



# Performance of Composite Insulators Used for Electric Transmission under Extreme Climatic Conditions

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Composite or polymeric insulators are being used in various parts of the world for high-voltage transmission and distribution lines. In some parts of India, places in the states like Rajasthan and Gujarat experience an increase in the daytime temperature up to 50 °C, while the nighttime temperature reduces as low as 3–5 °C. Because of these extreme temperature variations along with electric stress and humidity conditions, composite insulators have to perform well over their lifetime to ensure the reliability of the transmission network. In the present work, experimental conditions are simulated with temperature variation from 50 to 3–5 °C along with electrical stress, humidity variation, pollution, and ultraviolet radiations. Accelerated aging studies with these stresses are conducted to understand the degradation on the insulator similar to the field conditions. Surface resistivity measurements, leakage current analysis, and surface degradation studies using thermogravimetric analysis, scanning electron microscopy, energy-dispersive x-ray, and Fourier transform infrared spectroscopy (FTIR) are conducted. Some interesting results obtained from the study are presented. Experimentation under extreme conditions with polluted insulators showed considerable degradation which was inferred from the material testing analysis. The insulator slabs on which electrical stress was not applied showed a considerable peak at 1500 cm<sup>-1</sup> in the FTIR spectra, indicating the generation of low molecular weight PDMS chains from the bulk due to UV aging and thermal stress, while the degradation pattern of non-polluted sample was severe compared to the slab treated but was considerably less severe in comparison with the polluted insulator sample exhibiting pollution can considerably increase degradation rate.

**Keywords** composite insulators, leakage current, multistress, surface degradation, temperature, transmission

## 1. Introduction

The climatic conditions of western parts of India are known to be extreme: The summer temperatures rise as high as 50 °C, while the winter temperature reduces as low as 3–5 °C. Under these climatic conditions, evaluation of composite transmission insulators is very important for understanding long-term performance and reliability (Ref 1–3). To further identify the surface degradation of insulators (Ref 4–8), accelerated aging tests are carried out in the laboratory, and insulators are subjected to material analysis where the amount of degradation is estimated with reference to fresh sample. Yoshimura et al. (Ref 5) conducted extensive study on the impact of various stresses on the activity of composite insulators and presented a complete view of the analysis and its relationship with the physical mechanisms taking place in the silicone rubber insulators. In the present investigation, the leakage current measurements are used as a monitoring tool, and the thermal phenomenon occurring during the experimentation is obtained from the frequency transformation of the leakage current signal. The humidity is varied from 40 to 85% to simulate extreme

humid conditions. Rahul et al. (Ref 9) studied the performance of insulators at 50 °C and reported that due to the dynamic nature of silicone rubber and thermal effect of ambient temperature, diffusion of low molecular weight (LMW) polydimethylsiloxane (PDMS) chains from the bulk to the surface occurs, which is known as recovery of hydrophobicity. It is also found that the rate of recovery is faster in case of the aged insulators. Gubanski (Ref 8) and Ma et al. (Ref 10) evaluated erosion resistance of polymeric materials used for outdoor applications and studied the effect of corona and ozone on the mechanical as well as physical properties of silicone rubber material, and they concluded that corona mainly affects the mechanical strength of the material. Priyadarsi et al. (Ref 11) presented their findings based on the study conducted with seasonal variation in temperature with maximum temperature ranging from 35 to 45 °C in summer and 3–10 °C in the winter season. These data were required for the justification of the cycle which is followed for the multistress experiment presently. Various analytical techniques (Ref 12–20) are available to quantify the degradation on the surface; one of them is thermogravimetric analysis, where two quadrants appear in a TGA graph specifying decomposition of ATH (aluminum trihydrate) and the organic component of PDMS as a function of the applied temperature. Arshad et al. (Ref 13) studied the effect of humidity from 40 to 100%; they say that surface resistance decreases by about five times. Jayaram et al. (Ref 14) studied the relationship between harmonic components of the fast Fourier transform (FFT) and the intensities of various thermal phenomena occurring on the surface of the polymeric insulators. They showed that the peak may not be a valid parameter in evaluating the surface degradation intensity of the insulator. Also, the presence of various harmonic peaks with

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various arcing phenomenon taking place was correlated. Suda et al. (Ref 15) presented results pertaining to FFT of leakage current due to dry-band arcing, leakage current waveform is symmetrical, and there is presence of third and fifth harmonic depending upon the severity of the pollution and have shown that flashover can be predicted if the magnitude of third harmonic component in the FFT of the leakage current is increasing with time. The study by Nekeb et al. (Ref 19) has shown that when ultraviolet radiation (of wavelength 280-320 nm) is applied in cyclic manner, it affects the magnitude of the leakage current. Sarathi et al. (Ref 20) investigated the shape of leakage current before and after deterioration and found that if tracking has occurred, then insulator behaves as linear or resistive load and waveform is almost sinusoidal with fundamental as dominating frequency component. IEC 60093 (Ref 21) explains the procedure to measure surface resistance of the flat sample of the insulator. To understand the effect of pollution on the insulators, medium-level pollution as per (Ref 22) is applied and the performance studied. Along with these stresses, ultraviolet radiation is applied to simulate the sunrays. In the experimental investigations, emphasis is on thermal cycling (fluctuation), effect of relative humidity and pollution on the performance of the polymer insulator. Considering the available literature and facts, in the present investigation, efforts are made to extensively study and simulate extremes of climate that prevail in the northern and western part of the country and similar conditions prevailing elsewhere. IEEE Task force (Ref 23) suggested procedure for measuring the surface resistance for the full-scale insulators with application of the DC voltage, and the same is followed in the present investigation for both polluted and non-polluted insulator samples. With this in view, fine-tuning of the available experimental facility has been done in controlled climate chamber for carrying out multistress aging studies under application of electrical stress. The surface degradation of the insulator can be well correlated with the material performance which is supported by analyses like infrared spectroscopy, scanning electron microscopy, etc. Reddy et al. (Ref 24) has studied the ceramic insulator using surface charge simulation method (SCSM) and developed a field reducing electrode near the pin of the insulator.

## 2. Experimental Arrangement for the Investigations

Figure 1 presents the experimental arrangement; the facility consists of a specifically fabricated aging chamber of size 0.762 mt × 0.762 mt × 0.762 mt with provision for high-voltage (HV) wall bushing and leakage current (LC) measurement. In addition, the chamber has can accommodate UV lamps, heater, and humidifier to produce multiple environmental stresses simultaneously, and the temperature is varied from  $5 \pm 2$  to 50 °C.

Four UV lamps of Sankyo Denki G15T8E 15 W are used to simulate effective irradiance of 1 W/m<sup>2</sup>. The climatic chamber is connected to a control panel with precision controllers to control the parameters, an over-current and over-voltage protection is provided for safety. A 230 V, 50 Hz power supply is used for the aging chamber and its control panel, and an HVAC source of 30 kVA with output voltage ranging from 0 to 30 kV rms is used for the experimental investigations. 10 kΩ

resistive shunt is used to measure the leakage current (LC) at the ground side by tapping the voltage across it. Source voltage and LC are monitored using RIGOL make digital storage oscilloscope DS1102E (100 MHz, 1 GSa/s). Figure 2(a) and (b) shows the typical samples used for the investigations. Figure 3 presents the placement of samples one of the test samples is polluted for the investigations. The sample consists of PDMS (polydimethylsiloxane) and ATH (aluminum trihydrate) filler. The samples were obtained from different insulator manufacturing companies. The pollution slurry on the samples is applied as per the solid layer method of IEC 60507; initially the samples being hydrophobic, the pollution slurry was very difficult to be applied. So, the samples were immersed in water for a period of 72 h. This was done to temporarily remove the hydrophobicity of the samples. Then a pollution slurry was prepared, and the insulator is dipped into it to give it a uniform pollution layer. Forty grams of kaolin is mixed with 1000 g tap water with desired NaCl to give it desired conductivity.

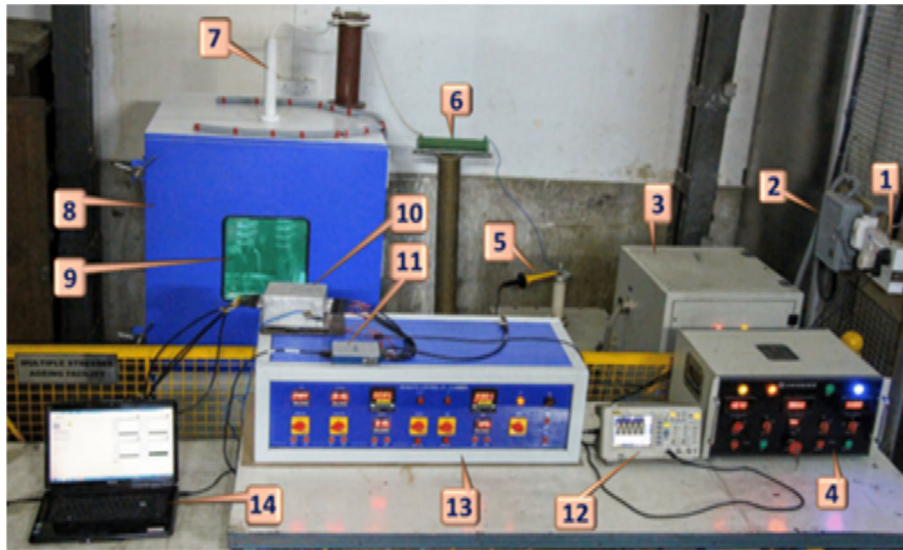
## 2.1 Selection of Parameters for Experimentation

The maximum temperature in summer in some of the places in the country reaches to about 50 °C and in the winter season drops to 3-5 °C, and this variation of temperature on insulator has to endure during lifetime along with humidity fluctuations, typically ranging from 35 to 95%. In the present experimental investigations, we have adopted humidity variations from 40 to 85%, UV of 1 W/m<sup>2</sup> for simulation of solar radiation. Electric stress applied is 10 kV rms for full-scale insulators using the factor of 34.6 mm/kV in accordance with the creepage length of specimen, and this is based on IEC/TR (Ref 25). Considering the selected parameters, multistress cycle is developed and adopted for the experiment as shown in Table 1, and the voltage stress is continuously applied with temperature variation from 50 to 5 °C and relative humidity from 40 to 85%.

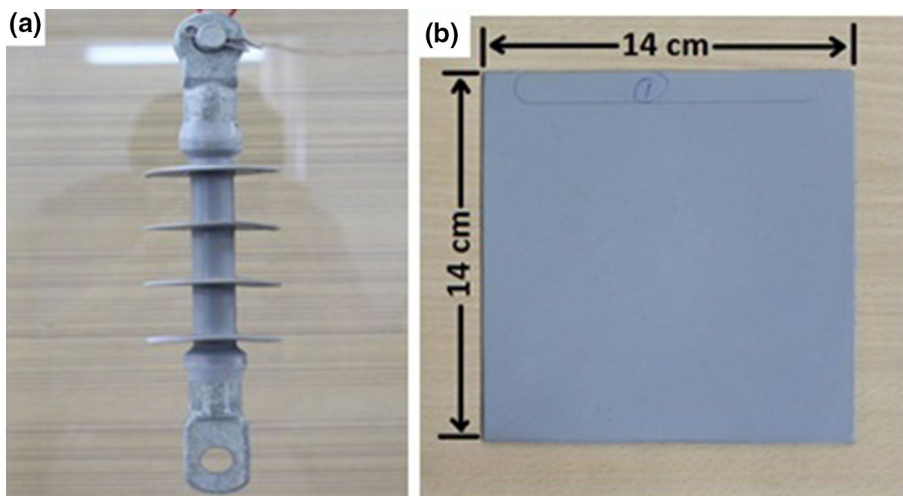
The 24-h cycle is divided into 15 h of night time (6 pm to 9 am) and 9 h of day time (9 am to 6 pm), and the other stresses are varied as per the time of the day. RH is maintained at 85% for 4 h as per standard IEC 62073 (Ref 26) and 40% during 6 to 2 pm, and the total duration of the experimentation was 1000 h.

## 3. Leakage Current Measurements and Analysis

The leakage current measurement is an important parameter which could be used to monitor the degradation of insulator housing surface. During the application of voltage across the composite insulator, the flow of current is dictated by the surface resistance of the material, and a negligible amount of current flows through the bulk of the insulator; due to finite volume resistance, it can be safely ignored in the present study. This surface resistance is sensitive to the inherent material characteristics which change under the application of various stresses or a rational combination of stresses; hence, monitoring of surface leakage current gives valuable information. The harmonic content in the leakage current plot gives information about the nature and intensity of the arcing phenomena taking place along the surface of the insulator (Ref 13, 14). The local heating due to dry-band arcing can raise the temperature at a certain part on the insulator thereby significant changes in material property may occur at that location. Moreover, there



**Fig. 1** Experimental arrangement for multistress aging studies 1: 230 V, 50 Hz power supply, 2: 400 V, 50 Hz power supply, 3: HVAC source, 4: HVAC control panel, 5: high-voltage probe, 6: current-limiting resistor 15 k $\Omega$ , 500 W, 7: high-voltage bushing, 8: aging chamber, 9: UV protected glass, 10: shunt box, 11: NI cDAQ for LC measurement, 12: digital oscilloscope, 13: control panel, 14: NI cDAQ data acquisition in Lab VIEW environment



**Fig. 2** (a) Sample full-length insulator and (b) flat slab

could be other heating phenomenon due to water droplet corona, discharges from the triple junction (metal electrode, silicone rubber and air junction), and thermal effect on the surface leakage current itself, and these activities are captured in the leakage current waveforms. Due to the nonlinear nature of the electrical arc, the harmonics included in the leakage current make the waveform symmetrical. This causes the inclusions of various low order odd harmonics in the leakage current waveform.

At the beginning of experiment as shown in Fig. 4, the leakage current waveform is almost sinusoidal, and the sinusoidal nature can be verified from the presence of high percentage of fundamental component. The sinusoidal nature is observed as the leakage current is controlled by the inherent surface resistance of the composite insulator. The presence of small number of harmonics that can be seen from the FFT of Fig. 4 may be attributed to the discharges which occur near the

high-voltage electrode of the insulator due to local field intensification, or may be due to some noise generated from the voltage source.

The leakage current waveforms are continuously monitored, and a typical waveform recorded after 500 h of experimentation is shown in Fig. 5. The nature of current is seen to become symmetrical due to the heavy inclusion of the odd harmonics, and these harmonics are observed in the current waveform mainly due to dry-band arcing and water droplet corona, high temperature, and the ultraviolet aging causing a temporary loss of hydrophobicity. High humid conditions prevailing in the chamber result in the formation of small water droplets on the surface, and the water droplets in the presence of high electric field along the surface of the insulators broaden and become ellipsoidal. Further partial arcs/discharges from the tip of the droplets start emanating, this is called water droplet corona. The localized heating caused due to water droplet becoming



Fig. 3 Samples inside the climatic chamber

Table 1 Adopted multistress aging cycle

Stress	6 pm-9 am	9 am-2 pm	2-6 pm
Humidity	40%	40%	85%
Temperature	5 °C	50 °C	50 °C
UV	Off	On	On
Electrical	10 kV rms	10 kV rms	10 kV rms

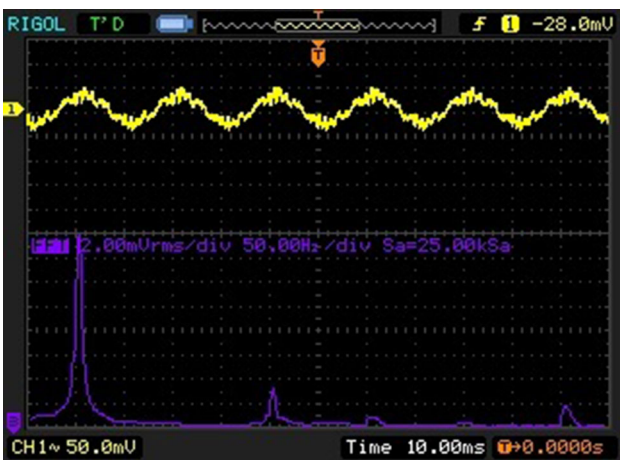


Fig. 4 Leakage current waveform at the start

ellipsoidal is responsible for the loss of hydrophobicity at some local places along the surface. Another mechanism of loss of hydrophobicity includes dry-band arcing. The ellipsoidal water droplets at some point get more elongated and form continuous channel along the surface. This continuous channel has high conductivity due to the presence of pollutants in it. The localized current density is very high along the path; the ohmic

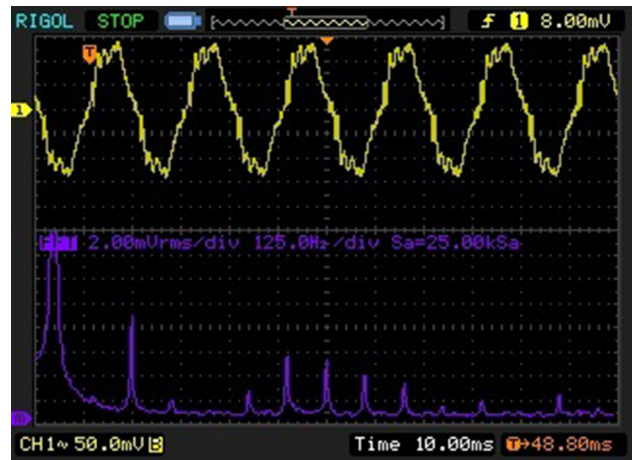


Fig. 5 Leakage current after 500 h of experimentation

loss at some places causes the water to evaporate. The vaporization of the water at discrete locations along the surface causes a considerable buildup of electric field. If the electric field at these locations exceeds the breakdown strength of air, discharges will begin. These discharges are called dry-band arcing. The heating caused by dry-band arcing is much more severe than the corona. The dry-band arcing along with corona causes intense localized heating and oxidation of the methyl group of the polydimethylsiloxane (PDMS). The methyl group is initially oriented toward the surface which results in the lowering of surface energy and renders a hydrophobic surface. As the heating continues the methyl groups get oxidized to silanol, the hydroxyl group of the silanol being polar causes a hydrophilic surface. If further oxidation is allowed, cross-polymerization of the silanol results in the formation of silica.

Figure 6 shows the leakage current waveform after 800 h of experimentation, an aging of the experimentation has resulted in the leakage current becoming almost sinusoidal, and a similar trend was observed at 1000 h. The reasons may be due to that high humidity pollutant might have partially washed away and hence the conductivity has decreased. The high temperature and ultraviolet radiation might have caused the aggravated motion of the low molecular weight (LMW) chains in dispatching to the insulator surface from the bulk. The LMW chains are mainly responsible for the recovery of hydrophobicity. Once the hydrophobicity is recovered, the arcing phenomena are reduced, and hence, the harmonic content of the leakage current is considerably diminished. The recovery of hydrophobicity can be only justified from the infrared spectroscopy.

#### 4. Fourier Transform Infrared Spectroscopy (FTIR) Analysis on Composite Insulators

Fourier transform infrared spectroscopy (FTIR) is conducted to analyze any type of bond breaking or bond forming inside the composite material under investigation. The technique gives a clear indication of the chemical formulation and at the same time indicates any form of chemical degradation that could have taken place on the material surface. Surface properties of polymeric or composite insulators are very important in determining the long-term performance. FTIR is an analytical

technique detecting breaking or making of bonds up to 10  $\mu\text{m}$  surface depth. In the present study, FTIR is carried out using PerkinElmer FTIR/FIR spectrometer equipped with the MIRA-CLE™ single-reflection horizontal attenuated total reflection (ATR) with diamond crystal. FTIR provides percentage transmittance on Y-axis and wavenumber on X-axis. The FTIR spectra obtained after 200 h of experimentation is shown in Fig. 7.

Some important observations made from Fig. 7 are: the band 3500-3700  $\text{cm}^{-1}$  corresponds to the formation of silanol in the PDMS structure. The side-chain methyl groups attached to the PDMS main chain get oxidized in the presence of dry-band arcing and form silanol, and significant presence of silanol in the polluted sample is been noticed. The main chain (Si-O-Si) bond breaking takes place in the band 1000-1130  $\text{cm}^{-1}$  region. From Fig. 7, no significant chain breaking is observed, and thus, it can be interpreted as not much degradation has started in the polymer material. The formation of silanol in the polluted sample is an indication of the initiation of the degradation.

Figure 8 shows the FTIR spectra of the samples after the completion of the experiment (1000 h). The band that show some considerable change in material composition include the formation of Si-OH (3690  $\text{cm}^{-1}$ ) and depletion of ATH (3400-3200  $\text{cm}^{-1}$ ). The formation of silanol is seen for the polluted

insulator. Moreover, no silanol formation is observed on the fresh sample as well as the non-polluted sample. The slab-type sample shows no such peaks, and thus, it can be convincingly inferred that the silanol formation is directly related to the oxidation of the methyl groups attached to the main chain of the PDMS. The formation of the silanol can be confirmed from the reduction in the peak corresponding to Si-CH<sub>3</sub> at 1260  $\text{cm}^{-1}$ . The oxidation to silanol in polluted condition can be attributed to the intense dry-band arcing which would have taken place along the surface of the polymeric insulators under high humid conditions. Moreover, the water particles of crystallization attached to the aluminum trihydrate are almost vaporized. The flatness of the FTIR spectra of polluted insulators in the region 3400-3200  $\text{cm}^{-1}$  is an indicator to the fact that the intense thermal phenomenon might have caused the water to vaporize completely, but the fresh and the unpolluted samples are showing almost overlapping peaks in this band. This is clear indicator of the fact that the thermal phenomenon which could have caused any form of erosion is not present in the unpolluted insulators. The only possible cause of the discharges on unpolluted insulators includes discharges from water droplet corona which are less intense compared to the dry-band arcing.

In case of flat (slab) samples, the peaks at 3690  $\text{cm}^{-1}$  and 3400-3200  $\text{cm}^{-1}$  are not visible, and it is to be noted that electrical stress was not applied to the flat samples, so basically UV and high temperature have played a significant role in covering the peaks due to silanol and the water in ATH. Incidentally, the slab samples have shown some interesting feature which is very much relevant to the study of electrical properties of insulators. In the range 1500-1400  $\text{cm}^{-1}$ , there is a prominent peak appearance (Fig. 8), and this peak is due to the generation of LMW chains in the bulk of the sample. These chains have migrated to the surface and have masked the peak due to ATH. The breaking up of chains due to the UV and high temperature is well documented in the literature (Ref 5). The formation of small siloxane chains can be verified from the peak at around 1008  $\text{cm}^{-1}$ , and the peak of the slab samples has reduced considerably due to main chain breaking. The peak for the non-polluted sample in the band 1500-1400  $\text{cm}^{-1}$  can also be seen but of lower intensity compared to the slab samples. These peaks are not present in case of polluted samples because the intensity of the dry-band arcing has caused the temperature to rise to a level that the LMW has evaporated from the surface. Another interesting fact to further validate is

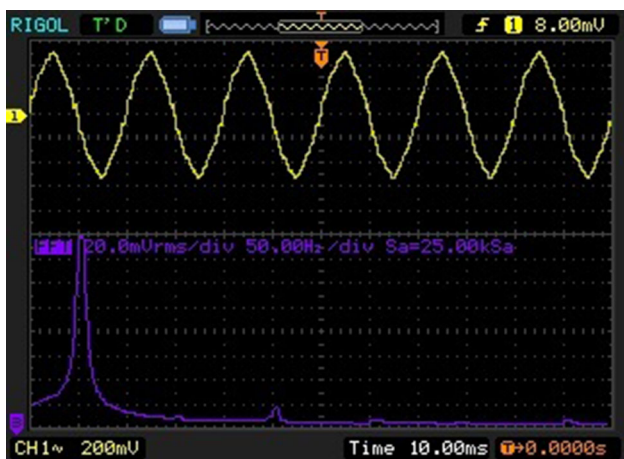


Fig. 6 Leakage current waveform after 800 h of experimentation

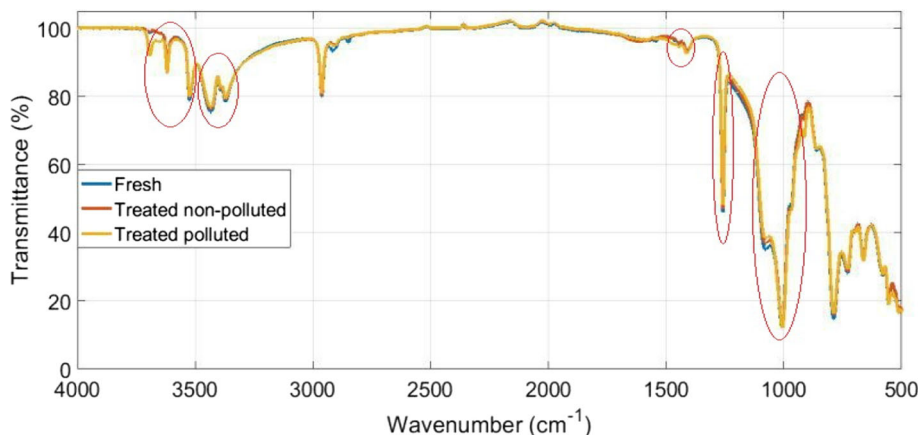
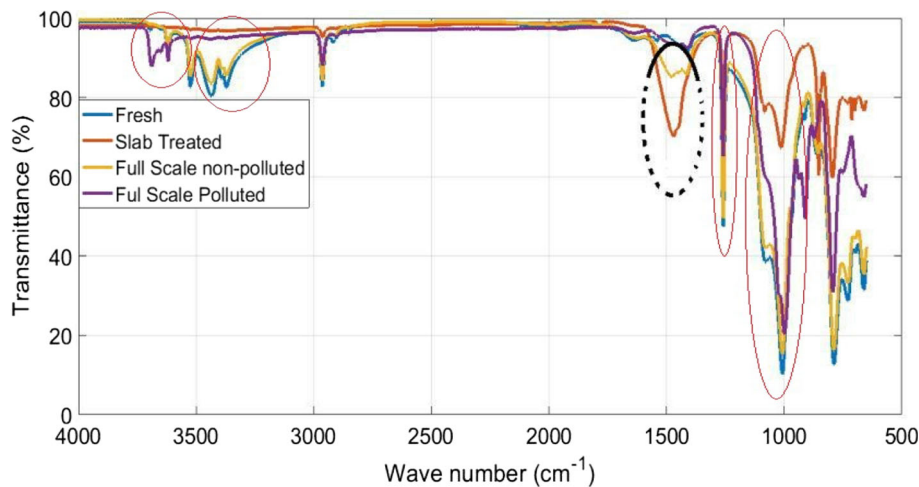


Fig. 7 FTIR spectra after 200 h of experimentation



**Fig. 8** FTIR spectra after 1000 h of experimentation

the reduction in the peak of the main chain in polluted insulator which is not that significant. This is mainly due to the cross-linking of the silanol formed due to oxidation of silica, and thus, the degradation of the polluted insulator is the most intense. Moreover, the peak at  $1500\text{--}1400\text{ cm}^{-1}$  band for the non-polluted insulator has been considerably reduced compared to the slab sample. This is mainly due to the less intense thermal phenomenon which could have affected the evaporation of the LMW molecules from the surface of the silicone rubber insulators. For the flat slab samples, electrical stress was not applied. So, the LMW chains are mainly generated from the bulk in the flat samples due to temperature and UV, but non-polluted samples are under continuous electrical stress. So, the arcing phenomenon which was happening along the surface of the non-polluted insulators is less intense compared to that happening along the surface of the polluted insulators. This arcing (of less intensity) causes vaporization of LMW chains. So, the peak at  $1500\text{--}1400\text{ cm}^{-1}$  is less for the non-polluted insulators when compared to the slab sample. The conclusions from the FTIR spectra can be justified during presentation of results for wettability class.

## 5. Thermogravimetric Analysis (TGA) on Composite Insulators

Thermogravimetric Analysis (TGA) is a method to monitor weight loss of the material with increase in temperature. As per the Arrhenius equation, rate constant of the chemical reaction is dependent on the temperature, and the activation energy required is given as:

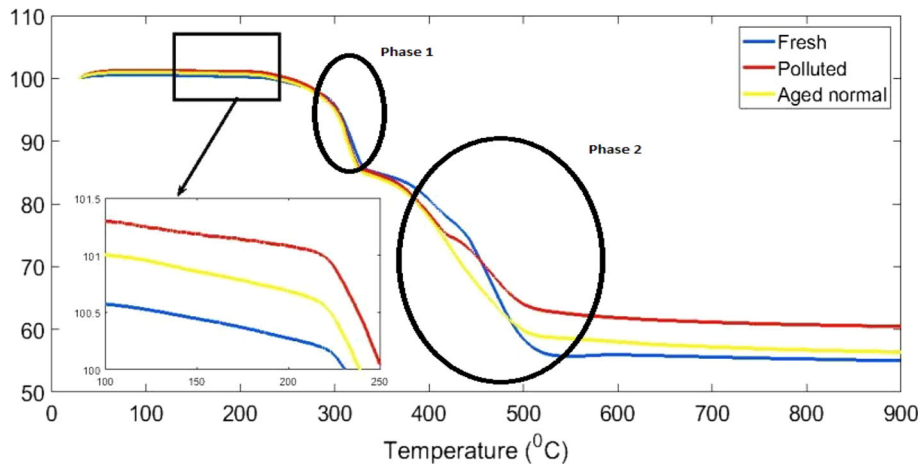
$$k = A \exp(-E_a/RT) \quad (\text{Eq 1})$$

where  $k$  is rate constant,  $T$  is the absolute temperature (in kelvin),  $A$  is the pre-exponential factor, a constant for each chemical reaction.  $E_a$  is the activation energy for the reaction, and  $R$  is the universal gas constant. As the rate of temperature is increased, the reaction rate increases. There could be certain chemical reactions like evaporation of moisture present in the material, and certain gases already present will evaporate. Besides evaporation, cross-linking and photooxidation will take

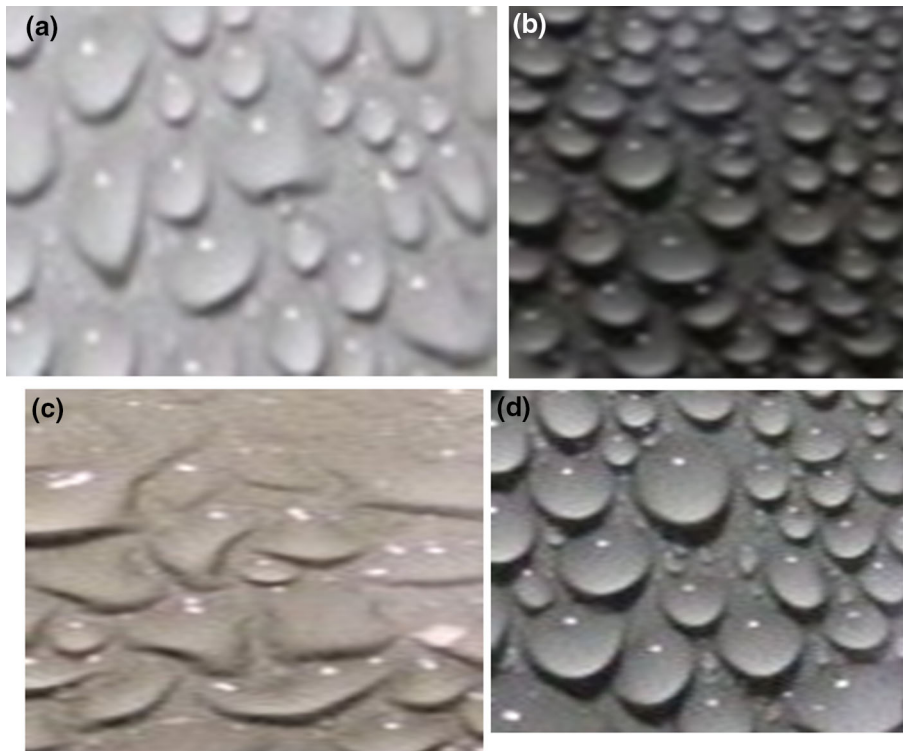
place on the surface of the material which will be responsible for the weight loss of the material.

TGA is conducted to characterize different composition of the aged sample, and Mettler Toledo/SDTA 851e model is used for the analysis. Thermogravimetric (TGA) measurement quantizes the change in mass of the sample that occurs when it is progressively heated at constant rate. The changes relate to the reaction during decomposition and loss of volatile material and reactions with the surrounding atmosphere. The composition of polymer volatilizes at different temperature leading to weight loss allows the composition to be quantitatively measured. TGA examines the mass changes as a function of temperature in the scanning mode. Samples were scanned from 0 to  $900\text{ }^{\circ}\text{C}$ . TGA is an important analysis used to study the thermal stability and organic component change in composite insulators which were subjected to accelerated aging. Referring to the TGA curve shown in Fig. 9, it can be divided into two regions which indicate two different phenomena which are taking place. Phase I indicates decomposition of ATH (aluminum trihydrate) filler, and phase II depicts decomposition of organic component of PDMS (polydimethylsiloxane). In phase I, shift of polluted insulator indicates slight decomposition of ATH, and this shows that some degradation has taken place and ATH is released due to some reaction or due to discharges or dry-band heating on the insulator surface. Phase II indicates decomposition of organic compound in PDMS ( $\text{CH}_3$ ,  $\text{Si-CH}_3$ ) bond broken, and this observation is corroborated with the FTIR results.

The TGA curve shows two-stage decomposition. The first stage corresponds to the ATH filler which has been used in the composite insulator to act as an anti-tracking agent. This ATH decomposition of the polluted insulators along with fresh and non-polluted (aged normal) is very small. This shows that the intensity of arcing along the surface of the polluted insulator is very low causing considerable damage to the filler portion. In the second stage, the polluted sample shows considerable main chain damage, and the percentage weight loss is less for the polluted insulator. This is because underarcing (which might be very low intensity to cause damage to the ATH) has caused a significant damage to the PDMS main chain. The damage is less for the aged normal sample when compared with the polluted sample but more than the fresh sample. This indicates that the dry-band discharges have resulted in main chain



**Fig. 9** TGA plot after 1000 h of experimentation



**Fig. 10** (a) Polluted insulator (400 h), (b) non-polluted insulator (400 h), (c) polluted insulator (1000 h), (d) non-polluted insulator (1000 h)

degradation (evaporation of PDMS short chains) from the surface of the insulators but the damage to the filler is minimal. This is because the filler has water of crystallization attached to it, which takes most part of the heat and prevents track formation. The first weight loss is taking place in the band 260-350 °C, whereas the second weight loss is from 350 to 540 °C. The curves are stabilized after 600 °C.

## 6. Wettability Class Measurements and Analysis

The wettability class measurements are conducted to verify the hydrophobic properties of silicone rubber samples. The measurements are conducted as per procedure cited in Ref 26.

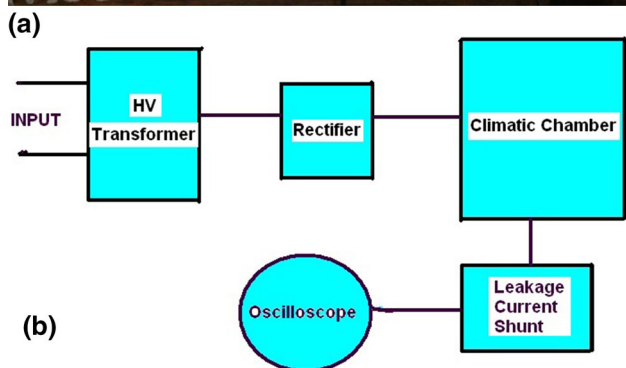
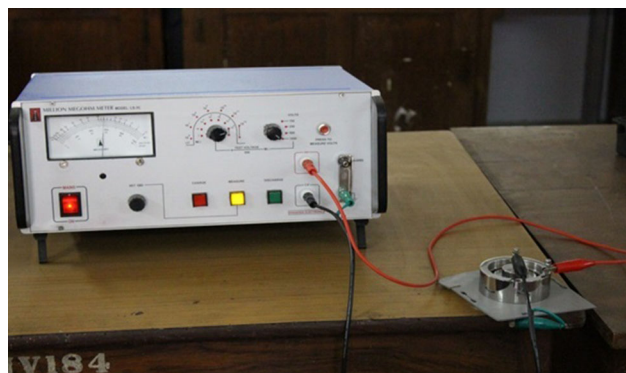
The wettability class measurement requires classifying the hydrophobicity loss of the material surface due to dry-band discharges, water droplet corona, and leakage current. Figure 10(a) and (b) shows the water droplet pictures of polluted and unpolluted insulators after 400 h of experimentation. The polluted insulator shows WC 4, whereas unpolluted insulator shows WC 2 classification. Figure 10(c) and (d) shows the water droplet accumulation on the surface of the polymeric insulators at the end of 1000 h of experimentation; Fig. 10(c) corresponds to the polluted insulator and Fig. 10(d) that of non-polluted insulator.

The wettability class measurement indicates WC 6 for the polluted insulator, but for unpolluted insulator it shows WC 2 after 1000 h of experimentation. These observations are attributed to the fact that application of pollution has caused

an increase in the conductivity of the water channels through which leakage current paths have been established. The sudden drying up of the channels results in the formation of the dry bands, and this has resulted in the development of intense arcs. The arc temperature has caused the LMW chains to evaporate from the surface as indicated in the FTIR analysis, resulting in the loss of the hydrophobic nature on the surface. But non-polluted sample has retained its hydrophobicity; this is mainly due to low value of the leakage current and very low intensity arcs. As seen from the FTIR spectra for the unpolluted insulator, the presence of LMW chains is observed, and these LMW chains are responsible for maintaining the hydrophobicity.

## 7. Surface Resistivity Measurement and Analysis

Surface resistance is a true indication of aging of an insulator, and it gives an indication about severity of contamination on insulator surface. Surface resistivity of insulating material is affected by temperature, humidity, electrical stress, and type of contamination. Surface resistivity measurements are conducted as per IEC 60093; Fig. 11(a) shows the setup for the experiment consisting of a dc generator (50-1000 V) and a three-electrode arrangement, and depending upon the value of resistance to be measured, the voltage level is selected. A three-electrode arrangement as per standard is used to measure the surface resistance of the sample. Typical value obtained for fresh sample is  $3 \times 10^{12} \Omega$ , and for the treated/aged sample, the value was  $1 \times 10^{10} \Omega$ . The measured values clearly depict surface changes and decrease in surface resistance of treated flat sample. For measuring surface resistance of full-scale insulator,



**Fig. 11** (a) Surface resistivity measurements for flat samples. (b) Block diagram of the experimental setup

we have followed the method suggested in Ref 23. The DC rectified voltage of 3.8 kV was applied in accordance with Ref 23 to full-scale insulators placed inside the chamber, and surface resistance/leakage current measurements were conducted for various values of humidity. Table 2 gives the surface resistance values with respect to the relative humidity.

From Table 2, it is clearly established that polluted aged polymer insulators show variation in the surface resistance as a function of humidity. It can also be interpreted that pollution and humidity serve a major role in decreasing the surface resistance, wherein polluted insulator have lost its hydrophobicity resulting in the decrease in surface resistance with respect to non-polluted polymer insulator. The reason for this behavior can be attributed to the loss of hydrophobicity under the presence of high humidity. The pollutant slurry, which was applied on the surface of the insulator, will be conducting once wet, and under high humidity, the water vapor helps the slurry to make it conduct. Once conduction starts, the heat produced due to conduction will cause the water to evaporate and dry bands to be formed. The high electric field across the dry band will cause the arcs across it, and the heat from the arc will cause evaporation of the LMW chains from the surface. Thus, the hydrophobicity will be lost, and hence in this way, high humidity indirectly affects surface resistivity and hydrophobicity.

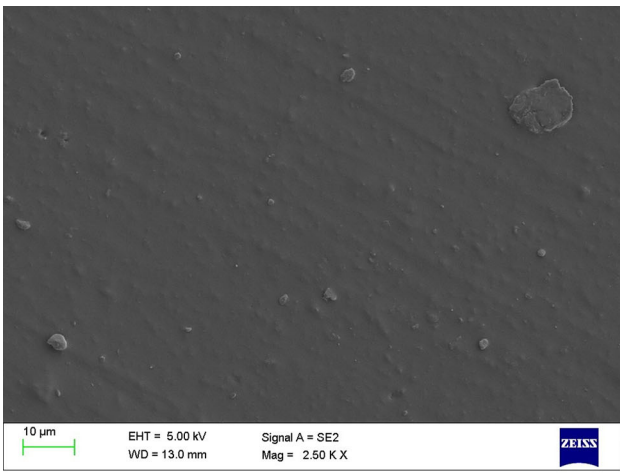
## 8. Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Analysis (EDAX)

SEM is conducted to detect morphological change that may have taken place on the surface of insulator. The SEM picture of the fresh sample is shown in Fig. 12(a) and that of the polluted insulator is shown in Fig. 12(b). The polluted sample has large number of whitish spots on the silicone rubber sheds, while the fresh sample is shows no such marks. The EDAX of the samples (shown in SEM) has been conducted to detect the elemental composition of the surface. The fresh sample shown in Fig. 13(a) contains less oxygen in comparison with polluted and aged sample (Fig. 13(b)). This is a clear indication of the fact that severe oxidation has taken place on the surface of polluted aged sample due to intense dry-band arcing along the surface due to high humidity and relatively low surface resistivity. The aluminum level has also decreased in the polluted/aged insulators as shown in Fig. 13(b), and the decrease in aluminum level is also indicated in the FTIR spectra. The magnitude in decrease in aluminum in the EDAX plot is due to the loss of ATH filler owing to intense heating phenomenon, and moreover, the silicone level has increased in the polluted insulators. The simultaneous increase in oxygen and silicone is clearly an indicative of the fact that intense

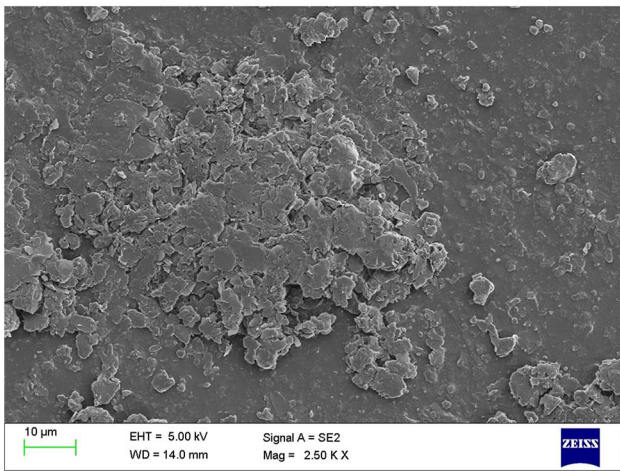
**Table 2** Surface resistance values at different humidity

Insulator	Humidity, %	Surface resistance
(a) Polluted	60	$9.5 \times 10^{10} \Omega$
(b) Non-polluted	60	$1.24 \times 10^{11} \Omega$
(a) Polluted	70	$7.4 \times 10^9 \Omega$
(b) Non-polluted	70	$9 \times 10^{10} \Omega$
(a) Polluted	85	$3.2 \times 10^8 \Omega$
(b) Non-polluted	85	$5 \times 10^{10} \Omega$





(a)



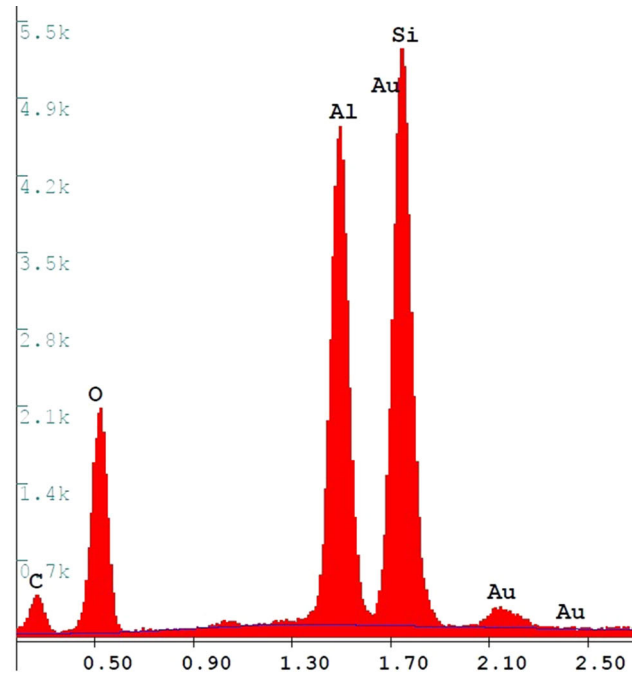
(b)

**Fig. 12** (a) SEM picture of fresh sample and (b) SEM picture of polluted aged sample

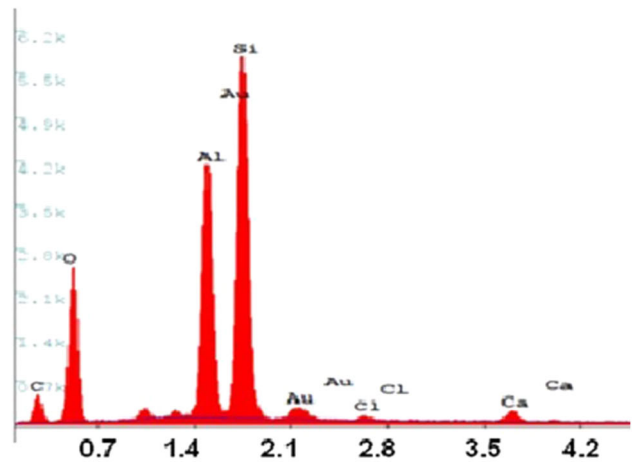
oxidation resulting in the formation of silica by cross-linking of the silanol groups could have resulted in case of polluted samples, the silica is responsible for the powder like appearance on the SEM pictures.

## 9. Tensile Strength Measurement

Tensile strength and percentage elongation at break the strength properties are used as a general indicator of the quality of the rubber compound. The tensile properties were measured using dumb-bell-shaped specimen as per IS 3400 (Ref 27). Dumb-bell-shaped samples for each composition were used. Tensile test was conducted by stretching the sample in the test machine until it breaks as. The amount of force required to break the material in tension and extent to which the specimen stretches or elongates to that breaking point are measured. Mechanical strength is one of the main parameter, and hence, tensile strength measurement is carried out for assessing and analyzing this parameter, and there are diverse chemical reactions which takes place on the surface of polymeric material like (a) increase in oxidative cross-linking, (b) presence of OH group, (c) cross-linking, and (d) hydrolysis.



(a)

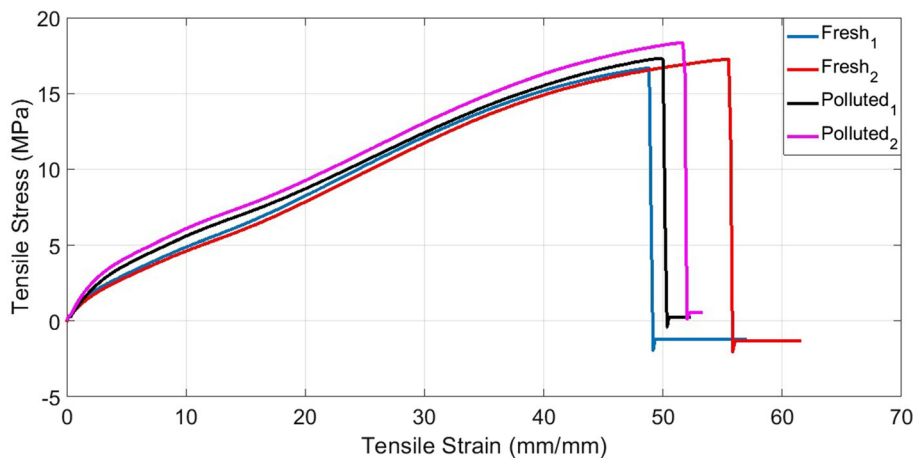


(b)

**Fig. 13** (a) EDAX of fresh sample, (b) EDAX of polluted aged sample

All these chemical changes affects the electrical and mechanical properties of the polymer insulator, and one of the probable reason could be UV and high polymeric surface temperature because of dry-band arcing, and for outdoor performance, insulator must retain mechanical integrity, and mechanical damages can be like cutting or splitting, which are not acceptable since they can expose FRP (fiber-reinforced plastic road) which can lead to brittle fracture.

Stress-strain measurements were performed with Instron 5967 screw-driven Universal Testing Machine (UTM) with load capacity of 30 KN at crosshead speed of 200 mm/min, and testing continued till the rupture of the sample. Photooxidation can also reduce elongation break. After experimentation for 1000 h, elongation break test is performed to check material integrity of the polymer housing results as shown in Fig. 14. It is clear that elongation break of treated aged sample is less than



**Fig. 14** Elongation break of treated sample compared to fresh sample

the fresh sample reason can be attributed to thermal cycling, and further FTIR has shown breaking of main chain Si-O-Si which is the reason for depolymerization, and there can be cross-linking reaction with the presence of UV, which is the factor for reduction in the elongation break of the treated sample with respect to the fresh sample. TGA analysis confirms the decomposition. Percentage reduction in break point extension is 4% which is not alarming and that could be because of recovery of hydrophobicity which happens at higher ambient temperature. So, recovery of hydrophobicity might have helped for reducing further degradation on the surface of polymer insulator, and in EDAX analysis, there is hardly any reduction in silicone content that gives an indication for the recovery of hydrophobicity might have taken place.

## 10. Conclusions

The aging study on composite insulators is attempted wherein insulators were subjected to extremes of climatic conditions with effect of pollution, humidity, UV, temperature, and electric stress. The major concern in insulator assessment is the surface properties of the material, and various material analyses were conducted to access degree of degradation on insulator surface.

Considerable surface leakage current along with dry-band arcing is seen to degrade the hydrophobic nature of the insulation. The evaporation of the low molecular weight chains is observed from the FTIR of the full-scale insulators, subjected to electrical field stress. But for the flat samples (E-field stress not applied), a sharp peak was observed in the  $1500\text{ cm}^{-1}$  region of the FTIR, which indicates the breakdown of main chains due to high temperature and UV. It is seen that even if electrical stress is absent, considerable main chain breaking is observed.

The application of electrical stress causes the LMW to evaporate from the surface resulting in the oxidation of the side-chain methyl group, along with formation of silanol which is responsible for the loss of hydrophobicity.

The white spots observed in the SEM are silica which makes the surface powdery; the silica is formed mainly by the cross-linking of the silanol groups. Pollutant with the water droplets resulting with high humidity has given rise to the high

conductivity on the surface. This has resulted in the increase in surface conductivity along with the flow of high leakage current followed by dry-band formation and arcing.

The dry-band arcing resulting in loss of hydrophobicity further could lead to pollution flashover. So extremes of thermal and humid conditions along with electric stress could have a strong correlation with polymer degradation happening in the field.

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