depolymerize with negligible effect shown for any additional mechanism. These findings confirm outcomes of earlier studies, reporting two thermal degradation mechanisms for silicone rubber filled with ATH, namely depolymerization and radical-based crosslinking [13]. On the other hand, EPDM has only been shown to undergo depolymerization [14]. It must be noted the additional residue determined for EPDM could have resulted from an incomplete (partial) decomposition, yielding black carbonaceous residue as shown in Figure 4 [14].

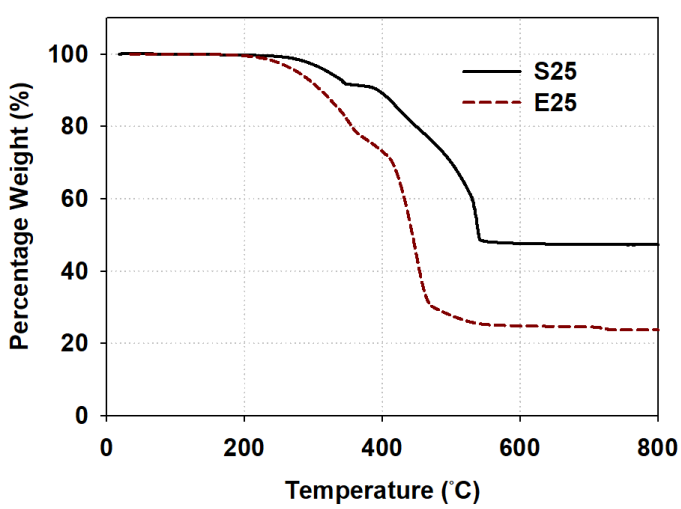

Figure 12. TGA of S25 and E25 in air.

The dehydration of ATH prior to silicone rubber depolymerization has been shown to leave alumina-based residue [13], thereby resisting the diffusion of oxygen and somewhat constituting a shield against the eroding dry-band arcing. Whereas, depolymerization of the host polymer taking place during dehydration of the filler would leave a more porous residue, thus leaving a more prone surface to oxidation and progression of erosion [13]. With depolymerization of EPDM known to take place at 300 °C during the main dehydration stage of ATH [12], EPDM would be expected to leave a more porus residue than silicone rubber [13]. Accordingly the enhanced erosion resistance obtained for S60 as compared to E60 may be justified.

Table 3. Residue and depolymerization levels of tested composites in TGA.

I.D		ATH		TGA Res. (wt %)	AR. (%) C	DDP. (%) D	Tot. wt % (A+B+C+D)
		H_2O wt% A	Al_2O_3 % B				
N_2	S60	20	38	55	17	25	100
	E60			42	4	38	100
Air	S60	20	38	55	17	25	100
	E60			43	5	37	100
Air	S25	9	16	47	31	44	100
	E25			24	8	67	100

It is important to emhasize in this context that the erosion suppression effect of the crosslinked residue on silicone rubber was only obtained when a sufficient amount of ATH was added, primarily for the prevention of the combustion/tracking failure. In other words, a critical amount of ATH is needed in order to suppress excessive crosslinking leading to combustion. Therefore, only with a sufficient amount of ATH added, crosslinking could have an additional secondary advantage in improving the erosion resistance of silicone rubber [15].

A clear reduction is shown in Table 3 for the amount of the depolymerized polymer when the ATH level in silicone rubber is 60 wt% as compared 25 wt%. This outcome is obtained because of the volume effect of the ATH filler, replacing the amount of fuel that depolymerizes and causes combustion. In addition, reduction in the amount of crosslinked residue is reported in Table 3 for S60 as compared to S25, which could explain reporting of a layered structure of crosslinked residue on the S25, but not on the S60 composites.

4 CONCLUSIONS

The failure mechanisms of silicone rubber and EPDM in the DC IPT are studied. Silicone rubber may fail the DC IPT due to combustion in the gas phase; whereas, EPDM may fail due to surface tracking with flame. Silicone rubber is shown to constitute a less prone fuel to the DC dry-band arcing as compared to EPDM, due to the ability of silicone rubber to form a fused residue during degradation, thereby enhancing the erosion resistance of silicone rubber as compared to EPDM. It is clearly highlighted that failure of silicone rubber in the DC IPT should rather be identified as combustion or erosion path failure, not as tracking, since no evidence of significantly conductive or carbonaceous residue was found. Accordingly, IPT methods and failure criteria need to be carefully selected and reported. The volume effect of ATH replacing the polymeric fuel in the composite is shown as a primary

governing factor preventing failure of both silicone rubber and EPDM in the DC IPT.

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