# Evaluation of Actual Field Ageing on Silicone Rubber Insulator under Coastal Environment

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**Abstract:** Insulators in the field experience synergistic effects of temperature, UV radiation, rain, clear mist, and contamination. One of the problems related to outdoor polymeric insulator is erosion and tracking of the weathershed which can affect the reliability of power system. This paper presents investigations on the performance of outdoor 63 kV silicone rubber insulators after seven years of field exposure. The insulator performances were evaluated in laboratory by measurements of leakage currents under clean fog and salt fog conditions. Also visual inspection, hydrophobicity classification and material diagnostic technique have been used to detect defective in service silicone rubber insulators. The polymer content of some surface regions decreased as degradation increased. Scanning electron microscopy, Thermo-Gravimetric, attenuated total reflectance-Fourier transform infrared spectroscopy analysis and energy dispersive x-ray analysis used to identify the elemental composition of virgin and aged surface of insulator. Peak values of leakage current and cumulative charge are measured in clean fog and salt fog chamber. Also, inclined plane tracking and erosion resistance test have been done on the silicone rubber samples. The changes in the surface morphology and material structure were examined before and after the ageing. [Majid Rezaei, Iman Ahmadi-Joneidi, Afsoon Parhizgar, Hasan Kahuri, Ahmad Sayani. **Evaluation of Actual Field Ageing on Silicone Rubber Insulator under Coastal Environment.** *Life Sci J* 2013;10(5s):199-205] (ISSN:1097-8135). http://www.lifesciencesite.com. 36

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## 1. Introduction

The first insulators were made of ceramic. However, over the last decades, polymeric equipment has been increasingly used in transmission and distribution power lines. Outdoor insulating material have exposed to outdoor and weather condition and so study of polymeric surface in outdoor insulation material is necessary in electric and material designs based on the chemical analysis, as well a variety of application field (Farzaneh, 2009).

Where silicon rubber (SiR) insulators are used as outdoor insulator, various environmental factors such as ultraviolet, rain and air pollutant deteriorate the material properties. Many methods have been used to detect defective in service polymer insulators, such as visual inspection, electric field measurement, infrared thermograph, hydrophobicity and morphology analysis (Samimi et al, 2012, Otsubo et al, 2003 and Ahmadi-Joneidi et al 2012).

One of the ways to measure natural pollutions on high voltage insulators is offline measurement of Equivalent Salt Deposit Density (ESDD) and Non-Soluble Deposit Density (NSDD). At present, these values mostly reflect the kind and density of pollutions.

Forecasting these parameters plays an important role in the safety and reliability of power system due to it is a main factor to arrange contamination (Joneidi et al, 2010, Joneidi et al 2011). The surface hydrophobicity of SiR insulators prevents water droplets to join and form a wet and highly conductive path. Silicone rubber recovers its hydrophobicity because of Low Molecular Weight (LMW) polymer chains that covers the surface (Farhadinejad et al, 2012). In practice, the hydrophobicity of surface is determined by measuring of the contact angle between surface of insulators and water droplets.

The thermal decomposition of silicone rubber can be caused by different chemical processes depending on the environmental conditions, and be related to the hydrolysis of siloxane bonds (Ramirez et al, 2008). Thermo-Gravimetric Analysis (TGA) can be used to determine filler content by measuring the weight loss of a small piece of sample as the temperature increases. The dehydration of the filler and the decomposition of the silicone backbone occur at different temperatures. The filler and polymer content can be estimated according to the weight loss values at different steps. By analyzing the evolved gas with mass spectrometry, detailed information about the decomposition products can be obtained (Majzoobi et al, 2011, Rowland et al, 2011 and Joneidi et al, 2011)

Analysis of surface changes can be carried out by Scanning Electron Microscopy (SEM). Energy Dispersive X-Ray Analysis (EDX) is a very effective surface sensitive technique for the assessment of degradation. It involves rastering (rectangular arrays of cells or pixels, each of which stores a value for the part of the surface) the surface to be studied with monochromatic X-rays which in turn eject electrons from the surface. The energy of these electrons is characteristic of the element from which it comes and varies slightly depending upon the bonding to adjacent elements. EDX technique can be employed to study elemental changes on the surface during ageing processes (Homma, 2000).

Attenuated total reflectance-Fourier transform infrared (ATR-FTIR) spectra of the samples have been used to detect bands related to the silicone and filler which provide information on the change in silicone and filler content (Sundararajan et al, 2004).

This paper describes the experimental results of actual ageing tests conducted on a silicone rubber insulator. It is organized with Section 2 describing the Field ageing and visual observation respectively. Section 3 and 4 presents the visual observation and ESDD, NSDD evaluation, which determine the amount of pollution on the insulator surface. Section 5 compares the hydrophobicity of different case studies. Section 6 and 7 clarifies the salt fog and clean fog tests respectively. Section 8 presents the Tracking and erosion resistance test. Sections 9 and 10 discuss the TGA and SEM imaging, performed on different insulators, before and after ageing, respectively. Section 11 and 12 clarifies the EDX and ATR-FTIR analysis on the surface of aged and virgin samples. The paper concludes in Section 13 with a summary of the key results of the paper.

Peak values of leakage current (LC) and cumulative charge are measured in clean fog and salt fog chamber. The changes in the surface morphology and material structure were examined before and after the ageing.

## 2. Field ageing and insulator characteristic

Insulators were high temperature vulcanized (HTV) silicone rubber with fillers of Alumina Trihydrate (ATH). The content of ATH was approximately 50%. Samples used in actual field ageing used for 63 kV line. The insulators were hanged on March 2005 under coastal and high humidity site. Insulators were exposed to UV radiation with high temperature, salt and material near the coastal sea. During the years, after 7 years, insulators were removed on January 2012 to mechanical and electrical test in laboratory. The characteristic of the test sites and insulators are provided in Table (1).

# 3. Visual observation

A visual inspection revealed that all the samples presented small cracks and in their polymer sheath, corrosion and oxidation in the end fitting, especially in the live fitting. By looking at the insulators, no significant surface changes were found on the insulators and that was seen that the color of the surface compared to the virgin sample changed. Figure (1) shows the picture of insulator after 7 years.

Table 1. Characteristic	of the t	test sites	and insulators
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Test Site	Coastal site		
Contamination	Heavy		
	Temperature:25		
Average weather	Humidity:60%		
Average weather	Annual		
	rainfall:120mm		
Insulator	HTV silicone rubber		
Voltage (kV)	63		
Specified mechanical load	80		
(kN)	80		
Arcing distance (mm)	810		
Creepage distance (mm)	3035		
Number of sheds	18		
Shed diameter (mm)	160		
Core diameter (mm)	22		



Figure 1-Visual observation after 7 years

# 4. Pollution level determination

The amount and type of pollution layer measured using the ESDD and NSDD. In addition to ESDD, NSDD should be measured, especially in case that much dust or sand is estimated to accumulate on the insulator surface in such an area as desert or industrial factories. The ESDD and NSDD of the insulators were calculated according to (IEC60507, 1996).

ESDD and NSDD were measured according to IEC 60507 to determine the amount of insulators surface contamination level. The drops shall be removed carefully before drying the layer. The collected salts by the brush are then dissolved in 1300 milligrams distilled water. The resulting suspension was kept stirred for at least 1 (min) before the measurement of its volume conductivity at its temperature. Also the water containing pollutants after measuring ESDD shall be filtered out by using a funnel and pre-dried and weighed filter paper. The filter paper containing pollutants shall be dried, and then be weighed. Table (2) shows the results of measured electrical conductance and calculated ESDD and NSDD in tested insulators.

IEC 60815 (2008) specification also categories insulators into one of five pollution classes, defined

by ESDD and NSDD according to figure (2). It can be concluded that the site pollution severity of these stations is very heavy.

Table 2. Result for calculation of ESDD and NSDD

Figure 2. ESDD and NSDD values for site pollution

#### 5. Hydrophobicity measurement

In order to analyze the ageing effect on the hydrophobicity of the insulators, the Swedish Transmission Research Institute (STRI) method is applied (STRI Guide, 1992). This method classifies the hydrophobicity of surfaces to seven Hydrophobicity Categories, HC1 to HC7. The HC1 refers to the highest surface hydrophobicity while HC7 represents the lowest hydrophobicity.

Amount of distilled water was squeezed several times on the surface of insulator. Figure (3) shows pictures of SiR insulator. Comparing pictures of figures concludes that the hydrophobicity of the samples after ageing is between HC1 and HC4 categories. It can be seen that the energized shed has the hydrophilic surface.



(a)	(b)	(c)	

Figure 3. Hydrophobicity picture of aged sample: a) top shed (HC1-HC2), b) Middle shed (HC3), c) energized shed (HC4)

### 6. Clean fog test

The test insulator was suspended vertically inside the fog chamber (1.5 m x 1.5 m x 1.5 m). The test voltage was 18 kVrms, 50 Hz. The leakage current was measured through a series resistance in the ground lead. A 2 kSa/sec sampling rate data acquisition system was used in this paper. A continuous flow of pure de-ionized water was used to generate fog in the chamber. The fog generation rate was 3 L/(hours). The particle size of the fog was approximately 7  $\mu$ m. The conductivity of the deionized water was 0.005 S/m. The samples were put into the fog chamber for 15 minutes. Fog generation and data acquisition were started simultaneously.

The peak value of leakage currents on the test samples were continuously monitored by the leakage current measuring system which measures and stores the positive and negative cumulated charge with values of 4.2 and 12.1 colon respectively. The volume power losses were measured equals to 0.82 W. Figure (4) show the Peak value of leakage current in clean fog test.



## 7. Salt fog test

The test insulator was suspended vertically inside the fog chamber (1.5 m x 1.5 m x 1.5 m), (Figure 5). The applied test voltage is determined by dividing the actual creepage distance in millimeters by 34.6. So, the applied test voltage (19.5 kV) was adjusted according to the actual creepage distance of 680 mm (IEC 62217, 2005).

Table (3) shows the experimental conditions of the salt fog ageing test according to the (IEC 61109, 2008). Figure (6) shows the peak value of leakage current in the last hours of salt fog test.

Table 3. Experimental condition in salt fog ageing test

test			
Sample	HTV silicone rubber insulator		
Salt-fog chamber	1.5 m x 1.5 m x 1.5 m		
Applied voltage (kV)	19.5		

Ageing time	1000 h
Water flow rate	$0.4 \pm 0.1 \text{ L/m}^3\text{h}$
Actual creepage distance	680 mm
Voltage stress	28.6 (V/mm)
Conductivity of salt- fog	16000 (µS/cm)



Figure 5. Salt fog chamber after 1000 hours test

The formal test criteria are no more than three over current trip for each specimen test and no tracking, erosion does not reach the glass-fibre core, and sheds are not punctured. There was no surface discharge during the 1000 hours.



#### 8. Tracking and erosion resistance test

To access the tracking and erosion resistance, the Inclined Plane Test (IPT) is used .but instead of computing the time to erode, the time was kept for 6 hour and the degree of damage is evaluated by measuring the erode volume of samples after the test.

According to (IEC 60587, 2007), four different test voltage levels specify; 2.5, 3.5, 4.5 and 6 kV (r.m.s) ac voltage and the flow rates corresponding to the test voltage levels are 0.15, 0.3, 0.6 and 0.6 mL/min respectively. In this present experiment, the test voltage has been fixed at 4.5 kV (r.m.s) for 6 h, the reason to choose this voltage level is that it is the most critical as arcing tended to concentrate at one or two points where it caused severe damage in the form

of extensive erosion. Conductivity of NH4Cl solution used is 2.5 mS/cm.

The experimental set up is shown in figure (7). R is a current limiting resistor and resistors R1 and R2 are voltage divider which is used to measure the output voltage of the 220 V/ 8 kV transformer. Resistor (Rsh) is used to measure the leakage current. For each test an average of 5 samples were subjected to the IP test. A computer data acquisition system was used to record the leakage current and voltage across each specimen separately. The leakage current is passed through a 33 k $\Omega$  shunt resistor. Eroded material from each sample is removed completely with a soft brush. The test electrodes are used only once because of severe ablation during the test. Before the test, all the specimens were washed with distilled water and cleaned with isopropyl alcohol.



Figure 7. Schematic setup of tracking and erosion resistance test

To characterize the damage, the damaged volume in each sample was measured by means of suitable mass and all weight measurements were done using a standard measurement with a least count of 0.1 mm. Weight of samples before and after the test were 11.08 and 11.065 respectively.

The end point is reached when the value of the current in the high voltage circuit through the specimen exceeds 60 mA or the track reaches a mark on the specimen surface 25 mm from the lower electrode. There was no problem in this test and it passed the test successfully. Figure (8) shows the samples during the test.



Figure 8. Samples during the IPT

# 9. Thermo-Gravimetric analysis

The weight loss and rate of weight change in a material, as a function of temperature was recorded

for both aged and virgin silicone composites .The temperature is increased from 25 to 600 °C. Figs. 9 and 10 show the TGA and Derivative Thermo-Gravimetric (DTG) curves of SiR insulator samples. The samples are chosen after separating the SiR layers from the insulator surface. It can be observed that increasing temperature up to ~190 °C does not affect on samples' weight. Figures show that over 190 °C all samples decompose at two stages. The first is due to the conversion of ATH to Al2O3. During this reaction, water is released. Also it has been found that evaporation of LMWS species can be started at this stage (Ahmadi-Joneidi et al. 2013).

It can be seen that temperature of First drop in aged and virgin sample are 196.19°C and 199.88°C. The second weight loss belongs to the degradation of silicone rubber in forms of LMWS, cross-linked silicone elastomer, and silica. It can be observed that temperature of second drop in aged and virgin sample are 345.53°C and 350.86°C respectively.

First drop in the sample weights is not major and Water started to be detected when the weight loss began at just over 190 °C. It ended at the same time when the first weight loss finished. However, the second drop is caused by the break of the side chain (CH3) from the Si backbone (Si-O-Si). At the end, only a non-volatile residue remains. Residual ash in aged sample was 60.52% and in virgin sample was 56.53%.



Figure 9. TGA and DTG curves for virgin sample



Figure 10. TGA and DTG curves for aged sample

# 10. Image Analysis

An analysis of the surfaces using SEM shows the molecular structural changes of the surface of the silicone rubber. The specimen size was  $1x1x 0.2 \text{ cm}^3$ approximately.

Figure (11) shows the micrographs for virgin and aged samples at 1000x. The overall observation is that there is no major degradation, such as cracking; also the virgin sample has a smooth, more homogeneous and less porous surface while the surface roughness and porosity increases with ageing for aged SiR Insulators.



Figure 11. SEM analysis on the surface of samples, (a) virgin, b) aged sample

# 11. Energy dispersive x-ray

EDX is an x-ray technique used to identify the elemental composition of materials. EDX systems are attachments to SEM instruments. The data generated by EDX analysis consist of spectra showing peaks corresponding to the elements making up the composition of the sample. The EDX survey spectrum of the aged and virgin sample revealed the presence of Oxygen (O), Carbon (C), Silicon (Si) and Aluminum (Al).

A distinct difference between aged and virgin samples is found. An increase in both the (Si) and (O) concentrations is observed for the aged sample compared to the virgin sample and the atomic concentrations of carbon decreased significantly for aged sample.

The results of quantitative analysis of EDX are represented in Table (4). It shows atomic percentage of the elements on the surface of the virgin and aged samples. Also the carbon to silicon(C/Si) and oxygen to carbon (O/C) ratios for sample are given in Table (4). Si-CH3 bonds are broken as a result of ageing and at broken chain. OH bonds are formed and created silanol groups. Therefore it can be proved that surface of the insulators loss their hydrophobic nature and gradually become hydrophilic. There was a decrease in the (C/Si) atomic ratio from virgin sample at 4.57 to aged Sample at 1.79 and an increase in the (O/C) ratio from 1.94 to 3.07. The exposure of the ATH due to erosion of the polymer in these samples may also contribute to the increase of the (Al).

On a virgin surface, there was a little amount of ATH and a thin layer of silicone covered due to the migration of the LMW silicone. That means that a little aluminum was detected. Aluminum levels of virgin and aged samples were detected on the surface 2.27 % and 3.6 % respectively. However, due to the non uniform particle size and the heterogeneous nature of ATH, change in aluminum content alone can not be used as a quantitative measure of degradation but provides supplementary evidence that the polymer has degraded.

Table 4. Result of EDX analysis

Atomic percent (%)	С	0	Al	Si	(O/C)	(C/Si)
Virgin sample	31.8	61.9	2.27	6.97	1.94	4.57
Aged sample	22.2	68.3	3.6	12.4	3.07	1.79

# 12. Attenuated total reflectance-Fourier transform infrared

ATR-FTIR is a tool which has been proven to be useful in chemical analysis on the surface of material. ATR-FTIR spectra of aged and virgin insulator samples were measured. The spectra were recorded for both aged and virgin silicone composites from 500 to 4000 cm-1.

The absorbance at 840- 790 cm-1 is characteristic for Si-alkyl group such as Si-(CH3)2. Absorption occur between 2962- 2920 cm-1 due to an aliphatic C-H stretch in CH3 and between 1270-1255 cm-1 due to asymmetric CH3 deformation of Si-CH3.Also, the absorbance at 1100-1000 cm-1 is due to asymmetric Si-O-Si stretching vibration. The absorption from 3700- 3200 cm-1 is due to Hydrogen bonding from ATH.

The size of specimens was approximately  $(1 \times 1 \times 0.2)$  cm<sup>3</sup> cut from the last shed on the high voltage end of each insulator. They were cleaned using isopropyl alcohol to remove deposition of pollution layer. When the spectra of the aged and virgin samples are compared, there were no significant changes in the bonding functional groups in the samples, indicating that the functional group change of the insulator samples was not identified by the ATR-FTIR technique employed.

Figure (12) shows ATR-FTIR absorption spectra as a function of time before and after ageing. The absorbance peaks at 3570 and 3670 cm-1 (O–H), 2960 cm-1 (C-H in CH3), 1260 cm-1 (Si–CH3), 1015 cm-1 (Si-O-Si), and 795 cm-1 (Si–CH3)2 correspond to the molecular vibration. As can be seen from these figures pick of IR spectra of aged insulator samples compared with virgin samples was decreased which means the number of C-H bonds decreases. Pick areas in Si-CH3 in virgin and aged sample are 4 and 1.67 respectively. Also, Peak areas in Si-O-Si in virgin and aged sample are 51.32 and 41.68 respectively. Increasing of ratio (Si-O-Si / Si-CH3) is an index for ageing. In virgin sample, peak area is 12.83 and with increasing ageing it reached to 24.95.



Figure 12. FTIR analysis a) virgin sample, b) aged sample

#### 13. Conclusion

The cracks in the polymer sheath are a risk factor. It is impossible to predict how long it will be before water penetrate between the rod and sheath, and how much time it will take for this to cause insulator failure. So, evaluation and regarding the state of polymer insulators is one of the important preventive affairs which increase the life time of insulator and reliability of transmission and distribution system. Material test released that the number of methyl groups at the SiR surface is reduced by the treatment, as shown by XPS and FTIR-ATR evidence. The aged sample has the highest porosity and roughness of all the samples. The hydroxyl and carboxyl groups were formed when Si-CH<sub>3</sub> and C-H were broken by ageing. The results obtained demonstrate that the hydrophobicity of polymer insulator was found to decrease with ageing and was attributed to formation of carbonyl groups and loss of methyl groups on surface of polymer. Electrical Test results show that the insulators were still in good condition and there was no major degradation observed in 7years

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