



Degradation of Silicone Rubber Insulators under the Effects of Carbon Smoke, Salt and Cement Deposits

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ABSTRACT

This research was aimed at finding the worst pollutant for silicone rubber insulators. In this study silicone rubber insulators were carbon smoked, salt deposited and cement deposited in real field and then aged for 5000 hours under International Electrotechnical Commission (IEC) 5000 hours multi stress aging conditions. The samples were analyzed at different intervals by qualitative (surface morphology, hydrophobicity classification) and quantitative (Leakage Current Measurement, Fourier Transform Infrared (FTIR) Spectroscopy, Non Soluble Salt Density (NSSD) Measurements) techniques in order to investigate any degradation/ recovery which may occur in them. Silicone rubber insulators have shown excellent resistance to carbon smoke. It means they have also excellent resistance to tracking. The expected life under the effect of carbon smoke or any other carbon based pollutant will be very high. The shortest life is expected when silicone rubber insulator is exposed to salt. The estimated life under salt stress is 18 years. The results indicate that cement and carbon pollution does not affect the performance of SiR insulators to significant extent. During this study all the insulator specimens preserved excellent properties and performance. This work is particularly helpful for those thinking to adopt the silicone insulators for construction of new lines in different polluted environments.

1. Introduction

Silicone rubber (SiR) insulators are rapidly taking market share since last 15 years. Life of these insulators is largely dependent on the environment in which they are used. Important properties of silicone rubbers such as leakage current and hydrophobicity are affected in different ways by environmental conditions. Leakage current which in turn is dependent on hydrophobicity is an excellent parameter to estimate state of a of silicone rubber insulators. Hydrophobicity pertain to surface property of silicone rubber under which low molecular weight components in the bulk of silicone rubber skim up to the surface due to difference in diffusion density. Silicone rubber has shown a strange behavior of reduction in hydrophobicity during early part of its life and later on recovery in the hydrophobicity. In other words hydrophobicity goes through cyclic changes during its life. It has been observed that temperature slows down the reduction rate of hydrophobicity, but increases the recovery rate by increasing the rate of diffusion of low molecular weight components from the bulk to the surface. The trend of hydrophobicity recovery depends on different environmental factors. Silicone rubber (SiR) insulators and coatings have considerably improved the reliability of high voltage transmission and distribution systems. Due to lower cost, lighter weight, and superior contamination performance of polymeric insulators, insulator industry has shifted its focus from porcelain to silicone based polymeric

materials. Since silicone rubbers belong to organic pendent group, so it makes them suitable for use in high voltage outdoor applications. Their low surface energy makes the insulator surface hydrophobic. This increases suitability of the insulators during rainy conditions and polluted environment. When the hydrophobicity is temporarily lost under any environmental conditions, it can be recovered due to migration of low molecular weight chains from the bulk to the surface. This ability to recover hydrophobicity is the main reason of their popularity for their applications in outdoor environment [1-3].

However, under prolonged conditions of heavy or continuous wetting combined with contamination, silicone rubber loses its hydrophobicity. Failures have been reported with the use of SiR insulators in heavily contaminated and moist environment. For a complete understanding of the aging phenomena, simulation of a realistic environment to conduct such studies is desirable [4-8].

Commercial use of SiR materials in making outdoor insulators has started only 20 years ago. These materials undergo biological degradation in nature so it is required to investigate their performance in polluted environments for long duration In order to have a realistic data of their behavior over a long time researchers are working in different parts of the world [7-10].

In this research work three identical SiR insulators were exposed to three different pollutants. The pollutants applied

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include carbon smoke, salt (mixture of NaCl, NaNO₃ and KNO₃), and pollution from cement industry. The carbon smoke and cement dust are commonly found in industrial areas. The salt pollution is very common in areas near sea. SiR insulators are commonly used in both these areas in wide abundance in developed countries and are expected to be used soon in Pakistan as well. So it is required to investigate their behavior under the effect of these pollutants. These insulators support conductors of overhead transmission and distribution lines.

2. Experimental Set-Up

This investigation about aging of insulators was carried out using three air tight wooden chambers having dimensions of 2'x1.5'x1.5' each. The size of chamber was selected in order to accommodate the insulator specimens comfortably. Three samples of SiR insulators each exposed to carbon smoke, salt and cement, respectively were suspended in a chamber. Each chamber has a facility of controllable humidity, temperature and ultraviolet radiations to simulate IEC 5000 hours multi stress aging conditions. The insulators were energized with 11KV ac source. Experimental setup is shown in Fig. 1.

Following set of different techniques were used for analysis of SiR insulators [1,2,6,9, 11-14].

- i. Surface Morphology
- ii. Hydrophobicity Classification (HC)
- iii. Leakage Current Measurement
- iv. Fourier Transform Infrared (FTIR) Spectroscopy
- v. Non Soluble Salt Density (NSSD) Measurements.

A brief description of type and machine/ equipment used in each technique is discussed below.

2.1 Surface Morphology

Surface morphology was studied using images taken from a high resolution camera after an interval of every 360 hours.

2.2 Hydrophobicity Classification

Hydrophobicity is a property of material due to which it repels the formation of continuous conducting water tracks on its surface. Hydrophobicity measurements were taken by using the method described in Hydrophobicity Classification Guide published by Swedish Transmission Research Institute (STRI). In this method the specimen under test is sprayed with water from a distance of one foot for 30 seconds. A high resolution camera is used to capture the image of the specimen. The image is compared to the standard images given in above mentioned guide [15]. The resultant match of the image is the hydrophobicity class of the specimen under investigation.

2.3 Leakage Current Measurement

Leakage current measurement was performed using a precision ac micro ampere meter (UT-70B) after an interval of every 360 hours.

2.4 FTIR

FTIR is a material analysis technique which gives the quantitative measurement of status of different chemical compounds inside a material. FTIR was done by using ATR-600 FTIR Machine. The result of FTIR is either an absorption or transmission spectrum. Any of absorption or transmission spectrums can be used to quantify degradation. Since the absorption values correspond directly to degradation, hence most of researchers use this approach in their analysis

2.6 NSSD Measurements

In this method pollution deposit on 1cm² area of each sample is collected by a precise digital scalar and weighed using a very precise small electronic digital scale with precision up to 0.01 gram.

3. Methodology of Study

In this research SiR insulators were installed in an environment where carbon smoke, salt and cement deposit were present. The first sample was installed at the exhaust of a brick furnace chimney. This sample was kept in horizontal orientation at the top of brick chimney so as to expose it to maximum of carbon smoke. In order to ensure huge carbon smoke the sample remained in that environment for a period of 6 weeks. The second sample was exposed to coastal area environment artificially. To simulate coastal area conditions a mixture of water with sodium chloride, sodium nitrate and potassium nitrate was used. These three salts were mixed together in ratio of two parts sodium chloride, one part sodium nitrate and one part potassium nitrate. Then 35 grams of this mixed powder was mixed in one litre of water. This gives a salinity of 3500 PPM and conductivity of 55000 µS/cm which closely resembles to that of sea water. This solution was sprayed on the second sample at regular intervals for 6 weeks. Through this process a sample was developed as it is installed in the coastal environment. The third sample was installed in a cement industry where cement pollutants were abundantly present in the environment. This sample was installed in open air at the height of 20 from ground and at a distance of 3 meters from cement grinder which grinds dry raw materials in the very first stage of cement production. The sample was kept in that environment for 6 weeks. As a result enough cement deposits were accumulated on the insulator surface to effect its performance.

All the above samples were then placed in wooden boxes separately and aged for 5000 hours according to IEC 5000 hours multi stress aging conditions. The cut samples

from each insulator were collected after every 360 hours during the aging period. These samples were analyzed using different material analysis techniques to observe any degradation/ recovery.

The aging process was carried out as per procedure laid down in the ASTM D4762 - 11a, ASTM D2865M - 06 and IEC 62217 ed2.0 standards.



Fig. 1. Photographs of a multi stress aging chamber, outside (left) and inside (right).

3. Results and Discussions

3.1. Surface Morphology

Surface morphology of silicone rubber samples was studied using images from a high resolution camera after an interval of every 360 hours. Some selected images are shown in Fig. 2.



Fig. 2. Surface morphology.

As shown in Fig. 2(a), the effect of carbon smoke has reduced to large extent during the aging. The effect of cement deposit has shown a good recovery as shown in Fig. 2(b). So it can be argued that the degradation due to

carbon smoke and cement deposit can be recovered with passage of time without any maintenance. However, from Fig. 2(c), it is observed that effect of salt on the insulators is less recoverable with aging. This implies that coastal environment is worst for these insulators.

3.2. Hydrophobicity Classification

Hydrophobicity is a property of material due to which it repels the formation of continuous conducting water tracks on its surface. The most popular method to measure hydrophobicity is STRI-hydrophobicity-classification-guide published by Swedish Transmission Research Institute. In this method the specimen under test is sprayed with water from a distance of one foot for 30 seconds. A high resolution camera is used to capture the image of the specimen. The image is compared with the standard images given in above mentioned guide [15]. The resultant match of the image is the hydrophobicity class of the specimen under investigation. Photographs of hydrophobicity classification after 5040 hours of aging for selected samples are shown in Fig. 3 and results of hydrophobicity classification for all samples are shown in Fig. 4.



Fig. 3. Hydrophobicity of samples after 5040 hours of aging carbon smoked (left), cement deposited (center), salt deposited (right).

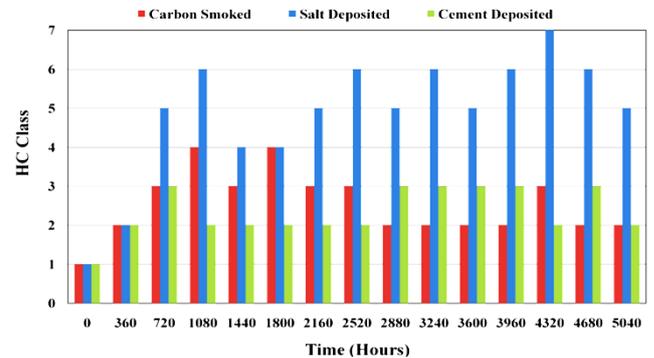


Fig. 4. Hydrophobicity classification of all samples.

Fig. 4 shows that the sample with salt deposits has lost hydrophobicity up to class 7. The reason is that salt penetrates in the silicone rubber materials rapidly because of its solubility in water. The sample with carbon smoke has shown degradation in hydrophobicity class up to 3-4. The degradation in this case is not very significant. The reason is that carbon smoke is insoluble in water and hence cannot penetrate in the surface of material to attack its low molecular weight components (LMW's). The cement has also caused moderate degradation in hydrophobicity up to class 4. In the presence of water and moisture the cement

forms a hard layer on the insulator surface. This layer acts as a protective coating for other environmental pollutants to attack the insulator, hence no significant degradation in hydrophobicity of the specimen.

3.3 Leakage Current

The leakage current magnitudes for all three insulator samples are shown in Fig. 5. The sample polluted with salt deposit has highest and one with cement deposit has lowest values of leakage current. The reason is that salt when mixed with moisture or water in the environment becomes a good electrolyte, whereas cement does not increase the conductivity of compound of cement and water. The trend of decreasing leakage current in carbon smoked and cement deposited samples show that they are recovering with aging contrary to salt deposited sample. However the maximum current in salt deposited sample is still 63 μ A which is well below the 5 mA limit of leakage current for the insulators [16]. These results are in-line with results of surface morphology and hydrophobicity, where salt deposited sample has shown highest degradation.

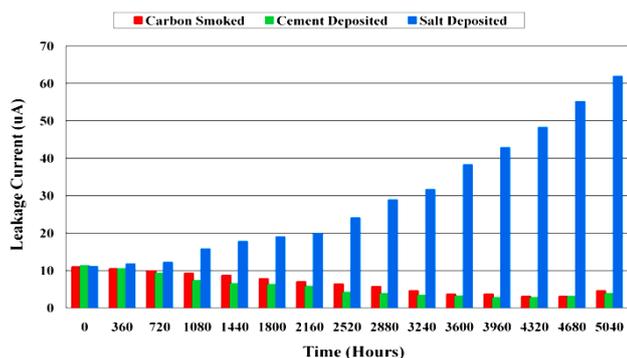


Fig. 5. Leakage current.

3.4 FTIR

A typical FTIR absorption spectrum is shown in Fig. 6.

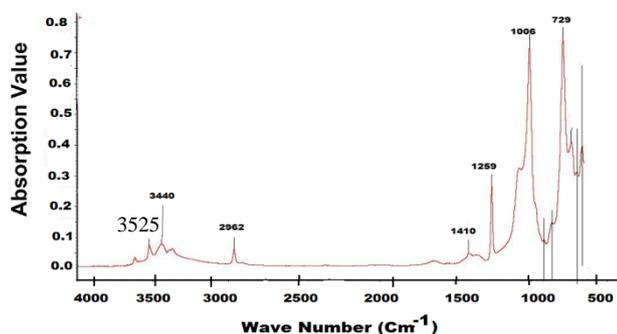


Fig. 6. A typical FTIR absorption spectrum.

In order to find overall degradation or recovery in SiR insulators, the two wave numbers at 1008 and 1258 are considered. The wave number 1008 corresponds to Si-O-Si asymmetric stretch and 1258 corresponds to C-C-C bond

strength in the silicone rubbers [18]. The ratio of absorption value at wave number 1258 to 1008 is found for virgin and aged samples, respectively. The results are shown in Table 1.

Table 1. Degradation from FTIR results.

Sample Name	Absorption at wave number		Ratio 1258/1008	Percentage degradation w.r.t Virgin
	1258	1008		
Virgin	7.7	12.3	0.626	-----
Carbon smoked	7.5	12.3	0.61	2.24 %
Aged Salt deposited	7.3	12.2	0.598	4.16 %
Aged Cement deposited	7.6	12.4	0.612	1.92 %

As shown in Table 1, the salt deposited sample has maximum degradation. But all the samples have maintained their properties as degradation is below the commonly suggested limit of 30%. The results shown in Table 1 for virgin and aged samples at both wave numbers seem to be having values very close but this change in absorption value is considered significant and reliable in the field of polymers research. This is very reliable and accurate method because it is as per guide lines laid in ASTM D-297-13, ASTM-STP-1320 and ASTM-STP-1426 standards [19-21].

3.5 Non Soluble Salt Density (NSSD) Measurements

The results of non soluble salt density measurements on variously stressed samples is shown in Fig. 7.

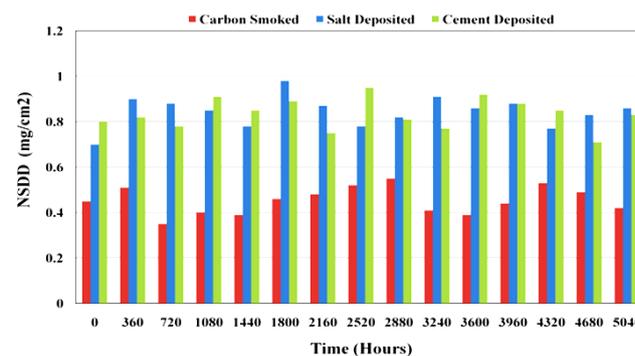


Fig. 7. NSSD measurement for all samples.

The carbon smoked sample has least NSSD measurements. So the carbon smoke is least sticky pollutant out of three pollutants under observation. Salt deposited sample has highest value of NSSD. This is directly in correlation with the results of previous sections where all other techniques also govern maximum degradation in salt deposited sample. It is expected that life of SiR insulators will be least under the effect of salt deposit, because it is most sticky and most conductive pollutant among the all

three studied. The salt deposited sample life will set a lower limit on washing or replacement cycle of these insulators in service. This fact is further investigated in next section of life modeling.

3.6 Life Modeling

In order to develop the relationship for expected life of silicone rubber insulators under the effect of pollutants studied, regression analysis was carried out using the data of leakage current as shown in Fig. 8. The equations obtained from regression are as below.

$$\text{Carbon smoked sample : } Y = -0.601 X + 11.31$$

$$\text{Salt deposited sample : } Y = 8.496 e^{0.000042011X}$$

$$\text{Cement deposited sample : } Y = -0.589 X + 10.22$$

The Y in above equations represents the leakage current and X is time. Following strict limits as laid in IEC 950 standards for calculating useful life of an outdoor insulation, we can set $Y = 5000 \mu\text{A}$ and find X which will be useful life of any sample. However, solving the equations of carbon smoked and cement deposit yield an invalid result of -8300 and -8470 hours which is not possible. This is happening because the leakage current is decreasing, but it cannot continue on decreasing, ultimately it will start increasing after dropping to some critical point which does happen during 5040 hours. So the life of carbon smoked and cement deposited samples cannot be predicted with this much aging but it can be safely stated that it will be much more than salt deposited sample.

If we put $Y = 5000$ in equation of salt deposited sample it results in $X = 157680 \text{ hours} = 18 \text{ years}$, which is still quite appreciable. The values for other two samples would be surely greater than this.

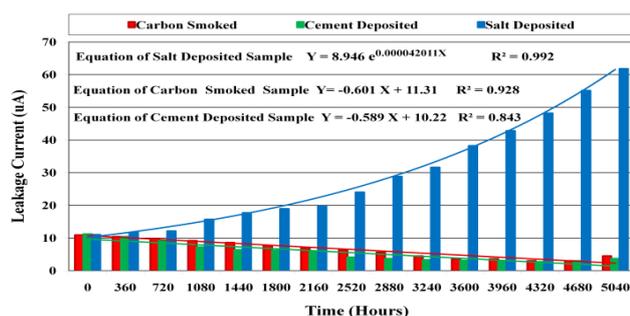


Fig. 8. Regression analysis for all samples.

4. Conclusions

Among all the three pollutants salt has shown the worst effect on the performance of SiR Insulators. When salt penetrates in the material, it effects the movement of LMW's from inner bulk of material to surface. This is the backbone phenomena of hydrophobicity recovery in SiR materials.

Silicone rubber insulators have shown excellent resistance to carbon smoke. It means they have also excellent resistance to tracking. The expected life under the effect of carbon smoke or any other carbon based pollutant will be very high. The shortest life is expected when silicone rubber insulator is exposed to salt which comes to be 18 years in this research. More long term salt/ fog aging of SiR and other thermo-set insulators is a prospect to be investigated.

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