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Performance Assessment of High-Temperature Vulcanized Silicone Rubber Insulators

Abstract: - High-temperature vulcanized (HTV) silicone rubber (SIR) is commonly employed in power distribution systems because of its ability to repel water. However, when exposed to environmental stress, it is prone to tracking and erosion. Fillers, such as alumina trihydrate (ATH), have been found to have an impact on these qualities. The most effective type and ratio of filler, however, are still uncertain.
This study aims to examine how different types, sizes, and weight percentages of fillers affect the tracking and erosion resistance of HTV-SIR. The evaluation of various filler configurations is conducted using Inclined Plane Testing (IPT). The assessment also includes Hydrophobicity tests and Thermogravimetric Analysis (TGA) along with IPT. Hydrophobicity tests help determine the stability of water-repellent properties under stress, while TGA assesses thermal stability and decomposition characteristics. Prior research indicates a correlation between the kind of filler and performance. This study aims to build on these earlier findings by identifying the best filler mixture for HTV-SIR composites used in power distribution systems that improve tracking and erosion resistance. This research lays the groundwork for enhancing the endurance and reliability of HTV-SIR materials through appropriate filler selection, potentially leading to a more efficient and reliable electrical grid.

Keywords: Composite Insulators, High-Temperature Vulcanization (HTV), Tracking & Erosion, filler. Hydrophobicity

I. INTRODUCTION

Glass and porcelain insulators have long been essential components of transmission and distribution lines. Nevertheless, since the 1960s, silicone rubber insulators have progressively been the dominant choice in the market because of their exceptional hydrophobic characteristics. High-temperature vulcanized (HTV) silicone rubber is often used to make composite insulators, like sheds and sheaths, less likely to creep and keep their hydrophobic surface. [1] [2] [3] [4]

Silicone rubber insulators withstand the combined effects of environmental, electrical, and mechanical loads, which can cause material deterioration and problems such as tracking and erosion. [5] However, HTV-SIR insulators are subjected to a harsh environment, experiencing a combination of electrical, mechanical, and environmental stresses. Over time, these stresses can lead to material degradation, manifesting as tracking and erosion. Tracking refers to the formation of conductive paths on the insulator surface due to electrical discharges, while erosion signifies the physical removal of material by these discharges. Thus, surface impurities have a major impact on the electrical performance of these insulators, making erosion and tracking issues worse. Researchers have been focusing on testing different HTV SiR mixes for tracking and erosion resistance using the inclined plane testing method, which is in line with IEC 60587 standards, over the past few years. [1], [6], [7], [8], [9], [10], [11]

Several research studies have shown that the type, size, and weight percentage of fillers in the polymer matrix have a big effect on how well composite insulator samples resist tracking and erosion. [12] Rahmat Ullah and colleagues [13]used inclined plane testing to check the high-temperature vulcanization silicone rubber (HTV-SR) with different micro- and nanofillers. As the test samples aged, their results showed a decline in tracking resistance. In 2014, the IEEE DEIS Outdoor Insulation Technical Committee began the process of establishing a standard for the inclined plane test (IPT), specifically for DC voltage. This involved completing round-robin testing in five different laboratories. The purpose of these experiments was to determine ratios between DC voltage and AC voltages for five silicone rubber specimens. [14]

The HTV silicone rubber insulators are tested to see how well they can stop tracking and erosion. Normal and acidic solutions are used to simulate areas that are affected by acid rain. [15] Studies have demonstrated that acidic rain pollutants cause considerable degradation of the insulator samples. FTIR research has confirmed that the damage is more severe under acidic circumstances compared to regular pollutants. [16] IPT tests have been conducted by

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several researchers to analyse the leakage current (LC) of silicone rubber samples. [8] , [17] These tests have yielded valuable information on the material's performance when subjected to stress.

Rahmat Ullah and his colleagues [13] conducted a study to examine the impact of adding silica and ATH fillers to silicone rubber. According to their latest research, it was found that a sample containing 2% nano silica showed the least amount of deterioration compared to all other samples examined. This emphasizes the importance of the type and proportion of filler in improving the material's ability to resist tracking and erosion.

To improve some specific properties like tracking and erosion resistance, thermal conductivity, relative permittivity, etc., several fillers are added to the SiR. Alumina-trihydrate (ATH, $Al_2O_3.3H_2O$), silica (SiO_2), Titanium Oxide (TiO_2) and Barium Titanate ($BaTiO_3$) are some of the inorganic oxide filler materials used for that purpose with SiR [18]. S. ILHAN and others [9] have done the tracking and erosion performance of HTV silicone rubber with different fillers - ATH and silica by using standard inclined plane tests according to IEC 60587 standards. [19] They concluded that ATH-filled HTV samples showed inconsistent behavior in terms of eroded masses. On the other hand, for the silica-filled samples, eroded mass decreases as the filler loading increases. Few researchers have done the dynamic drop testing to access the Hydrophobicity class of HTV silicone insulating material with different filler loadings. [8], [20].

The current study seeks to determine the most effective insulating material by selecting the most appropriate type and ratio of filler for HTV-SiR materials used in electrical power distribution systems. The objective is to characterize a composite material that provides exceptional resistance to tracking and erosion, thereby enhancing the durability and dependability of insulators under challenging environmental circumstances.

This research emphasizes the critical role of filler selection and enhancing the tracking and erosion resistance of HTV-SIR composites used in power distribution systems. By understanding the influence of filler type, size, and weight percentage, researchers aim to develop cost-effective industrial-grade HTV-SiR materials with superior performance and extended service life, contributing to a more reliable and efficient electrical grid. Thus, this research is likely to attempt:

To identify the impact of fillers on HTV-SiR Performance: The research investigates how the type, size, and amount of fillers significantly affect the resistance of HTV-SiR composites to tracking and erosion, which are key factors in their performance and longevity.

To develop a Method for Augmenting Filler Mix: By utilizing Inclined Plane Testing (IPT), the study establishes a method for comparing the effectiveness of different filler combinations for HTV-SiR composites. This paves the way for identifying the optimal filler mix that enhances both tracking and erosion resistance.

To advance the development of more durable and reliable HTV-SiR Materials: By focusing on optimizing filler selection, this research lays the groundwork for creating HTV-SiR materials with superior durability and reliability. This ultimately contributes to a more robust, efficient, and dependable electrical grid.

II. Sample Preparations

A. Materials

The samples can be classified based on the base material they were prepared from in the industry, specifically industrial-grade HTV SiR composites, as depicted in Table 1.

Fig. 1 Insulating material sample A

The base material is Dow corning XIAMETER™ HV 1660/65 Silicone Rubber Compound is colorless, translucent silicone rubber base with flexibility, high transparency, and good mechanical properties. etc. The sample prepared for testing is a specimen measuring 50 mm x 120 mm with thickness of 6 mm as shown in Fig. 1.

B. Blends preparation

The process involves simple blending, followed by hot-compression moulding, and post-curing techniques, carried out in sequence.

1) Base Material Composition:

Dow corning make XIAMETER™ HV 1660/65 Silicone Rubber Compound is used as base rubber. A blend of silicone rubber compound mixture is reinforced with filler particles (silica, alumina trihydrate – ATH).

2) Blending Process:

The HTV-SiR composites are prepared using a high-shear blender. The blender uses high force to create turbulence and ensure homogenous mixing of the Silicone Rubber Compound base and filler particles.

3) Hot-Compression Moulding:

The blended mixture is then shaped into the desired form using a mould by applying heat and pressure. This step ensures the material takes on the final shape of the insulator component.

4) Post-Curing:

After moulding, the material undergoes a final curing process at elevated temperatures to complete the vulcanization process and achieve the desired mechanical and electrical properties.

5) Volume fraction calculation for filler:

For a 1 cm3 volume; filler material (ATH or silica) has x cm3 volume and Silicone Rubber Compound base has (1 – x) cm3 volume.

$$\frac{m_{ATH}}{m_{ATH} + m_{SiRubber}} = 0.1 \rightarrow 10\%\ wt\ ATH\ filled\ sample$$

III. INCLINED PLANE TEST SETUP

Inclined plane testing is a method used to evaluate the erosion and tracking resistance of insulating materials. During this test, a specimen of the insulator material is placed on an inclined plane and exposed to an electrical voltage and an electrolyte solution. The erosion and tracking resistance of the material is determined by measuring the amount of erosion or tracking that occurs on the surface of the specimen over time.

Silicone rubber insulators are commonly used in power transmission and distribution lines because of their excellent electrical insulating properties, resistance to environmental stresses, and lightweight. However, they can be susceptible to erosion and tracking, which can lead to failure of the insulator. Inclined plane testing is a valuable tool for assessing the erosion and tracking resistance of silicone rubber insulators and for developing new and improved materials.

The testing was conducted following the guidelines outlined in the Indian Standard IS 9947: 2011 (Equivalent to IEC 60587: 2007), which specifies, an approved test method (Inclined Plane Testing) for evaluating resistance to tracking and erosion of polymeric insulating materials. [19][21]

A. Specifications of IPT test set up

Error! Reference source not found. displays a photograph of the test setup used for IPT testing.

Make : Rectifier & Electronics Pvt. Ltd.
Model No. : 11556/65(P)19-20
Rating : 1 kVA
Cooling : A/N
Voltage : 230 V / 0-10 kV

Fig. 2 Photograph of the test setup

B. Contaminant Preparations

Contaminant liquid was prepared using 0.1% by weight of ammonium chloride (NH4Cl) and 0.02% by weight of TRITON X100 (non-ionic wetting agent) in distilled water. During each test, 2 liters of contaminant liquid is prepared & allowed to settle down for 24 hours.

Fig. 3 Photograph of contaminant preparation

C. Testing Methodologies

To investigate erosion using the IPT, two methodologies are employed using a test set up indicated in Fig. 2. The First method employed is the constant tracking voltage method and the second one is the step-wise tracking voltage test method.

D. Constant Tracking Voltage Method

For this test method, two sample variants are prepared at MIDAS silicone as per the details in Table 1 and Table 2. Five identical samples of each type were prepared for testing.

Table 1 Prepared Test Sample Details

Sample Identifier	**Type of Polymer insulating material**	**Hardness**	**Specific gravity gr/cm^3**
A	HTV	Shore A, 70	1.55
B	HTV	Shore A, 69	1.56

Table 2 Details of fillers

Sample Identifier	Filler Type	Level (%)	Curing agent	Mean Particle size, D50
A	ATH	100 phr	2 phr Peroxide	3.6 µm
B	ATH & Silica	75 phr + 25 phr	2 phr Peroxide	4 µm

Each sample was cleaned using isopropyl alcohol and then rinsed with distilled water. Then it was kept at room temperature for 24 hours before the testing. The insulating sample is sandwiched between two electrodes, one of which is connected to a high voltage (HV) source and the other to the ground.

After setting up of test parameters as specified in Table 3, and fixing the insulating sample using mounting support, the contaminant was allowed to flow through the filter paper pad so that uniform flow between the top and bottom electrode occured. The flow rate was adjusted to 0.6 ml/min using a peristaltic pump, and series resistors of 33 kΩ were chosen, in line with this specified test voltage.

The test voltage was raised to 4.5 kV within 10 seconds and then it was maintained at 4.5 kV constant for 6 hours. The vertical distance between the upper and lower electrodes is kept at 50 mm, resulting in an average electric field strength of 90 V/mm across the test sample when subjected to a test voltage of 4.5 kV.

Table 3 Constant Tracking voltage test parameters

Test Voltage	4.5 kV
Test Duration	6 Hours
Contamination flow rate	0.6 ml / min.
Ambient temperature	26 ± 2 ºC.
Ambient humidity	45 ± 5 %

Fig. 4 Samples - A & B - before test

E. Constant Tracking Voltage Method

To further investigate tracking and erosion, another method, as specified in the standard IS 9947: 2011 the step-wise tracking voltage method is employed. The testing apparatus and the digital readouts are shown in Fig. 5 further illustrate the conditions under which the samples were tested, providing a comprehensive understanding of the assessment process.

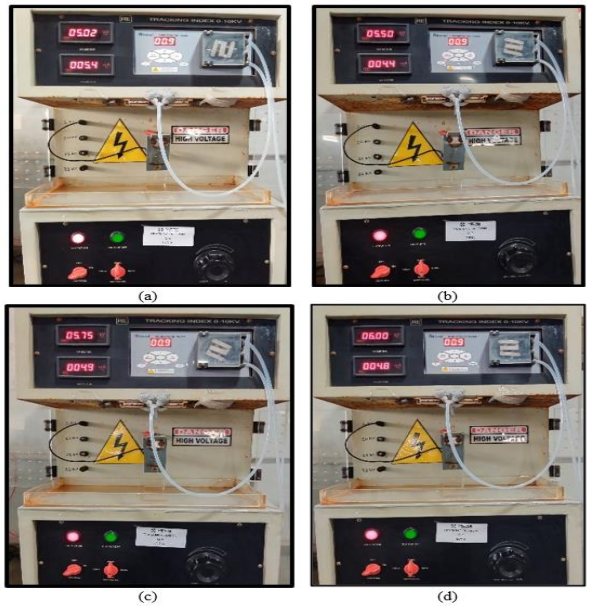

Fig. 5 Photograph of Step-wise tracking voltage test

Sample A was tested using the step-wise tracking voltage method with the starting voltage kept at 4.5 kV. The rate of contaminant flow is adjusted initially at 0.6 ml /min. The voltage is maintained for 1 hour and then increased by a step of 250 V / hour. The rate of contaminant flow is maintained as per the corresponding voltage level as specified in the standard IS 9947: 2011.[21]

IV. HYDROPHOBICITY TEST SETUP

Both samples were placed in the Hydrophobicity test setup as shown in the Fig. 6.

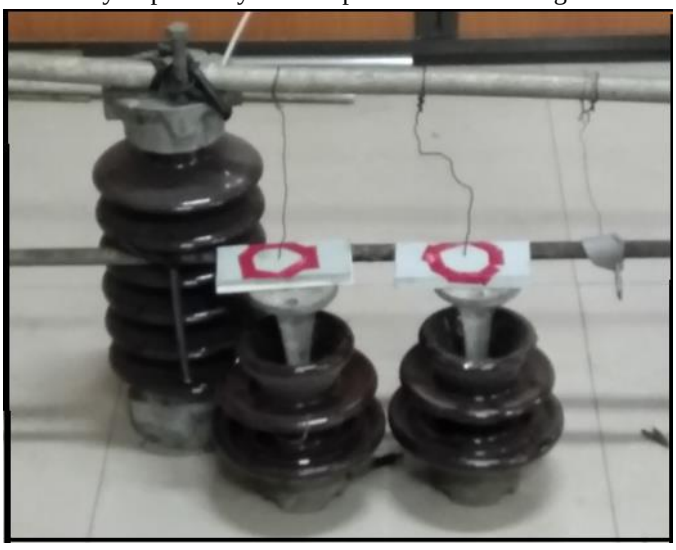

Fig. 6 Hydrophobicity test setup

The surface of selected samples was cleaned with isopropyl alcohol and then re-cleaned with the help of distilled water and a clean cotton cloth. Both specimens, which were cleaned 24 hours before the tests, were kept in room conditions of 23±2o C temperature and 50±10% humidity up to the start of the tests. Then the surface is allowed to

dry and then sprayed with water. Recorded the Hydrophobicity classification in line with STRI guide for Hydrophobicity classification [2] as displayed in the image in Fig. 7.

Fig. 7 Hydrophobicity check before HV test

As per the standards REC 76/2006 and ASTM G 53, both the samples are subjected to corona discharges by applying 12 kV for a duration of 100 hours. A standard point-plane electrodes with a gap distance of 1 mm were employed in order to create a non-uniform electric field. The details about test parameters are given in the Table 4.

Table 4 Hydrophobicity test parameters

Applied Voltage	12 kV
Test Duration	100 Hours
Electrode Gap Distance	1 mm
Ambient temperature	26 ± 2 ºC.

Water droplets were sprinkled on the surface of the material and the performance of the samples was seen as shown in the Fig. 8.

Fig. 8 Hydrophobicity check after HV test

V. THERMOGRAVIMETRIC ANALYSIS (TGA)

Thermal Gravimetric Analysis is a method of thermal analysis. It is used to determine sample composition by measuring the weight of each component as it volatilizes or decomposes under controlled conditions of temperature, time, and atmosphere. HTV samples were cut into small pieces of about 11-15 mg and were heated in platinum crucible in nitrogen atmosphere from ambient temperature to 900°C at a heating rate of 10°C/min. All samples tested at Shah-Schulman Centre for Surface Science and Nanotechnology (SSCSSN), Dharmsinh Desai University, Nadiad using STARe instrument TGA/DSC 1 (Make - METTLER TOLEDO).

VI. RESULTS & ANALYSIS

A. Constant Tracking Voltage Test Method

During constant tracking voltage tests, it was found that all samples of both variants A and B, survived 6 hours at 4.5 kV. Hence, the reported result for both the variants A and B is Class 1A, 4.5.

To further validate the tracking and erosion, and differentiate between the two variants, fresh samples were prepared and underwent a Constant Tracking Voltage test continuously for 12 hours at 4.5 kV with all other parameters kept as per the standard IS 9947: 2011.[22] The test voltage was raised to 4.5 kV within 10 seconds and then it was maintained at 4.5 kV constant for 12 hours. After continuous 12 hours of testing, it was observed that Variant sample B shows clearly visible intensive erosion compared to Variant sample A.

The mass of every sample for both variants was noted both prior to and following the test, utilizing a microbalance possessing a precision of 100 micrograms.

Table 5 Weight of Samples after T&E test

Sample Identifier	**Initial Weight gm.** $\boldsymbol{Wint.}$	**Final Weight gm.** $\boldsymbol{Wfinal}$	**% Erosion in Mass** $\boldsymbol{Emass}$
A	A1 – 61.11	A1 – 59.14	3.22 %
	A2 – 61.18	A2 – 58.90	3.72 %
	A3 – 61.13	A3 – 58.10	4.95 %
B	B1 – 61.25	B1 – 55.18	9.91 %
	B2 – 61.50	B2 – 55.25	10.16 %
	B3 – 61.32	B3 – 55.46	9.55 %

The data in Table 5 indicates differences in the initial and final weights of both samples before, and after tracking and erosion test.

The percentage of mass erosion was determined using the subsequent formula:

$$Emass = (Wfinal - Wint.)/Wintial$$

Here, Wintial Wfinal, and Emass represent initial weight, final weight, and eroded mass, respectively. The average Erosion in Mass for Sample A is 3.96 %, while for sample B is 9.87 %.

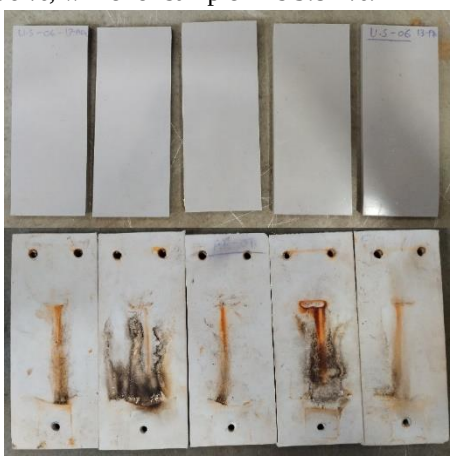

Fig. 9 Samples - Before & After T&E test

The Fig. 10 indicates differences in the tracking depth after inclined plane testing for 12 hours. The Fig. 10 provides a detailed visual representation of the effects of IPT process on HTV silicone rubber samples, sample B clearly shows more erosion damage near lower electrode.

Fig. 10 Samples after 12 Hours of Testing

B. Step-wise Tracking Voltage Method

During the step-wise tracking voltage test method, the automatic tripping mechanism for current in a high-voltage test circuit is set at 60 mA. Another checkpoint is the observation of the track on the test specimen. The endpoint of the test was considered when either the current in the high-voltage exceeds 60 mA for at least 2 seconds or the track reaches the mark on the test sample surface 25 mm from the lower electrode.

For test sample specimen A, it was observed after starting the test at 4.5 kV, and step increase of 250 V per hour, the high voltage tracking test setup never tripped due to an increase in current beyond 60 mA. During visual observations at every hour, it was observed that the test specimen developed a track and visible erosion on the sample surface 25 mm from the lower electrode at test voltage 7 kV. Hence reported result for sample variant A is Class 2B, 6.75.

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C. Hydrophobicity class test

From Table 6, it was observed that ATH-filled HTV silicone specimens, display stable hydrophobicity performance. However, silica-filled HTV silicone specimens showed unstable hydrophobicity performance. As per the STRI HC classification guide [22], sample type B reported HC class 2, i.e. Only discrete droplets are formed where, receding contact angle (θr) $50° < \theta r < 80°$ for the majority of droplets. This indicates partial loss of hydrophobicity compared to sample type A, which reported HC class 1, i.e. Only discrete droplets are formed, $\theta r \approx 80°$ or larger for the majority of droplets.

Table 6 Observed Hydrophobicity class after HV test

Description	Sample type	Observed HC class
Before test	A	HC 1
	B	HC 1
After corona test (100 hours)	A	HC 1
	B	HC 2

D. Thermogravimetric Analysis (TGA)

The Thermogravimetric Analysis (TGA) results for both samples (before & after T&E test) provide critical insights into their thermal stability and decomposition characteristics, which are crucial for assessing erosion resistance.

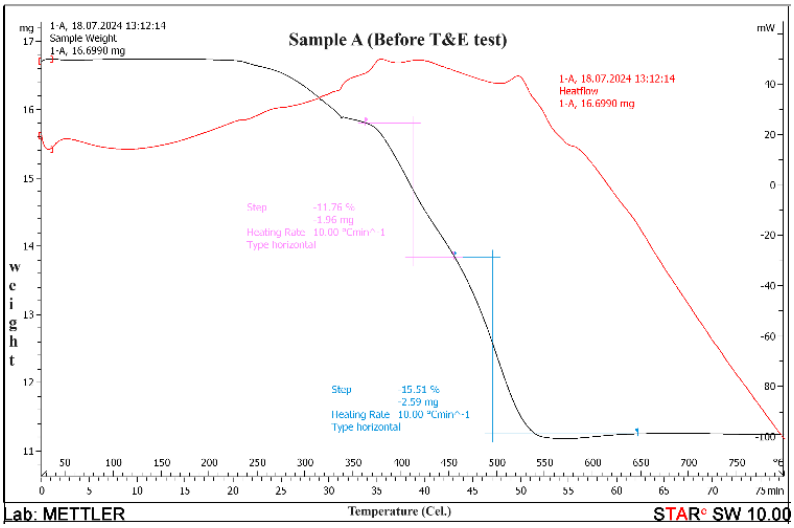

Fig. 11 TGA - Sample A (Before T&E test)

Thermogravimetric Analysis of samples reveals critical insights into their thermal stability and composition. The plot shows two distinct weight loss stages, indicated by a black curve for weight loss and a red curve for heat flow. The first weight loss step occurs between approximately 300°C and 400°C, corresponding to a weight reduction of 1.96 mg, which constitutes 11.76% of the initial sample weight of 16.6990 mg. This initial loss is due to the evaporation of volatile components or the decomposition of less thermally stable substances. The second, more significant weight loss step occurs between 400°C and 500°C, accounting for a loss of 2.59 mg or 15.51% of the initial weight. This stage represents the breakdown of the primary organic components of the sample. The analysis concludes with a final weight of approximately 12.1490 mg, indicating the presence of thermally stable residue. The heating rate was consistently maintained at 10.00 °C/min throughout the analysis.

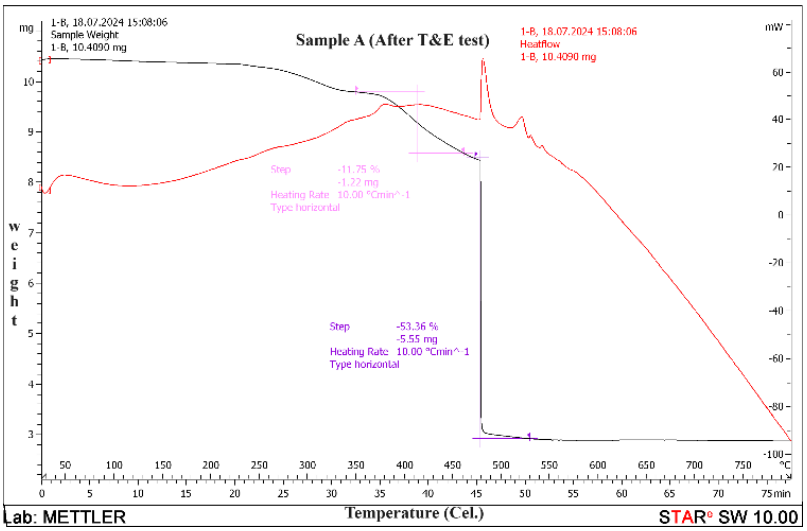

Fig. 12 TGA - Sample A (After T&E test)

Sample A after T&E test exhibits two distinct weight loss steps: an initial minor loss (1.22 mg) between 50°C and 350°C, likely due to volatile components, followed by a major loss (5.55 mg) from 350°C to 550°C, indicating the decomposition of organic components. The total weight loss and significant decomposition at higher temperatures suggest a higher content of thermally unstable materials, potentially leading to greater erosion under thermal stress.

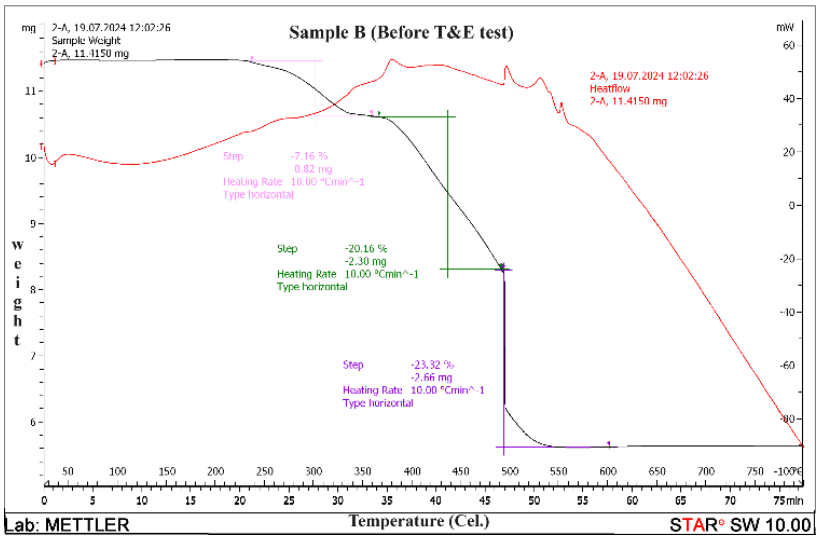

Fig. 13 TGA - Sample B (Before T&E test)

Sample B before T&E test shows three weight loss stages: a minor loss (0.82 mg) between 200°C and 300°C, a more substantial loss (2.30 mg) from 300°C to 400°C, and a final loss (2.66 mg) from 400°C to 500°C. The gradual and distinct decomposition steps indicate a composition with varied thermal stability. The presence of components that decompose across a wider temperature range may contribute to moderate erosion resistance.

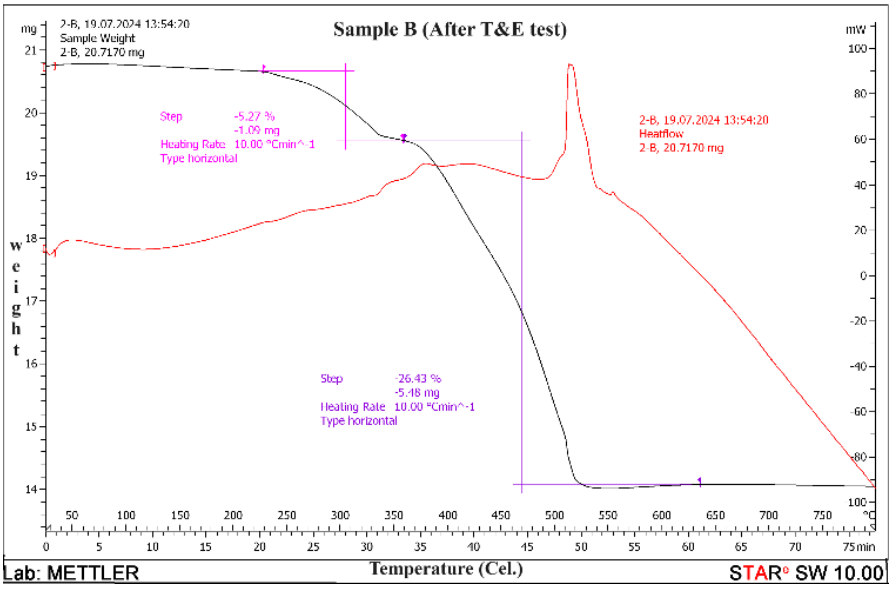

Fig. 14 TGA - Sample B (After T&E test)

Sample B after T&E test has two primary weight loss stages: an initial minor loss (1.09 mg) from 200°C to 300°C and a significant loss (5.48 mg) from 300°C to 400°C. The substantial decomposition in the second stage suggests a high content of volatile and thermally unstable components. However, the lower initial weight loss compared to Sample 1-B indicates a potentially higher resistance to low-temperature thermal erosion.

It is evident from the analysis that, sample A before T&E shows the least total weight loss and the highest thermal stability, suggesting it is more resistant to erosion and thermal degradation. Whereas Sample A after T&E test experiences significant weight loss, indicating lower stability and higher susceptibility to erosion. Further, Sample B before T&E has a substantial weight loss spread across three stages, indicating a complex composition but less stability than sample A. Whereas Sample B after the T&E test shows a moderate weight loss with decomposition at relatively lower temperatures compared to sample A, suggesting lower thermal stability. Thus, Sample A is the most stable material with the least weight loss and the highest resistance to thermal degradation, making it the better material in terms of erosion resistance.

VII. Conclusion & Remarks

Comparing ATH-filled and silica-filled HTV silicone rubber insulators show notable disparities in their performance when subjected to high-voltage conditions. Both versions successfully passed the initial 6-hour test at 4.5 kV, gaining a Class 1A, 4.5 rating. During extensive testing, Variant B demonstrated a substantially higher level of erosion, with an average mass reduction of 9.87%, in contrast to Variant A's 3.96%. Variant A demonstrated improved stability in the step-wise tracking voltage test, achieving a Class 2B rating at 6.75 kV.

It also exhibited stronger voltage endurance without tripping at elevated voltages. Variant A's superior heat stability was further validated using thermogravimetric analysis. In addition, the hydrophobicity tests showed that the samples filled with ATH maintained a constant hydrophobicity, unlike the ones filled with silica. The results highlight the need to choose suitable additives to improve the long-lasting and dependable qualities of HTV silicone rubber insulators used in high-voltage situations. Insulators filled with ATH show exceptional overall performance.

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