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A Study on the Development of New Silicone based Polymeric Outdoor Insulator Material for Enhanced Properties

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Abstract

Polymeric insulators have been increasingly popular in recent years as a result of their superior performance in contaminated environments due to their hydrophobic properties. However, research into the ageing condition of polymeric materials and their practicality for large-scale use is currently ongoing. Insulator deterioration is caused by environmental tracking and erosion factors. As insulators age, they develop immature failures and inconsistencies in their functioning. pollution performance of polymeric insulators is a vital factor in the quality and reliability of the power system. Over some time, dry band arcing can initiate the flashover and it causes degradation in the form of erosion and tracking. Polymeric insulators' performance is heavily influenced by the constituent materials and their properties. There is a critical need to investigate innovative filler materials that can be combined with existing polymeric base materials to form composites. In this context the proposed research use silicone rubber as a base polymeric material, to which additives are added to produce three distinct composites by varying the filler concentration. Preliminary studies were made to evaluate the hydrophobicity, dielectric strength, hardness, specific gravity, tensile strength, ultimate elongation and tear strength properties of this HTV silicone rubbed-based composites by using ASTM standards and IEC 60587 requirements. Studies were also made by accelerated ageing on sample material by using the IPTE test. The results show substantial improvement in the electrical and ageing properties.

Keywords: Ageing, Dielectric Strength, Filler Material, Hardness, Inclined Plane Tracking and Erosion, Recovery of Hydrophobicity, Specific Gravity, Tear Strength, Tensile Strength, Ultimate Elongation

1. Introduction

Polymer insulators have been introduced and widely employed in recent decades due to their superior pollution performance. Composite or non-ceramic insulators are insulators built of polymer materials. In comparison to porcelain insulators, non-ceramic insulators have various advantages. The most significant benefit of polymeric insulators is that they operate better in polluted environments due to their hydrophobic surface properties under wet situations such as rain, fog, and dew. Water is forced to be deposited in the form of discrete beads due to this water-resistant characteristic. As a result of the reduced surface wetness, discharge activity and dry band arcing on the polymeric surface are reduced, while anti-pollution performance improves. They are also resistant to vandalism and have a high mechanical strength-to-weight ratio.

Silicon rubber is the only housing material capable of transferring its water-repellent properties to a surface pollution layer. As a result, leakage currents are minimized and the possibility of flashover occurrence is also reduced. Furthermore, these silicone rubber insulators don't need to be cleaned. High thermal stability, stable performance throughout a wide temperature range and strong resistance to corona, ozone, and weathering are all characteristics of SiR. For more than 30 years, it has demonstrated its exceptional appropriateness for outdoor applications, even in the harshest of environments. Silicone rubber is a polymer that is commonly used to insulate outdoor areas.

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It keeps its hydrophobicity and the capacity to transfer it to adherent contaminants throughout its service life.

The deterioration of insulator material over time, or the impact generated after a specified duration of service in its field, is referred to as insulator ageing. Insulator ageing is primarily concerned with the deterioration of the outer sheath/shed. Deterioration of insulator materials is caused by the breakdown of large molecules, which results in a decrease in molecular weight. External influences cause the substance to break down slowly. It starts on the insulator's surface and works its way down into the substance. The insulator's electrical and mechanical performance degrades as it ages. Therefore, determining their life expectancy is problematic.

Many utilities have complained that the distribution class polymeric insulators have failed in the northern region of India. The performance of the insulator is mainly based on the quality of the silicon rubber used along with the filler materials. The use of bad-quality compounds will result in early failures of the insulators. In order to study the failure and improve the quality of the silicon rubber compound the filler concentration was varied keeping the silicon percentage constant.

2. Material Preparation

The base polymer was mixed with a series of additives to make silicone rubber. HTV SiR is being produced for use as an outside housing material in AC composite insulators in the current study. To make the HTV silicone rubber, the basic polymer PolyDiMethyl-Siloxane (PDMS), reinforcing filler fumed silica, extending filler Alumina Tri-Hydrate (ATH), mould release agent silicone oil, colouring agent carbon black, and vulcanizing agent organic peroxide were carefully selected and blended.

To make the rubber mixture, the base material PolyDiMethylSiloxane (PDMS) was mixed with reinforcing filler and mould release agent in a Sigma mixer for one hour. In a sigma mixer, this material was again mixed with extending filler for one hour. Colourant, additive, and vulcanizing agents were used to make a master batch of the colouring agent, which was then added to the rubber mixture using a two-roll mill. In a two-roll mill, the rubber compound was mixed for 10-15 minutes.

2.1 Preparation of Rubber Sheets

Rubber sheets of thicknesses 2mm and 6mm were prepared for testing the different properties of the HTV silicone rubber compound. The sheets were prepared by a compression moulding machine. The curing temperature of the HTV silicone rubber was 160 degrees centigrade and the curing time was 10 minutes. A programmed compression moulding machine with curing time and curing temperature defined was used. Moulds of the required size were taken and heated to 160 centigrade. The uncured HTV silicone rubber sample was weighed according to the required thickness and placed in the pre-heated mould. A pressure of 160 kg/cm^2 was applied and left for 10 minutes for curing. The cured rubber sheets were taken out and used for testing different properties. The rubber sheet used in this research work is made with the following percentages shown in Table 1.

Table 1. Rubber sheet material prepared with different formulations

S. NO	MATERIAL	SAMPLE-1 (in "%")	SAMPLE-2 (in "%")	SAMPLE-3 (in "%")
1	Silicone rubber	46	48	43
2	ATH (Processing aid)	51	49	54
3	Mold releasing agent	1	1	1
4	Curing agent	1	1	1

3. Experimental setup and test procedure

Polymeric materials are widely employed in HV (High Voltage) applications due to their excellent characteristics and ability to withstand pollution. However, with time, they begin to degrade due to the combined effects of voltage and pollution. An accelerated ageing test is carried out in the laboratory to investigate the effects of ageing caused by the combined effects of voltage stress and pollution.

Mechanical, electrical, physical, thermal, and material qualities are all important characteristics of rubber compounds. Mechanical properties such as tensile strength, ultimate elongation, and tear strength were investigated; electrical properties such as resistance to tracking and erosion, loss and recovery of hydrophobicity by corona ageing test, dielectric strength, and arc resistance were investigated; and physical properties such as hardness (shore-A) and specific gravity were investigated for three different composite filler materials according to ASTM and IEC standards.

3.1 Inclined Plane Tracking and Erosion Test (IPTE Test)

IPTE tests are performed with a continuous duty 50 Hz 230 V / 15 kV AC testing transformer with a 5 per cent output voltage stabiliser that may be changed up to around 10 kV and a rated maximum current of 1 A. During the IPTE test, the test samples are exposed to a constant 4.5kV AC rms voltage for six hours. On the high voltage side, a 33 k (200 Watt) series resistance is utilised, and the liquid contaminant flow rate is set to 0.6 ml/min. Figure 1 depicts the schematics of an AC Inclined Plane test setup.

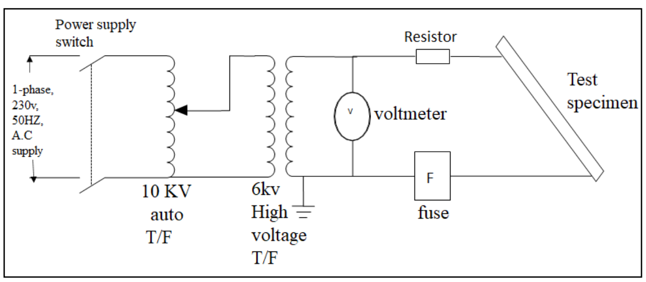


Figure 1. Schematic diagram of IPTE test.

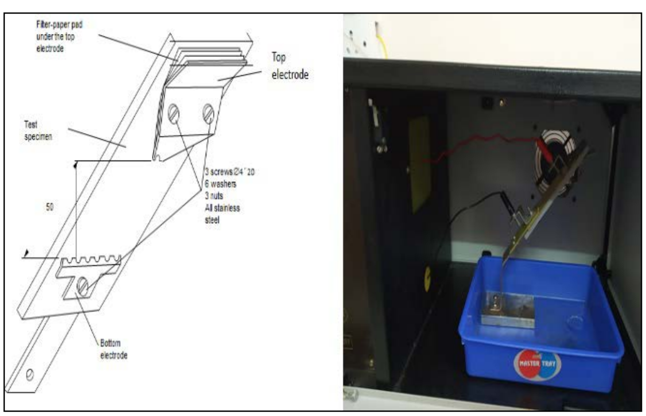


Figure 2. IPTE experimental test set-up.

Conditions for tracking and erosion test

No over-current tripping i.e., the leakage currents should not exceed more than 60mA.

- No tracking and erosion take place on the surface
- Tracking occurred longer than 25mm with a radius greater than 0.25mm from the bottom electrode, the sample was treated as failed.
- Without tracking if only erosion occurred. The depth of the erosion is more than 3mm depth, the sample was treated as a failure.

3.2 Recovery of Hydrophobicity by Corona Ageing Test

The pin-plane electrode system for corona ageing is shown schematically in Figure 3, where T1 is a voltage regulator with a capacity of 20 kVA, T2 is a test transformer with a rated voltage of 15 kV and capacity of 10 kVA, V is a capacitor voltage divider, Rp is a 25 k protecting resistor, and Pin and Plane make up the pin-plane electrode system for corona ageing test. The STRI guide is use to determine the degree of hydrophobicity of the insulators' surfaces.

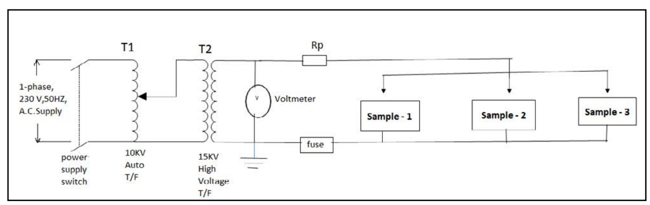


Figure 3. Schematic diagram of corona ageing test.

3.3 Hardness Test

A shore-A durometer is a portable tool that uses a truncated cone indenter tip and a calibrated steel spring to measure the resistance of rubber to indentation. When the durometer is placed on a flat rubber sample, the indenter point of the durometer is forced back toward the durometer body. The spring opposes and resists this force. After strong contact between the durometer tip and the sample, a reading is taken within two seconds. The average value was obtained from three readings. The hardness was measured using an HTV silicone rubber sheet with a thickness of 6 mm. This test was performed in accordance with the ASTM D 2204 reference standard.

3.4 Dielectric Strength

Dielectric strength is the maximum voltage required to break the insulating material. Higher dielectric strength indicates higher quality of insulator material.

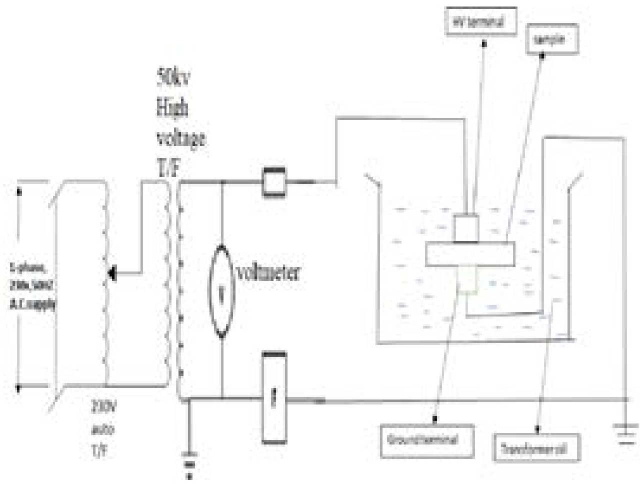


Figure 4. 50kv breakdown voltage tester.

Breakdown voltage was measured using a 50kV BDV tester as shown in Figure 4. A 150mm X 150mm test sample was cut from a rubber sample with a thickness of 2mm and analyzed in an oil medium according to ASTM D 149/IEC 60243. The specimen was sandwiched between the top electrode of size 30mm and the bottom electrode of size 20mm. Test voltage was applied at the rate of rise 2kV/second up to the breakdown. The voltage at which the specimen got punctured was divided by specimen thickness and noted as dielectric strength. Dielectric strength is measured in kV/mm.

3.5 Dry Arc Resistance

Arc resistance is the electrical property of polymer material. It makes the surface of the insulating material conductive. When an electric current flows through an insulator's surface, a conductive path is formed on the surface of the polymer insulator over time or the polymeric material's capacity to resist a high voltage and low current electrical arc. The time it takes to make a polymer material electrically conductive under high voltage and low current laboratory conditions are known as arc resistance. The time it takes for an arc to form is measured in seconds (Figure 5).

Flat specimens of size 150mm X 150mm were cut from the cured HTV silicone rubber sheet of thickness 2 mm. An arc resistance tester was used to measure the arc

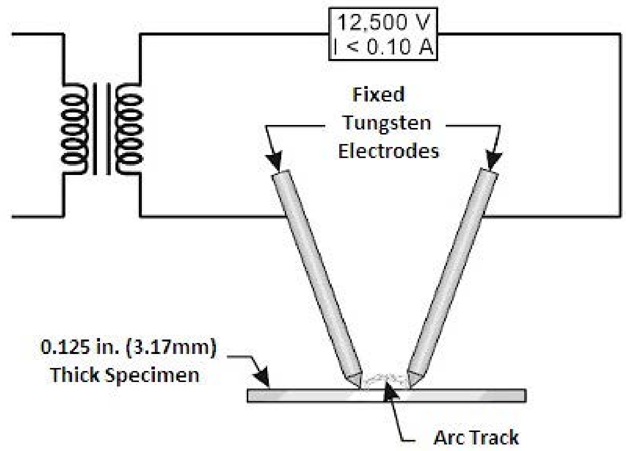


Figure 5. Schematic diagram of arc resistance tester.

Figure 6. Arc resistance tester.

resistance as shown in Figure 6. When the test began, the test sample was positioned below the electrodes, and an arc was formed between the two electrodes. The spacing between both electrodes was kept at 6 mm in accordance with ASTM D495. Arc resistance was defined as the time it took to generate conductive channels on the specimen by arcing.

3.6 Tensile Strength

Tensile strength is defined as the maximum tensile stress applied in stretching a specimen to rupture. Or the force required to break the rubber specimen is called tensile strength. It is expressed in megapascals or kN/cm^2. It is necessary to measure the task needed to get the rupture of a rubber material to qualify a rubber mechanically.

Tensile strength is the mechanical property of the material. Tensile tests determine how strong and stretched an object is. The following calculations can be made from the tensile strength results: (1) tensile strength at the yield point (2) tensile strength at the breaking point. (3) strain (4) tensile modulus (5) elongation at yield point (6) elongation at the breaking point. Tensile tests are usually performed on electro-mechanical or universal testing machines that are easy to maintain and fully standardized.

3.6.1 Experimental Test Set Up to Measure the Tensile Strength and Ultimate Elongation

Tensile strength tests are performed on a universal testing machine, also called a tensile strength testing machine. The universal testing machine consists of a test frame which is equipped with a load cell, self-tightening roller tensile grips, testing software and an extensometer.

Figure 7. Universal testing machine.

Tensile strength is usually measured as the amount of force in N/mm^2 needed to pull a test sample to the point of material failure. Three polymeric test samples were cut into a dumbbell shape with a dumbbell cutter press.

Specimen thickness is measured with a digital micrometre and input directly into the software. Width is measured with a vernier calliper and input directly into the software. The test was carried out using the universal testing machine as shown in Figure 7. This test is performed by placing a dumbbell-shaped model test sample in between the grips or jaws of a universal testing machine. gradually pull the grip until the dumbbell-

Figure 8. Dumbbell cutter press.

Figure 9. Dumbbell-shaped Samples.

shaped test sample is broken. As the pull progress, the sample is extended from the top end at a uniform rate, which is proportional to the rate at which load or pull force increases. Further pulling of the test sample beyond the proportional limit and elastic stress limit leads to permanent elongation or deformation of the test sample. The tensile strength of a specimen is the force applied to it at the time of rupture. The stress and strain curve can be used to determine tensile strength and ultimate elongation. This test was performed in accordance with ASTM D 412 (Figures 8 and 9).

4. Results and Discussions

Different electrical and nonelectrical properties of HTV silicone rubber compound are mainly studied in this research work. Results of the research work are presented here for different compositions of SiR material.

4.1 Electrical Properties

Electrical properties like inclined plane tracking and erosion test, recovery of hydrophobicity by corona ageing test, dielectric strength test, dry arc resistance test were examined for each different formulation of SiR material.

4.1.1 Inclined Plane Tracking and Erosion Test

Resistance to tracking and erosion test was conducted in AC voltage following the constant voltage application method (Method-I IEC-60587 and ASTM D2303) continuously for six hours duration. The constant voltage of 4.5kV AC was applied to the SiR samples. The results of the tests are presented and discussed below.

Sample-1

On the silicone rubber samples (S1.1, S1.2, S1.3, S1.4), there was no tracking or erosion, and all samples sustained the 4.5kV test voltage, with the exception of sample S0, which had a low concentration of silicon rubber and a high quantity of filler. As seen in Figure 10, sample S0 failed the IPTE test early on. Materials added as impurities or fillers in other silicone rubbers have a huge effect on the performance of SIR insulators, as they enhance the concentration of dynamic LMW components. It has been discovered that increasing the ATH filler type in HTV silicone rubber has a significant impact on anti-tracking capabilities.

The hydrophobicity of the test samples was also noticed in addition to the tracking and erosion. All of the samples lost their hydrophobic nature immediately after the test, as seen in Figure 11. A material's hydrophobicity is determined by the presence of Low Molecular Weight Components (LMW) on its outer surface. The greater the LMW on a material's surface, the higher its hydrophobicity, and vice versa. The loss of hydrophobicity is caused by the removal of low molecular weight components from the surface, which are eliminated either by excessively wetting conditions combined with the application of an electrical field or by dry band arcing caused by carbon tracking on the surface.

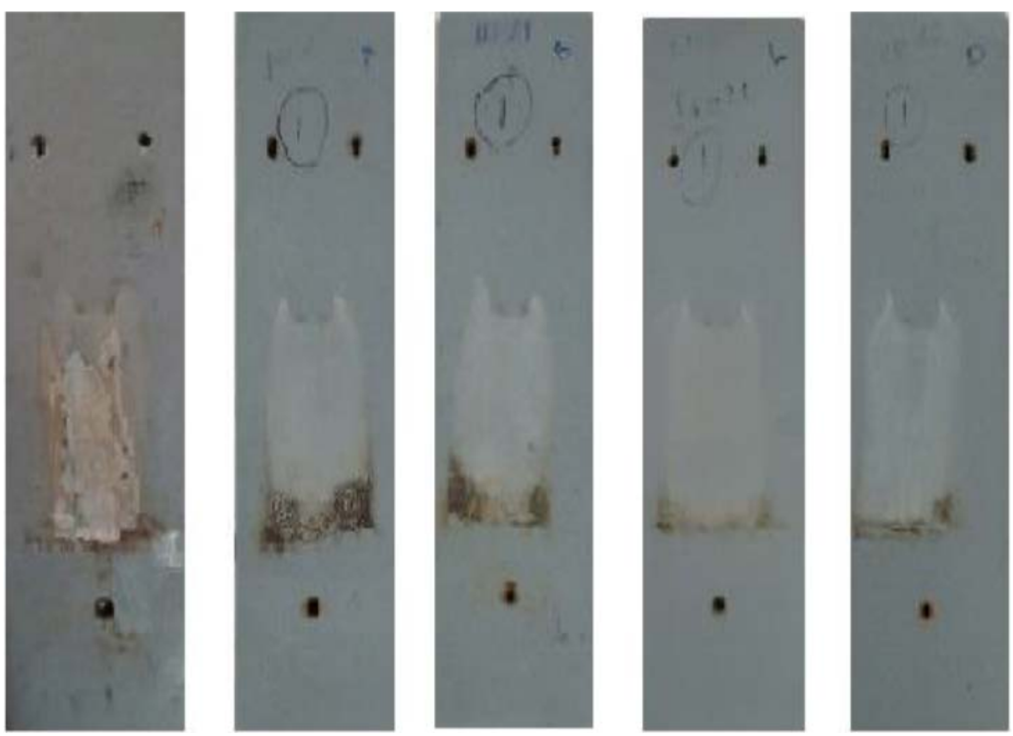


Figure: S0 Figure: s1.1 Figure: S1.2 Figure: S1.3 Figure: S1.4

Figure 10. Test samples after the IPTE test.

Figure: s1.1 Figure: S1.2 Figure: S1.3 Figure: S1.4

Figure 11. Samples loss hydrophobicity after the IPTE test.

Natural diffusion, on the other hand, causes the movement of low molecular weight chains within the material even when no external solvent is used. Due to the removal of a significant amount of LMW from the surface, a transfer of LMW from the inner side to the surface occurs as a result of this diffusion process, which tends to restore LMW content on the surface and, therefore, hydrophobicity.

Table 2. Sample conditions after 4.5 kV IPTE

S.No	Sample No	Remarks
SAMPLE-S0	S0	Failed at 4.5kv AC
SAMPLE-1	S1.1 S1.2 S1.3 S1.4	Withstood 4.5kv AC Withstood 4.5kv AC Withstood 4.5kv AC Withstood 4.5kv AC
SAMPLE-2	S1.1 S1.2 S1.3 S1.4	Withstood 4.5kv AC Withstood 4.5kv AC Withstood 4.5kv AC Withstood 4.5kv AC
SAMPLE-3	S1.1 S1.2 S1.3 S1.4	Withstood 4.5kv AC Withstood 4.5kv AC Withstood 4.5kv AC Withstood 4.5kv AC

The failure of S_0 can be mainly due to the low percentage of silicone rubber material in the polymer matrix. The image of the samples was obtained at the end of each test and hydrophobicity was assessed using the STRI guide. It is also perceived that there is a loss in hydrophobicity of the samples with the progression of the test shown in Table 3.

Table 3. Loss of hydrophobicity after IPTE.

Sample	Unaged	Aged
Sample-1	S1.1 - HC-1 S1.2 - HC-1 S1.3 - HC-1 S1.4 - HC-1	HC-6 HC-4 HC-5 HC-5
Sample-2	S2.1 - HC-1 S2.2 - HC-1 S2.3 - HC-1 S2.4 - HC-1	HC-3 HC-3 HC-3 HC-3
Sample-3	S3.1 - HC-1 S3.2 - HC-1 S3.3 - HC-1 S3.4 - HC-1	HC-3 HC-4 HC-3 HC-3

Among the three compositions, S_2 & S_3 performed well in IPTE by means of recovery of hydrophobicity.

4.1.2 Recovery of Hydrophobicity by Corona Ageing Test

The hydrophobicity of all the samples was determined, and they were categorised into seven classes, ranging from HC1 to HC7. The hydrophobic and hydrophilic surfaces HC1 and HC7, respectively, are completely hydrophobic and hydrophilic. The difference in contact angle, which reflects a hydrophobic transfer, was discovered after exposing the corona to three different substances. The surface lost its hydrophobicity after the corona was created on the sample, as shown in Figure 12, and within 48 hours, the surface regained its hydrophobic nature, as classified as HC1.

Within 48 hours, all of the samples regained their hydrophobic nature due to the transfer of LMW from the inner side to the surface, which begins due to this diffusion process and tends to restore LMW content on the surface and, therefore, its hydrophobicity.

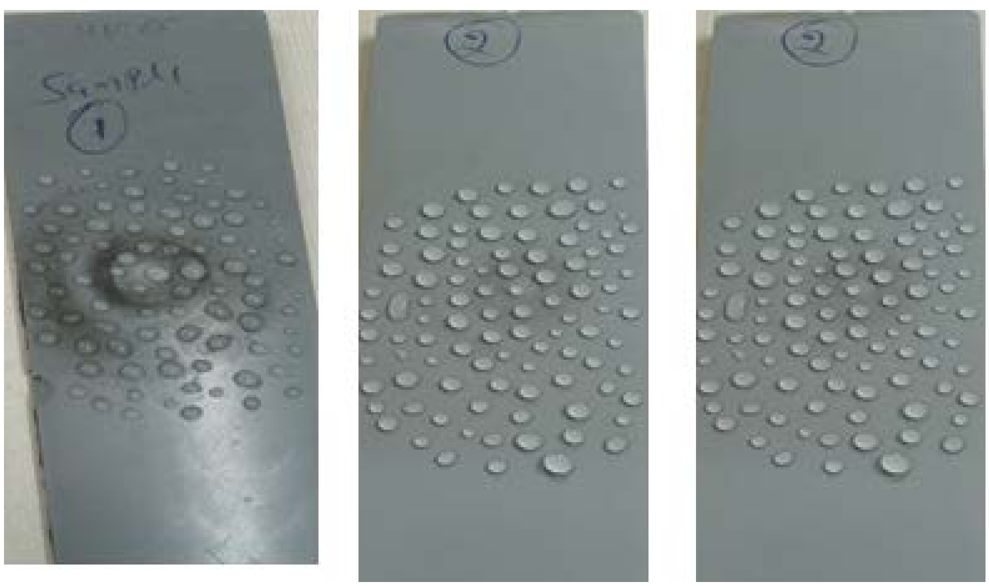
4.1.3 Dielectric Strength

Break down voltages and dielectric strength values of different formulations as shown in Table 5. HTV silicone rubber used in high-voltage outdoor applications must have a dielectric strength of at least 17.5kV/mm as per the standard. As indicated in Table 5 the cured silicone rubber compound›s BDV (Break Down Voltage) is proportional to the concentration of the filler ATH. Formulation 3 has a higher Dielectric strength, which decreases as the ATH content of the material decreases.

The dielectric strength test was passed by all three groups of samples, according to ASTM D 149/IEC 60243 standards.

Sample-1 **Sample-2** **Sample-3**

Figure 12. Change of hydrophobicity after the corona ageing test.



Sample-1 **Sample-2** **Sample-3**

Figure 13. Samples recover hydrophobicity within 48 hours.

Table 4. Hydrophobicity of samples

Sample	Aged sample HC classification	Within 48 hours HC classification
Sample-1	HC-2	HC-1
Sample-2	HC-5	HC-1
Sample-3	HC-5	HC-1

Table 5. Dielectric strength values for different formulations of silicone rubber

Sample Group	Sample dimensions	Co-sample	Break down voltage	Dielectric strength
Sample-A	(15mm*2mm*15mm)	Sample-A1	40KV	19.45kv/mm
		Sample-A2	37.8KV	
Sample-B	(15mm*2mm*15mm)	Sample-B1	35.9kv	18.7kv/mm
		Sample-B2	38.9KV	
Sample-C	(15mm*2mm*15mm)	Sample-C1	39.4kv	19.625kv/mm
		Sample-C2	39.1KV	

4.1.4 Dry Arc Resistance

Figure 15 depicts the arc resistance values of various formulations of HTV silicone rubber for high-voltage outdoor applications, as well as the specified minimum value. For HTV silicone rubber used in high-voltage outdoor applications, the standard minimum arc resistance value is 200 seconds. The arc resistance of the 48 per cent cured rubber compound with the 49 per cent concentration of filler ATH has been determined to be the highest. Figure 14 depict the results of the tests on the three test samples.

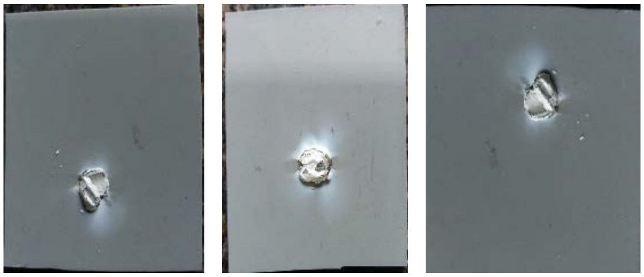


Figure 14. Samples after the dry arc resistance test.

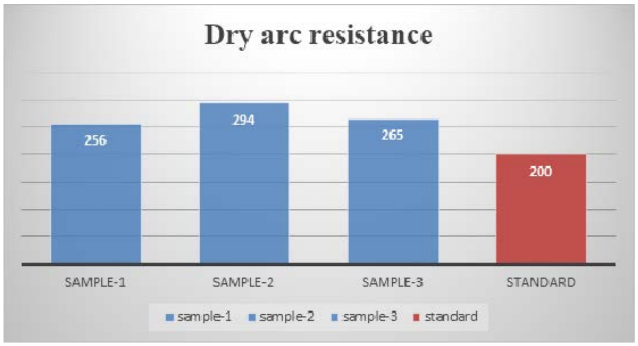


Figure 15. Arc resistance values for different formulations of silicone rubber.

All the samples pass the dry arc resistance test as per the ASTM-495-1973 standard.

4.2 Mechanical Properties

Tensile strength, ultimate elongation, and tear strength were investigated for each formulation, and the results were plotted in the graph.

Figure 16 depicts the tensile strength of HTV silicone rubber for high-voltage outdoor applications for various formulations and the standard minimum value. HTV silicone rubber with a minimum tensile strength of 4 N/sq.mm is employed in high-voltage outdoor applications. The tensile strength of Formulation 3 is stronger, however, it diminishes as the filler ATH concentration is reduced.

The ultimate elongation values for various formulations and the standard minimum value of HTV silicone rubber for high-voltage outdoor applications are shown in Figure 17. HTV silicone rubber used in high-voltage outdoor applications has a standard minimum elongation value of 100 per cent. Elongation is greater in Formulation-2 than in Formulation-3 and Formulation-1.

Figure 18 displays the tear strength results for several formulations of HTV silicone rubber for high-voltage outdoor applications, as well as the required minimum value. The tear strength of HTV silicone rubber used in high-voltage outdoor applications must be at least 12 N/mm. Tear strength is stronger in Formulation-3 and diminishes as the filler ATH content decreases. When the filler concentration rises while the silicone rubber concentration falls, the tensile and tear strength of the rubber compound increases.

4.3 Physical Property

The physical properties of different formulations of HTV silicone rubber made by varying the concentration of filler ATH were studied and compared with the standard formulation. The formulations are designated as S_1, S_2 and S_3. Hardness (Shore A) was recorded for each formulation and shown in Figure 19.

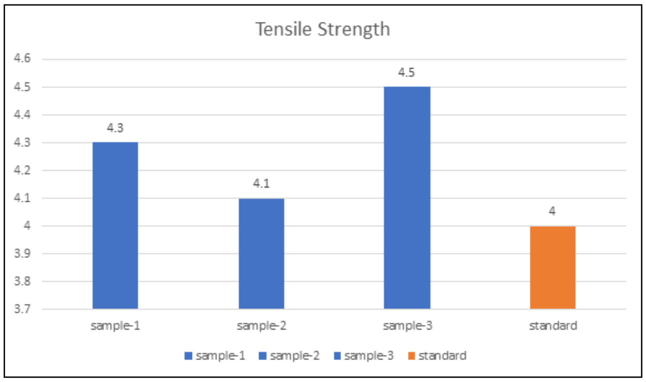


Figure 16. Tensile strength values for different formulations of silicone rubber.

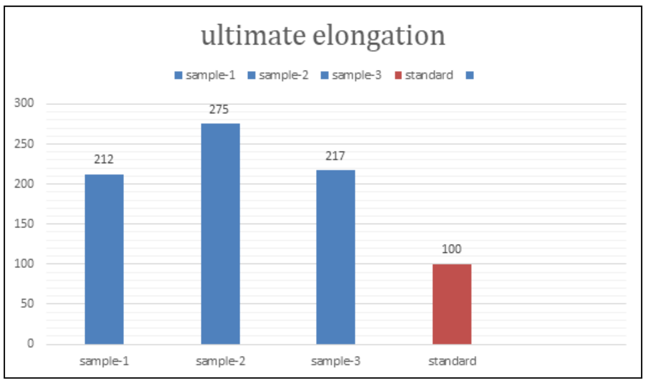


Figure 17. Ultimate elongation values for different formulations of silicone rubber.

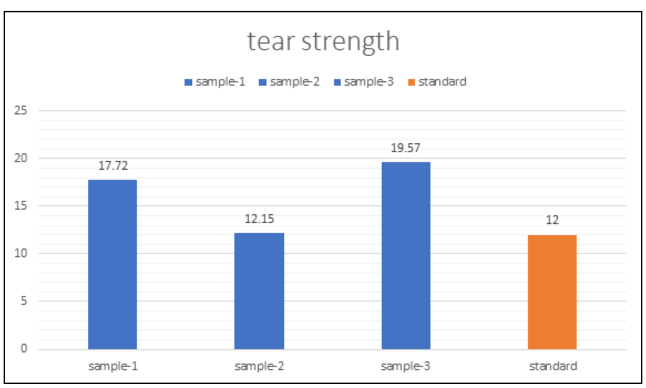


Figure 18. Tear strength values for different formulations of silicone rubber.

The hardness (shore-A) values for various formulations are shown in Figure 20, as well as the standard range for hardness values. HTV silicone rubber has a defined hardness range of 61 to 75 for outdoor use. The hardness values of Formulation S3 were determined to be in the standard range when compared to those of Formulations

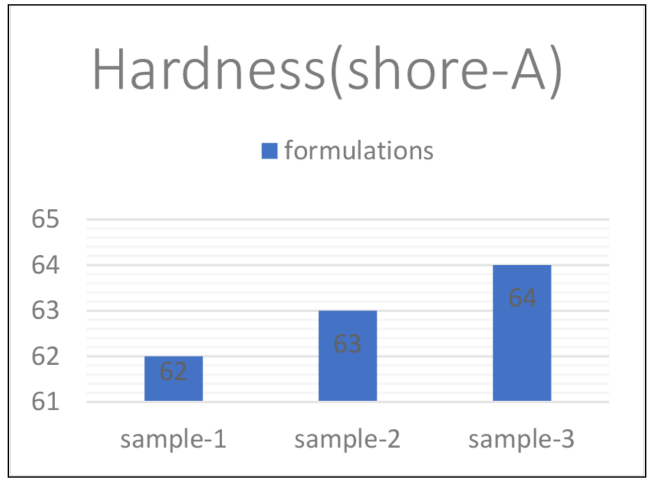


Figure 19. Hardness values for different formulations of silicone rubber.

S2 and S1. When compared to the other formulations S1 and S2; S3 was shown to be the most effective. Rubber with a hardness of less than 61 is soft, whereas rubber with a hardness of more than 75 is too hard for high-voltage outdoor use. With increasing ATH filler loading, the hardness value is increased.

5. Ageing of the Material Performance

To improve the sample's ageing performance, it was subjected to a continuous 100-hour inclined plane tracking and erosion test at 6kv. Test specimens can tolerate up to 92 hours of exposure. This ageing could give the end of life of the material for the sample tested.

Standard creepage distance is (500-800) mm &

Standard Specific creepage distance is 20 mm/kv

Specific creepage distance = (creepage distance ÷ applied voltage)

$20 = (500 \div V\sqrt{3})$

$V = (500 \div 20\sqrt{3})$

$V = (500 \div 34.6)$

V = 14.56KV

For 50mm creapage distance v = (50 ÷ 34.6)

= 1.44kv

1.44kv is sufficient to initiate tracking and erosion on the insulator sample surface over a 50mm creepage distance. The applied voltage of 6 kV is four times the actual value. As a result, the tested specimen is more suited for outdoor use.

Figure 20. Sample after 100 hours IPTE test.

6. Conclusions

The electrical and non-electrical properties of SiR materials were examined in this study. The IPTE test was carried out on SiR material in order to determine whether existing SiR insulator housing materials were suitable for outdoor use. Following is a summary of the findings of the detailed research:

The low percentage of Silicone rubber (13%) along with ATH filler fails to sustain the applied voltage for six hours and there was massive erosion observed on the specimen in inclined plane tracking and erosion test. 46 wt%(S1), 48 wt%(S2), 43 wt%(S3) Silicone rubber with 51 wt %(S1), 49 wt%(S2) ATH and 54 wt%(S3) ATH filler samples could able to resist the applied voltage for six hours duration. Adding ATH filler to the silicone rubber matrix increased tracking and erosion resistance.

All three samples recover the hydrophobicity within 48 hours in the corona ageing test. Immediately after the test, sample-1 did not have much effect on the corona compared to Sample-2 and Sample-3.

Among all the three samples, Sample-3 shows better electrical and non-electrical performance, which has the higher ATH filler concentration (54%). The sample performance increases by increasing the ATH filler concentration along with the increasing silicone rubber as base material.

7. Scope for the Future Work

Current research focuses on analysing the behaviour of polymeric insulators subjected to laboratory conditions. The silicone rubber material is added with a new filler material and the sample is analysed for outdoor suitability. A new composition of the material is developed to withstand long-term ageing performance, which can be used for outdoor applications.

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