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Performance of HTV SiR as Outdoor insulation at High Altitudes

Muhammad Amin[1] and Mohammad Akbar[2]

1. Electrical Engineering Department, COMSATS Institute of Information Technology, Wah Campus, prof_amin01@yahoo.com
2. Electrical Engineering Department, Wah Engineering College, University of Wah, akbarm3@hotmail.com

Abstract

Because of several advantages over traditional ceramic insulators, polymeric insulators are gaining popularity in electrical power transmission and distribution systems as outdoor insulation. However, being organic in nature, these insulators degrade in outdoor environment and their life-expectancy needs to be assessed in the environment prevailing at potential sites of outdoor installation. For first ever study of polymeric insulators in Pakistan, HTV-SiR insulators, having promising credentials internationally, were chosen to undergo assessment in the simulated environment representing Pakistani conditions. Aging of these insulators was investigated under varying level of UV radiations and pollution to reproduce Pakistani conditions prevalent in different regions. Because of some practical consideration, the aging study was conducted at low-pressure conditions to simulate high altitude applications. The aged samples were analyzed using ATR-FTIR spectroscopy, SEM, hydrophobicity tests and through physical observations. The study revealed that, though these insulators experienced more degradation at low pressure but still maintained acceptable performance.

Key Words: Degradation, Polymeric Insulators, UV-radiation, FTIR, Hydrophobicity.

1. Introduction

The research in this paper deals with performance assessment of polymeric insulators at high altitudes representing mountainous areas in Pakistan. This is a pioneering work and first of its kind ever conducted on aging of polymeric insulators at low pressure to simulate high-altitude conditions where strong UV radiations are experienced [1]. The colder environment at high altitude makes heat-effect on aging as irrelevant. In this study therefore, low-pressure and low temperature were maintained along with a combination of varying intensity of UV light representing day and night conditions. The material chosen in this investigation was HTV-SiR which has shown promising performance in international studies [2,3].

The ultra violet light which is one of the major factors for degrading polymeric material, originates from sun, corona and dry-band arcing. The wavelength of energy from sunlight that is destructive to polymers is between 250 and 320 nm. The destructive energy constitutes less than 5% of total radiation reaching the surface of the planet. The absorption of the UV radiations results in chemical degradation of the polymer structure which can affect the dielectric and weather-resistant properties of the polymer. The rate at which degradation occurs depends on the intensity and wavelength of the radiation which vary with season, elevation, latitude, and time of the day.

For foreseen-able practical height of 2600 m of transmission lines in Pakistan, the atmospheric pressure reduces to 55 cm Hg while in low-lying area of small height of about 150 m above sea level, it

is 74.5 cm Hg [4,5]. The intensity of UV radiation increases at the rate of 4 % for every 305 m (1000 ft) increase in height [6,7]. At a height of 2600 m, the intensity of UV radiation shall be 30.8 % higher than its intensity at sea level. The average intensities in Pakistan during winter and summer are 1.175 mW/cm^2 and 1.875 mW/cm^2, respectively [8,9]. At a height of 2600 m, this translates to 1.53 mW/cm^2 and 2.54 mW/cm^2 in winter and summer, respectively.

To enhance severity of aging in the present study, the intensity of UV radiation was raised to twice the average value (i.e., to 4.9 mW/cm^2). The temperature decreases with height at the rate of 5.5^{o}C for every 1000 m [10]. The average temperature in Pakistan is 20^{o}C and 40^{o}C in winter and summer, respectively. When considered at a height of 2600 m, it reduces to 15.5^{o}C and 35.6^{o}C in winter and summer, respectively. Accordingly, the average of winter and summer temperature at the height of 2600 m (i.e 25.6^{o}C) was used in the present study. The pollution severity level was kept from medium to high.

This paper presents the outcome of a aging investigation on polymeric insulators at low pressure under polluted, unpolluted, energized and un-energized test conditions.

2. Experimental Arrangement

The study was conducted in a transparent glass vacuum chamber of 18 cm diameter and 20 cm height contained in a cubical box of 60 cm x 60 cm x 60 cm. The UV radiations were applied by UV lamps installed on three sides of the cubical box. UV lamps manufactured by Sankyo Denki Corporation, Japan were used. Each lamp gave UV output equal to 5W and emitted radiations having wavelength of 253.7 nm. The experimental setup is shown in Fig. 1.

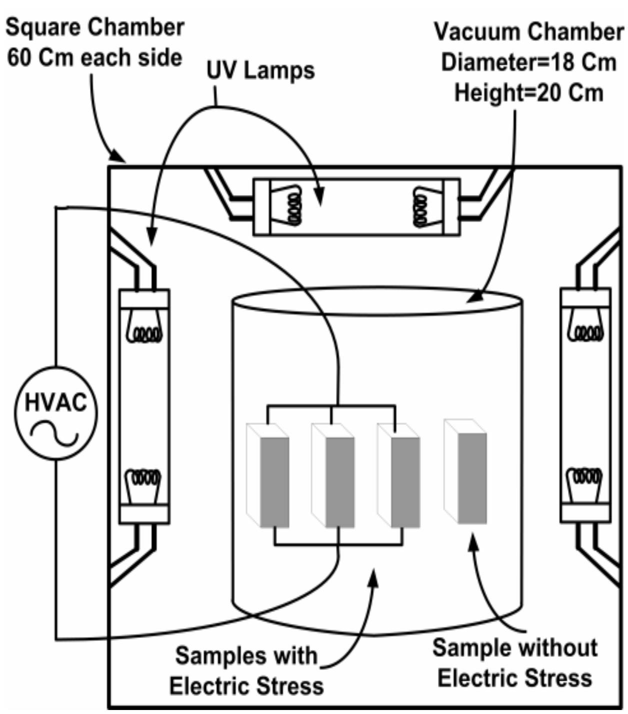


Fig 1. Experimental setup.

The main goal of present investigation was to see as how polymeric insulators age on high–altitude transmission lines operating at various altitudes whether experiencing clean or polluted environment. The study also intended to understand as how such material will perform for other applications where electrical-stressing shall not be applicable. The experiments were accordingly designed to include a set of parameters for each case study which will be described below.

2.1 Aging at low altitude

To undertake this study, 0.5 cm thick rectangular HTV-SiR plates of two different sizes measuring 8 cm x 11 cm and 16 cm x 22 cm were used. For better and broader understanding of aging, the samples were prepared differently. Some samples were kept un-energized but with varying degree of pollution. Similarly, other samples were energized at 35 mm/kV with or without pollution. All samples was distinctly designated and were exposed to the same intensity of UV radiations. The studied eight samples, their sizes, pollution level and other test parameters are summarized in other test conditions are summarized in Table 1. All the eight samples were placed in the cubical box and remained exposed to UV radiation of 4.9 mW/cm^2 for 35 days. Two samples (A7 and A8) however, remained exposed to UV radiation up to 49 days.

2.2 Aging at medium altitude

2.2.1 *Studying aging under polluted conditions*

Four polluted Samples, each measuring 4 cm by 4 cm were placed in a vacuum chamber made of transparent glass. This chamber was further placed in a cubical box shown earlier in Figure 1. The objective was to study aging of polluted polymeric insulators at a medium altitude. The design of this experiment and associated test parameters are given in Table 2.

2.2.2 Studying effect of electric stress and direct sunlight on aging

In this study, five samples (C1, C2, C3, C4 and C5) were chosen. The first four samples were placed in the vacuum chamber which in itself was contained in a transparent cubical box. The fifth sample (C5) was placed in another vacuum chamber but was exposed to direct sunshine. Other test parameters are given in Table 3. As shown in this table, the test pressure was kept constant at 50 cm Hg which is representation of a medium altitude.

Table 1. Aging parameters of polymeric insulators at low altitude.

Sample designation	Sample Size b x l (cm x cm)	Sample electrical status	Pollution level (mg/ cm^2)	Test pressure (cm Hg)	Exposure to UV radiation of 4.9 mW/cm^2 (days)
A1	8 x 11	Un-energized	0.17	72	35
A2	8 x 11	Un-energized	0.45	72	35
A3	8 x 11	Un-energized	0.68	72	35
A4	8 x 11	Un-energized	0.70	72	35
A5	16 x 22	Un-energized	0.86	72	35
A6	16 x 22	Energized	0.86	72	35
A7	16 x 22	Energized	0 (clean)	72	35 42 49
A8	16 x 22	Energized	0 (clean)	72	35 42 49

Table 2. UV-radiation aging of polymeric insulators at medium altitude.

Sample designation	Size of sample l x b (cm × cm)	Pollution level (mg/cm^2)	Test pressure (cm Hg)	Intensity of UV radiation (mW/cm^2)	Exposure to UV-radiation (days)
B1	4 × 4	0.31	50	4.9	60
B2	4 × 4	0.32			
B3	4 × 4	0.6			
B4	4 × 4	1.29			

Table 3. Aging at medium altitude under different stress conditions.

Sample designation	Sample size l x b (cm×cm)	Electric stress (mm/kV)	Test duration (days)	Test pressure (cm Hg)	Temperature inside vacuum chamber (^{o}C)	Intensity of UV radiation (mW/cm^2)
C1	4 × 4	35	60	50	25.5	3.75
C2	4 × 4	40				
C3	4 × 4	45				
C4	4 × 4	50				
C5	4 × 4	0	125	50		Sunshine

2.3 Aging study at different altitudes

This study was intended to understand aging of polymeric insulators at different altitudes. Here, polymeric insulators of three different chemistry were investigated. Two samples of each type; one under energized and the other under un-energized conditions were tested. The energized samples were stressed at 35 mm/kV. Details of each sample and other test conditions are given in Table 4. Using samples D1, D2, D3, another experiment was also performed where these samples were aged at a test pressure of 50 cm Hg for different durations spanning upto 125 days.

3. Results and Discussions

Through various experimental designs, samples of polymeric insulators were exposed to aging under different set of conditions given in Tables 1 through 4. The results were carefully checked and analyzed using various analytical tools and techniques. Each aged sample underwent physical inspection for any possible signs of cracking, chalking, erosion and discoloration etc.

It became known through visual observation that all investigated samples retained their surface conditions intact without any visible sign of degradation [11,12]

3.1 FTIR spectroscopic analysis

3.1.1 Description of FTIR spectroscopic method

Since aging of polymeric material covers changes in the local bond-structure of the material and its interaction with the molecules of other materials [13], the same can be identified using Fourier Transform Infrared (FTIR) technique. The FTIR spectroscopy provides structural information and identifies compounds. It can also be used for quantitative measurement as well. It is mostly used to identify organic compounds but in some cases, inorganic compounds can also be identified. The present study employed state-of-the-art FTIR spectroscope, Model Nexus 6700.

Table 4. Aging study of different polymeric insulators at various altitudes.

Samples designation	Sample stressing condition	Size of sample	Pressure (cm Hg)	Duration (days)	Material of sample
D1	Without electric stress and with solar radiation	5 cm × 30 cm	24	7	HTV-SiR rod without ATH and without filler surface treatment.
			50	7	
			60	7	
D2	With electric stress and solar radiation	5 cm × 30 cm	24	7	HTV-SiR rod without ATH and without filler surface treatment
			50	7	
			60	7	
D3	Without electric stress and solar radiation	15 cm × 15 cm	24	7	HTV-silicone plate containing silica and ATH
			50	7	
			60	7	
D4	With electric stress and solar radiation	5 cm × 30 cm	24	7	HTV-silicone plate containing silica and ATH
			50	7	
			60	7	
D5	Without electric stress and solar radiation	5 cm × 30 cm	24	7	HTV-silicone rod containing silica and ATH
			50	7	
			60	7	
D6	With electric stress and Solar radiation	15 cm × 15 cm	24	7	HTV-silicone plate containing silica and ATH
			50	7	
			60	7	

For polymeric insulators, the absorbance at peaks between wave numbers 1004~1008 and 1254~1259 is taken to estimate its deterioration. For this purpose, the portion of graph between wave number 1000 and 1258 is taken and a few lines are drawn as shown in Figure 2. The length of line AB is divided by the length of line CD. This ratio is determined from graph for each tested sample and is called APR_{TS}. This ratio is also measured for virgin sample. The reference value found by FTIR of virgin sample is called, The APR_{OS}. APR_{TS} and APR_{OS} are then compared to find the shifting in absorbance peaks that directly represents deterioration according to following formula.

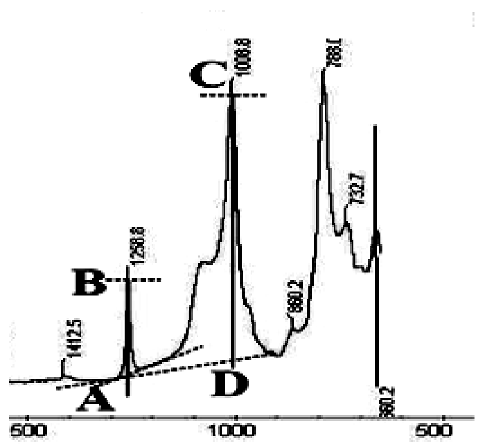


Fig 2. Analysis of aging of polymeric insulators using FTIR spectroscopic technique Change of absorption peak ratio - $\dfrac{APR_{TS} - APR_{OS}}{APR_{OS}}$

For example, from graph shown in Fig 2, the degradation is calculated as;

{(0.92-0.85) / 0.92} x 100 = 7.6 %

As per experimental design, various samples of polymeric insulators were aged differently as given earlier in Tables 1 through 4. The aging assessment was carried out using FTIR analysis technique and results are presented and discussed in the following sections.

3,1.2 Samples aged at low altitude

The aging of samples A1 to A8 given in Table 1 was measured and the results are given in Table 5. It is clear from Table 5 that at pollution level of 0.68 mg/cm^2 and above, no degradation occurred. Moreover, energized clean plate degraded more than its un-energized counterpart

Table 5. Aging conditions and measured degradation by FTIR spectroscopy

Sample designation	Exposure to UV radiations (days)	Pollution level (mg/cm^2)	Measured degradation (%)
A1	35	0.17	-6.7
A2	35	0.45	-6.5
A3	35	0.68	0
A4	35	0.70	0
A5	35	0.86	0
A6	35	0.86	0
A7	35	0	-6.29
(Un-	42	0	-8.66
energized)	49	0	-20.94
A8	35	0	-12.70
(Energized)	42	0	-12.28
	49	0	-23.58

The pollution solution was prepared using 40 g/l of Tonoko and sodium chloride of varying amount to achieve desired pollution severity. To better see the trend of aging under un-energized and energized conditions, the data given in Table 5 for insulator samples A7 and A8 is graphically shown in Figure 3. In this figure, the black curve is the representation of measured difference of degradation between energized and un-energized samples as a function of duration of UV exposure. The blue curve (which is exponential in character) is approximation of original graph through curve fitting which can be expressed by an equation, $y = 56.427\, e^{-0.0634x}$. This shows that difference in aging (with and without electric stress) is decreasing exponentially, implying that the effect of electric stress may vanish after some time [14].

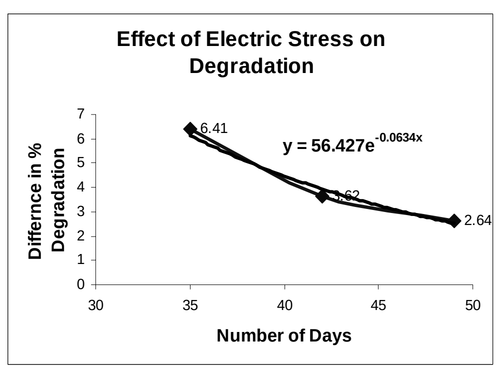


Fig. 3 Degradation under electric stress.

Similarly, aging of samples A7 and A8 measured for different durations of UV exposure is plotted in Figure 4 to see the tendency of aging. This figure shows that the effect of UV radiations on clean insulators both under energized and un-energized conditions. It is clear that degradation increases with duration of exposure to UV radiation. The energized sample degrades more than its un-energized counterpart. However, the degradation pattern is almost same which implies that electric stress has its own effect on material aging. However difference of degradation between them diminishes with increase in exposure time. The maximum measured degradation was 23.58 %.

3.1.3 Aging at Medium altitude

a) Effect of pollution severity

Four samples of polymeric insulators (B1 to B4) aged at a medium altitude (corresponding to 50 cm Hg) as per Table 2, were analyzed through FTIR technique and degradation was measured with particular interest on the effect of pollution severity. The percentage degradation of these samples are given in Table 6.

Table 6. Aging of polymeric insulators under polluted conditions at medium altitude.

Sample designation	Exposure to UV radiations of 4.9 mW/cm^2 (days)	Pollution level (mg/cm^2)	Measured degradation (%)
B1	60	0.31	-9.716
B2	60	0.32	-15.38
B3	60	0.60	-17
B4	60	1.29	0

From Table 6, it is clear that material degradation increases with the increase of pollution severity up to 0.6 mg/cm^2. However, as pollution severity is increased substantially, the degradation stops. It appears that heavy pollution provides a protective layer which makes it immune to any damage of UV radiation.

b) Effect of Electric Stress

To understand the effect of electric stress, four samples (C1 to C4) each measuring 4 cm x 4 cm were aged under same conditions but were stressed differently as shown in Table 3. The test pressure was 50 cm Hg which represented medium altitude. The fifth sample (C5) which was also kept in a pressure chamber at 50 cm Hg was exposed to direct sunlight. Aging of these samples measured through FTIR technique for each value of electric stress is given in Figure 5.

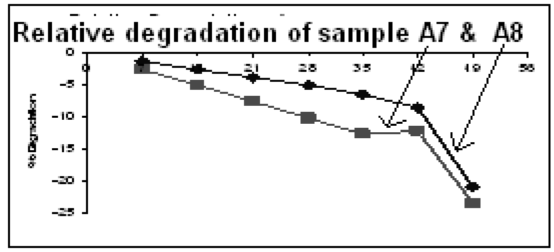


Fig.4. Relative degradation of samples A7 and A8.

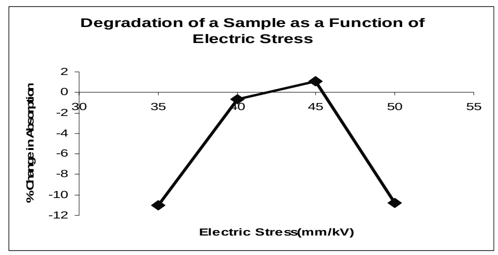


Fig.5. Sample degradation as a function of electric stress

It is clear from Fig. 5 that the samples have shown large degradations at two stress levels of 35 mm/kV and 50 mm/ kV, while at 40 mm/kV and 45 mm/kV, almost no degradation occurred. This indicates that there might be an optimum value of electric stress for a specific material under certain environmental conditions. For the material under investigation, the optimum stress is between 40-45 mm/kV. The FTIR results of fifth (C5) sample are shown in Table 7.

It is clear from Table 7 that sample C5 have shown no degradation even after exposure of 125 days to direct light which implies that the low-pressure of 50 cm Hg, has no effect on material degradation. This may be attributed to recovery during night-time when there is no UV radiation. Other four samples (C1 to C4) under energized conditions have shown some degradation which can be attributed to electric stress.

3.1.4 Samples aged at different altitudes (Short term aging)

In this experiment, an attempt was made to study aging of three polymeric insulators having different chemistry which were earlier identified in Table 4 as D1, D2 and D3. Each sample was used in pair; one energized and the other un-energized. This experiment catered for short term aging of one week. The aging at different values of test pressure was measured through FTIR technique and the results are given in Table 8.

Table 7. Degradation of C5 exposed to direct sunlight at a pressure of 50 cm Hg.

Sample exposure (days)	Absorption ratio	Change in absorption ratio (%)
Original (0)	0.92	
70	0.92	0
95	0.92	-0.58
125	0.92	-

It is clear from Table 8 that for D1 (un-energized sample), there is a decrease in the "percentage change in absorption ratio" as we increase the pressure. As pressure goes closer to normal atmospheric pressure, the degradation decreases almost linearly. As for its counterpart energized sample (D2), it was observed that with the increase in pressure, there is an increase of the percentage change in absorption ratio. This means that for this material, electric stress has caused accelerated aging. Similarly, in case of samples D3 and D4 (which have different chemistry than D1 and D2), with the increase in pressure there is a decrease of the percentage change in absorption ratio. Here, it is observed that this particular material has tendency to degrade more at low pressure.

For sample D5, it was noticed that with the increase in pressure varying from 24 cm Hg to 50 cm Hg, there is an increase of the percentage change in absorption ratio but as the pressure increases from 50 cm Hg to 60 cm Hg, there is a decrease of the percentage change in absorption ratio. For sample D6 (which is energized counterpart of D5), it was noticed that with the increase in pressure, there is a decrease of the percentage change in absorption ratio. Compared to the un-energized sample (D5), the energized sample (D6) showed more degradation indicating thereby that electric stress has the accelerating effect. The same behavior was observed in case of samples D1 and D2.

In another study, sister samples of D1, D3 and D5 were aged at a given pressure of 50 cm Hg for different durations of exposure. The test conditions and measured absorption ratio for each case are given in Table 9.

It is obvious from Table 9, that sample D1 (HTV-SiR rod without ATH and without filler surface treatment) is degrading more compared with samples D3 and D5 (i.e HTV-silicone rod containing silica and ATH and HTV-silicone plate containing silica and ATH)

Table 8. Degradation of polymeric insulators of different chemistry.

	Absorption ratio						**Change in absorption ratio (%) (degradation)**						**Duration of exp. at low pressure (days)**
Sample / Pressure	D1	D2	D3	D4	D5	D6	D1	D2	D3	D4	D5	D6	
Normal	0.72	0.72	0.94	0.72	0.92	0.92							
24 cm Hg	0.78	0.63	0.85	0.87	0.92	0.79	-9.03	-11.83	-9.8	-5.64	0.90	-15.28	07
50 cm Hg	0.66	0.62	0.84	0.92	0.91	0.91	-7.63	-13.87	-6.46	-0.132	-0.51	-1	07
60 cm Hg	0.68		0.91	0.91	0.91		-5.53		-3.03		-0.32		07

Table 9. Degradation of the samples for extended exposure.

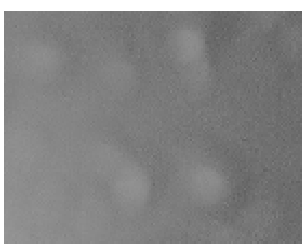
Pressure	Absorption ratio			Change in absorption ratio (%) (degradation)			Exposure at low pressure (days)
	Sample			Sample			
	D1	D3	D5	D1	D3	D5	
Normal	0.72	0.92	0.92				
50 cm Hg	0.57	0.92	0.92	-21	0	0	70
50 cm Hg	0.67	0.92	0.92	-7.29	0	-0.58	95
50 cm Hg	0.60	0.88	0.92	-16.46	-4.59	0	125

3.2 Hydrophobic analysis

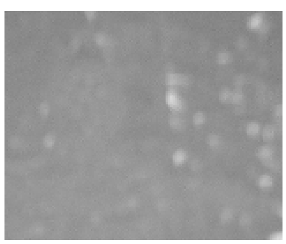
3.2.1 STRI method

The insulator samples which were aged under a variety of conditions (earlier given in Tables 1 through 4) were examined for their surface hydrophobicity characteristics.

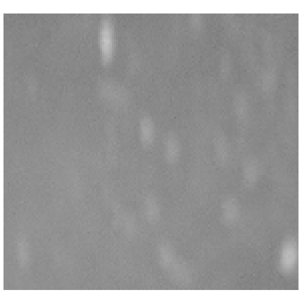
For samples aged as per Table 1, STRI method which is simple to apply was used to determine hydrophobicity performance [15]. The pertinent photographs are shown in Figure 6 where from hydrophobicity classifications were determined which are given in Table 8.



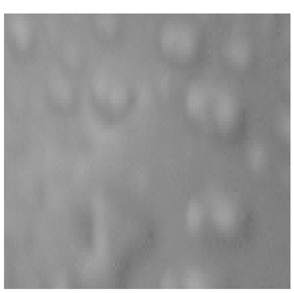
(a) Sample A1 (0.17mg/cm^2)



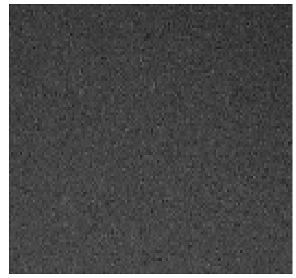
(b) Sample A2 (0.45 mg/cm^2).



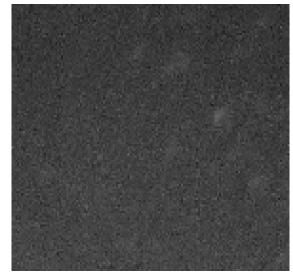
(c) Sample A3 (0.68 mg/cm2)



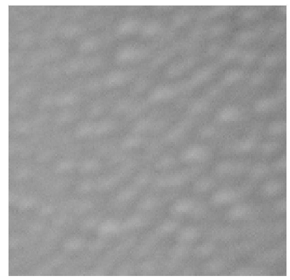
(d) Sample A4 (0.7 mg/cm2).



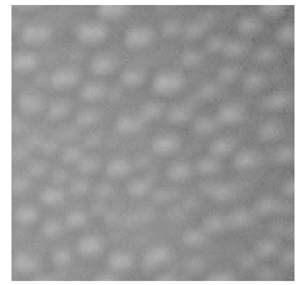
(e) Sample A5 (0.862 mg/cm2)



(f) Sample A6 (0.862 mg/cm2).



(g) Sample A7 (clean)



(h) Sample A8 (clean)

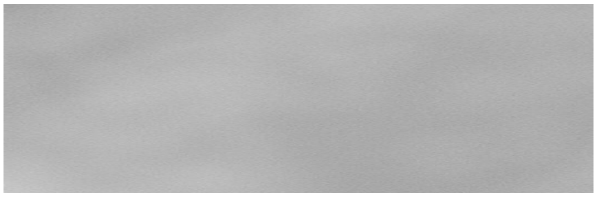
Fig. 6. Photographs of aged samples in Table 1 for STRI classification.

Table 10 Hydrophobicity classifications of samples aged at low altitude (Table 1).

Contact angle (degree)	**Sample designation**	**Pollution Severity (mg/cm^2)**	**Absorption peak at 1258**
121	A1	0.17	0.217
122	A2	0.45	0.219
130	A3	0.68	0.287
140	A4	0.7	0.262
115	A5	0.862	0.258
109	A6	0.862	0.211
-	A7	clean	0.267
-	A8	clean	0.288

It is clear from the hydrophobicity classifications from Table 8 that no sample lost hydrophobicity and according to STRI hydrophobicity classification, the aged samples of Table 1 remained in class HC1-2 [13,15].

Similarly, the un-energized samples given in Table 4 (D1, D3 and D5) aged for two distinct durations of 7 days and 125 days at different altitudes were analyzed by the STRI method using relevant images given in Figure 7.

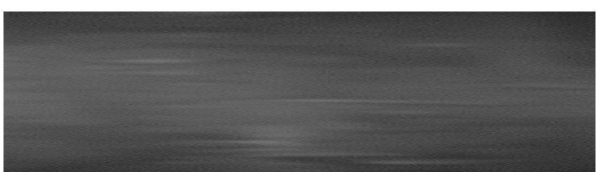


Sample D1 aged for 7 days.

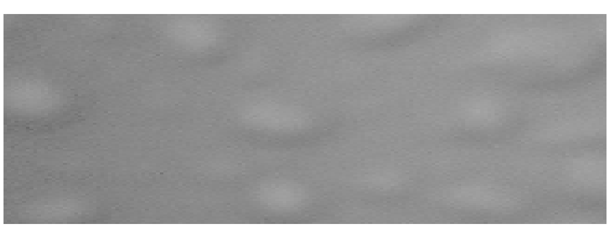
Sample D1 aged for 125 days.

Sample D3 aged for 7 days.

Sample D3 aged for 125 days.



Sample D5 aged for 7 days



Sample D5 aged for 125 days

Fig 7. Images to determine hydrophobicity of samples aged at different altitudes (Table 4).

The results show that samples did not lose hydrophobicity and fall in HC1 according to STRI hydrophobicity classification. This is due to very important property of SiR, whereby it transfers hydrophobicity into outer layers, and gradually covers the outer surface and becomes hydrophobic after certain time. In spite of extremely harsh conditions, the hydrophobicity loss of a silicon rubber insulator is temporary to a large extent, as in the bulk of silicone rubber, there exists reasonable quantities of highly mobile low-molecular-weight (LMW) chains even if loss of these components from surface have occurred [18].

Service experience and laboratory tests under the effect of UV radiation show that silicone rubber insulators maintain almost same level of hydrophobicity if exposed to stress of UV radiation alone. The reason for this could be acceleration of diffusion process of LMW inside the bulk of SiR insulators by the energy contained in UV radiation [19].

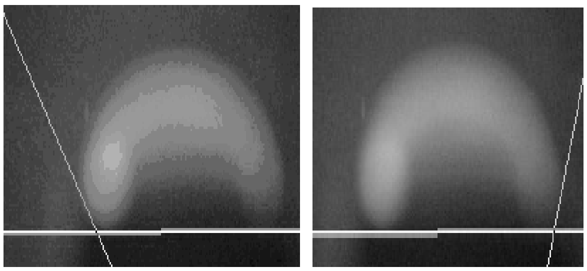
3.2.2 Contact angle measurement

A more reliable hydrophobicity test method is based on contact angle which is measured by liquid droplet method. Here, a drop of water is dropped on the sample and photographed by digital camera and the image is converted into black and white photograph using MATLAB image processing tool and contact angle is measured using Adobe measuring tool.

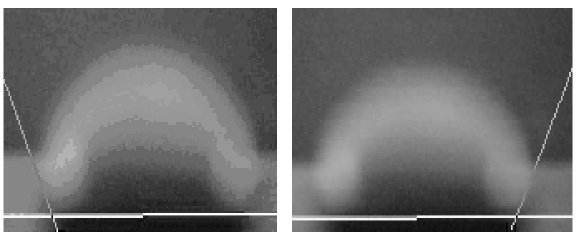
Four samples (B1 to B4) aged as per Table 2 were analyzed to determine contact angle through photographic measurements given in Figure 8. As per relevant criteria of contact angle measurement technique, all the four samples (B1 through B4) retained hydrophobic characteristics.

Similarly, the method of contact angle measurement was applied to five samples (C1 to C5) aged at medium altitude as per Table 3 and the pertinent photographic results are given in Figures 9 and 10.

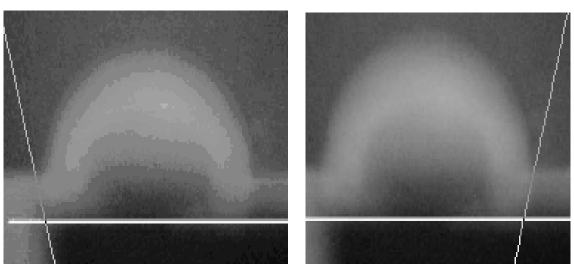
As per criteria of contact angle, samples C1 and C4 which remained stressed at 35 mm/kV and 50 mm/kV, respectively experienced more degradation compared with samples C2 and C3 which were stressed at 40 mm/kV and 45 mm/kV, respectively. These results are in conformity to those measured through FTIR spectroscopy.



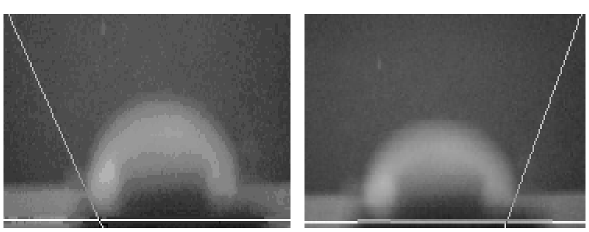
(b) B1 (0.31mg/cm^2) Angle 55^{o} Angle 73^{o}, contact angle 116^{o}



(c) B2 (0.32mg/cm^2) Angle 65^{o}, Angle 64^{o}, Contact angle 115.5^{o}

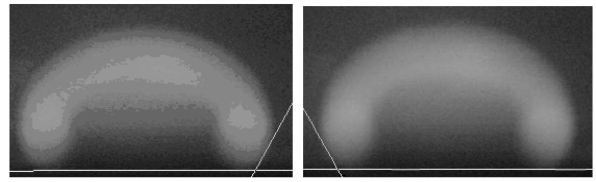


(d) B3 (0.6 mg/cm^2) Angle 72^{o} Angle 72^{o}, Contact angle 108^{o}

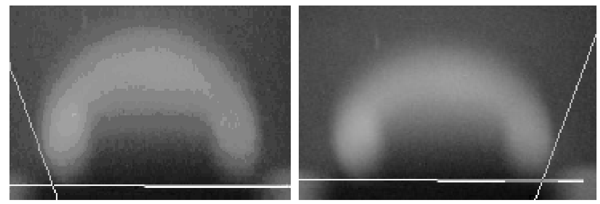


(a) B4 (1.29mg/cm^2) Angle 61^{o} Angle 65^{o}, Contact angle 117^{o}

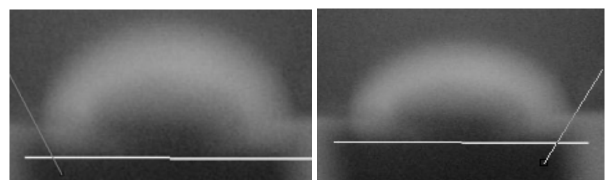
Fig.8 Hydrophobicity measurement of samples aged at medium altitude (Table 2) using liquid droplet method.



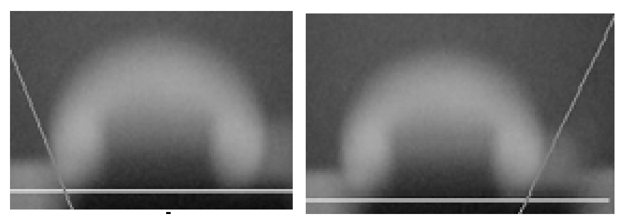
Angle 60.67^{0} **Angle 59.16^{0}**
Virgin Sample (Contact Angle 120.085^{0})



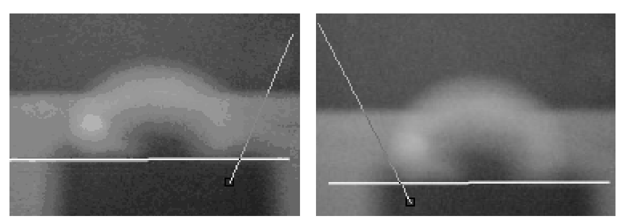
Angle 64.65^{0} Angle 67.83^{0}
(a) Sample C1: 35 mm/kV (Contact Angle 113.76^{0})



Angle 60.79^{0} Angle 60.75^{0}
(b) Sample C2: 40 mm/kV (Contact Angle 119.23)



Angle 65.75^{0} Angle 60.66^{0}
(c)Sample C3: 45 mm/kV (Contact Angle 116.795^{0})



Angle 67.89^{0} Angle 61.31^{0}
(d)Sample C4: 50 mm/kV (Contact Angle 115.4^{0})

Fig. 9 Contact angles of samples aged at medium altitude (Table 3).

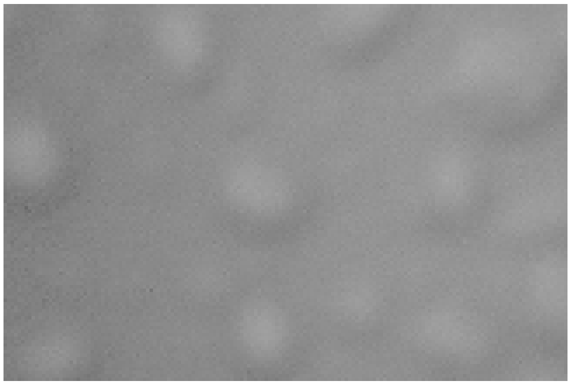


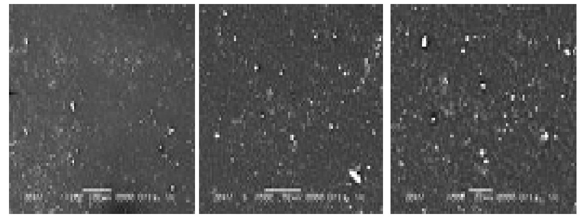
Fig.10 Hydrophobicity charactering action of C5 through FTIR method.

The hydrophobicity characterization of sample C5 through photograph given in Figure 9 was done by employing FTIR spectroscopy. It did not show any degradation and falls in corresponding STRI class 1.

3.3 Aging analysis using scanning electron microscope (SEM)

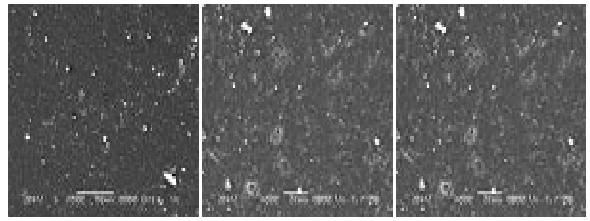
SEM analysis is one of the techniques to understand aging of polymeric insulators. In this study, the SEM (JSM 6460 resolution 3 Nm, magnification 300,000 times, JEOL, Japan) was used to understand the degree of aging of some selected samples which have been aged at medium altitude as per test conditions given in Table 3.

SEM micrographs of samples at different magnifications, 200x (1cm =100 µm), 500x (1 cm = 50 µm) and 800x (1cm = 20 µm) are shown in Fig. 11 for samples (C1, C2 and C3) which were stressed at 35 mm / kV, 40 mm / kV and 45 mm / kV, respectively. From the micrographs, it was observed that the surface became rough but no cracks were observed. However, the surface morphology (shape, size and the arrangement of the particles on surface of the sample) appeared to change with stress. It was also noted that surface became rough and the filler dispersion got more non-homogeneous as the stress was increased. Similarly, the surface integration increased with more lumped particles with the increase of stress. Although, the surface roughness of aged samples increased compared to a virgin Sample but this increase was not significant to adversely affect the hydrophobic character of the samples.



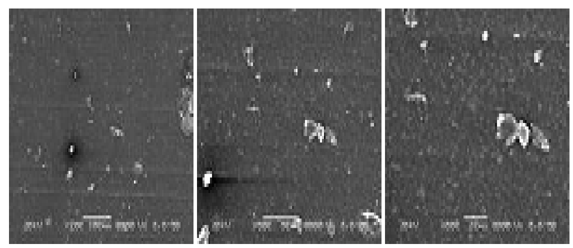
200x 500x 800x

(a) original (Virgin Sample)



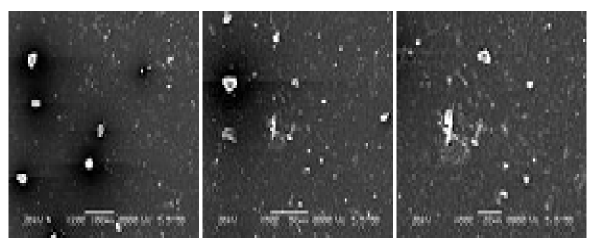
200x 500x 800x

(b) Sample C1 stressed at 35 mm/kV



200x 500x 800x

(c) Sample C2 Stressed at 40 mm/kV



200x 500x 800x

(d) Sample C3 Stressed at 45 mm/kV

Fig.11 SEM micrographs of aged samples as per Table 3.

As compared to the virgin condition, with the increase of stress from 35 mm/kV to 45 mm/kV, the roughness increased which did not match with the results of FTIR, leading thereby to the conjecture that roughness may increase without actual degradation. Such types of apparently contradicting results were reported by other researchers studying silicone rubber [20, 21] where significant morphology changes were observed by x-ray diffraction (XRD) but the same was not supported by the corresponding changes in either leakage current or FTIR-peak heights. In another study by Raji Sundararajan et al, higher leakage current activity was supporting the SEM results while FTIR study results and STRI hydrophobicity classification were on the contrary[21].

4. Transforming Slab Results to Actual Insulators

For all experimental work in this study, simple plates and rods were used because of the size limitation of the vacuum chamber. The authors have conducted a large number of experiments both in the field as well as in the laboratory using plates, rods and actual insulators as specimens. In the context of aging, it was found that among all the samples, plates degraded the most followed by the rods and the least aged samples were actual insulators [22]. Therefore, extensive data collected on plate samples offers better and conservative guidance for practical applications.

5. Conclusions

A pioneering research to explore potential of silicon rubber insulators for applications on high-altitude transmission lines was undertaken with special attention to their aging under a variety of prevailing practical conditions. The insulators were aged through UV radiation in simulated environment representing pollution severity from light to heavy both under energized and un-energized conditions. Modern state-of-the-art tools and techniques were employed to assess material aging. Main findings are summarized below"

1. Clean energized insulators degrade more compared to their un-energized counterparts. As the duration of aging is increased, the effect of electric stress on aging diminishes gradually. However, the degree of aging did not reach to a level which may adversely affect the electrical performance of polymeric insulators.

2. The effect of pollution on aging was found quite interesting. As the pollution severity is increased, the aging also increases. However, for pollution level exceeding 0.60 mg/cm^2, the degradation stops irrespective of whether the insulator is energized or not. It appears that heavy pollution protects the surface from any adverse effect of UV radiation.

3. The rate of aging has linkage with chemistry of the material. For example, HTV SiR without ATH and without filler surface treatment, degraded more compared with its counterpart with ATH and filler surface treatment.

4. Aging of SiR insulators at medium altitude (corresponding to 50 cm Hg) has given stress-related results whereby appreciable aging was noticed at stress level of 35 mm/kV and 50 mm/kV, while there was almost no aging at stress level of 40 to 45 mm/kV. This apparently does not conform well with those observed through SEM analysis. This requires further investigation.

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