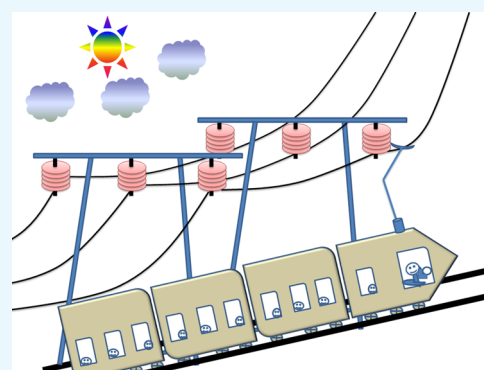


Degradation and Stability of Polymeric High-Voltage Insulators and Prediction of Their Service Life through Environmental and Accelerated Aging Processes

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ABSTRACT: Polymeric composite insulators consisting of core fiber reinforced polymer insulators covered with polydimethylsiloxane (PDMS) housing are now replacing conventional ceramic insulators especially for high-voltage power transmission lines due to some specific advantages. Unlike ceramics, polymers have relatively shorter life. Outdoor insulators experience different electrical, mechanical, chemical, and thermal stresses during service. The long-term service performance of these insulators and their service life estimation is an important issue, but it is complicated and time-consuming. The objective of the present investigation is to check the rate of property deterioration during service and to find the approximate lifetime. Working insulators with different ages were collected from service, and the changes in mechanical and electrical properties and hydrophobicity of the PDMS cover against aging time were measured. The service life estimated from the change in mechanical properties and surface hydrophobicity (using MATLAB software) was compared with the service life of a new compound subjected to accelerated aging tests. Prediction of service life is helpful for replacement of aged insulators from service to avoid interruption in power transmission.



1. INTRODUCTION

Age-resistant polymeric materials are used for different outdoor applications such as roof covering, paints, coating, automotive, and housing or cover for outdoor composite insulators in power transmission lines.^{1–5} However, polymers are organic materials that slowly degrade with time during their service life due to different environmental factors such as UV radiation, heat, moisture, pollutants, ozone, and oxygen.^{6–12} These insulators perform their service in an open atmosphere throughout the season. Power transmission is a global requirement; consequently, these insulators face different climatic conditions during their service.^{6–10} The open-atmosphere degradation of polymers is slow but steady, as revealed through the degradation of different mechanical properties and the change in their appearance. However, the change in electrical properties becomes important when polymeric composites are used as insulators for high-voltage power transmission lines. These composite insulators are made up with two important components:^{13,14} a core insulator to provide electrical resistance and mechanical strength coupled with a cover or housing for environmental protection made up of polymers such as silicone elastomer [polydimethylsiloxane (PDMS)], ethylene propylene diene elastomer (EPDM), ethylene vinyl acetate (EVA) copolymer, epoxy, and polyethylene.^{15–20}

In power transmission lines, the electrical insulator is one of the most important components. Any weakness present in the insulator system may cause leakage current and finally failure of

the insulator, causing partial or complete shutdown of power in the grid depending upon the magnitude of failure.

Ceramic insulators which were used from the inception are now getting replaced by polymeric composite insulators in comparatively lower voltage applications because of certain specific superiorities of composite insulators over conventional ceramic insulators during service, such as drastic weight reduction for composite insulators eventually providing an opportunity for economical and lighter tower design for power transmission and ease of transportation, handling, and replacement of insulators. Polymeric insulators provide good retention of hydrophobicity under wet conditions and surface contamination and thereby exhibit better performances in environmentally polluted areas and improved resistance to vandalism.^{4,17,21–27} The successful performance of the composite insulator depends on the quality of individual components and also on the quality of different interfaces present in the system. The elastomeric cover should be firmly bonded with the core and provide environmental protection and prevention of water leakage through the composite insulator.^{13,14} The core [fiber reinforced polymer (FRP) rod] is made up of a glass fiber reinforced matrix polymer (polyester and epoxy).^{28,29} The cover/housing is derived from PDMS,^{15,16} the most popular choice, or other polymers such as EPDM,^{17,27,30,31} EVA,^{18,32,33} epoxy,³⁴ and polyethylene.³⁵

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Environmental and electrical stress during service causes insulator surface degradation.^{36,37} Different detrimental factors adversely affect the service life of the composite insulator during service, but the first attack will be experienced by the outer cover/housing. The detrimental factors are heat, moisture, pollutants, and UV radiation from the sunrays and electrical discharge.^{6,7,17,32,38,39} Though PDMS has very good immunity against moisture, heat, light (UV rays), and oxidation, because of its strong backbone chain of $\sim\text{Si}-\text{O}-\text{Si}\sim$, prolonged exposure to these detrimental conditions generally initiates multiple reactions such as oxidative degradation, photocatalytic degradation, and hydrolysis.⁴⁰ As the Si-C bond is weaker than the Si-O bond, it may be thought that degradation of polymers during service starts from the organic moiety $-\text{CH}_3$ and ultimately affects the backbone chains ($\sim\text{O}-\text{Si}-\text{O}\sim$).⁴¹ The continuous migration of low-molecular weight (LMW) fragments of PDMS from the bulk to the surface for retention of surface hydrophobicity is also affected by aging during service. Slow but continuous loss of LMW fragments during service leads to loss of hydrophobicity, favoring the formation of an electrical erosion path on the polymeric cover. Deep erosion of the cover may expose the FRP core to the outside environment. Service hazards such as electrical discharge, sand storm, rain, and acid rain act as cumulative detrimental factors for the ultimate failure of insulators.^{30,42-47} As mentioned earlier, the composite insulator consists of different components and they have specific electrical and mechanical properties to meet the service requirements. The failure of any individual component as well as different interfaces present in the system may be fatal. Both installation and replacement of insulators are hazardous and time-consuming processes which adversely affect power supply. Therefore, the long-term performance of the polymeric housing/cover plays an important role in the service life of composite insulators. Proper inspection, maintenance, and timely replacement of aged insulators before failure are key requirements for power supply.

During service, the matrix polymer may degrade by two phenomena: (1) the scission of main backbone chains and (2) the cross-linking of fragmented chains.^{32,48} PDMS (silicone elastomer) is preferred over other polymers as a housing material because of its high environmental stability and retention of hydrophobicity over a long period of service.^{36,49} The hydrophobic surface reduces the tendency of dry-band discharge under wet conditions.⁵⁰ As stated earlier, as long as the migration process of LMW fragments from the bulk to the surface continues, the surface hydrophobicity is well retained.^{42,51-56} Figure 1 shows the pictures of new (unused) (a), working (b), and failed (c) insulators.

The natural aging of the outdoor insulator housing occurs because of the UV radiation present in sunrays.^{6,17} The UV radiation coming from sunrays contains different types of UV radiations such as UVA, UVB, and UVC with varying wavelengths (400–100 nm).⁵⁷ UVC (100–290 nm) with the lowest wavelength range gets filtered by the atmosphere and does not reach the earth surface. Therefore, solar UV radiation consists of mostly UVA (320–400 nm) and some UVB (290–320 nm), and these wavelength ranges are crucial for high-voltage composite insulators working in open-atmosphere power transmission lines.^{58,59} Apart from solar radiation, insulators also experience UV radiation at their service conditions, where degradation of polymers is faster and severe.^{60,61} In fact, these insulators may face UVC for a

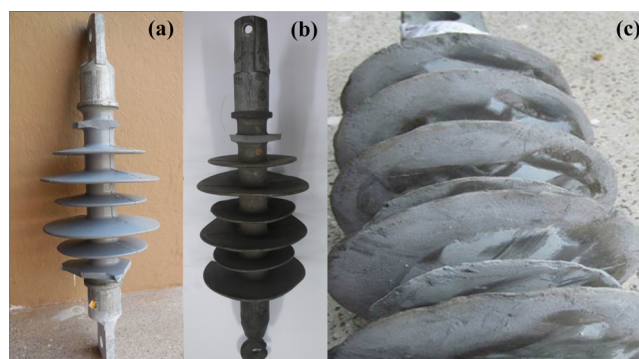


Figure 1. Pictures of (a) new (unused), (b) working, and (c) failed insulators.

short time duration in the event of electrical discharge occurring at the vicinity of the insulators when effective filtering is not possible. The frequency (wavelength), intensity, and duration of exposure to incident UV radiations determine the severity of polymer degradation, but all of these factors are variable. The deteriorating effect of UV exposure is not fatal by itself, but it is a slow and continuous process that accelerates failure under mechanical and electrical stresses experienced during service. Different atmospheric deposits on the polymer housing may provide some degree of UV protection.²⁷

In the present work, samples of working insulators from the field after 1 to 9 years of service were collected and subjected to different tests (mechanical, electrical, and hydrophobicity) to evaluate their conditions and to calculate the rate of deterioration of some properties against service time. Further, using some standard software, an effort was made to estimate the probable average lifetime of the polymeric housing. The field results were also compared with those of accelerated aging tests done in a laboratory on a standard compound used for insulator housing.

The approximate service life estimation of these insulators used in railway track will be helpful for timely replacement of adequately aged insulators before failure without affecting the train service.

2. EXPERIMENTAL SECTION

2.1. Materials. Composite insulator samples include new insulators (zero service period), working insulators with service duration of 1 to 9 years, and silicone polymer-based standard insulator compound [containing ~ 45 wt % alumina trihydrate (ATH)]. All were obtained from Indian Railways. The average climatic conditions of the region (northern India) from where these samples were collected are very similar, where annual temperature may range from 1 to 48 °C with an average temperature of 35–40 °C with dust-laden winds and 85% of average rainfall/year (990 mm). The average duration of sun exposure is 8–12 h/day.⁶²⁻⁶⁴

2.2. Natural Aging. Naturally aged working insulator samples originated from overhead high-voltage power transmission lines under open-atmosphere environmental conditions. These samples were collected from power transmission lines and were usable at the time of replacement.

2.3. Accelerated Aging. The accelerated UV aging test was carried out for 9 h in an UV chamber with high-intensity UV radiation. The UV chamber obtained from Western Quartz (USA) (1800 W quartz lamp and wavelength 250–350 nm) was used (ACS 21–22, cabinet built by Advance Curing

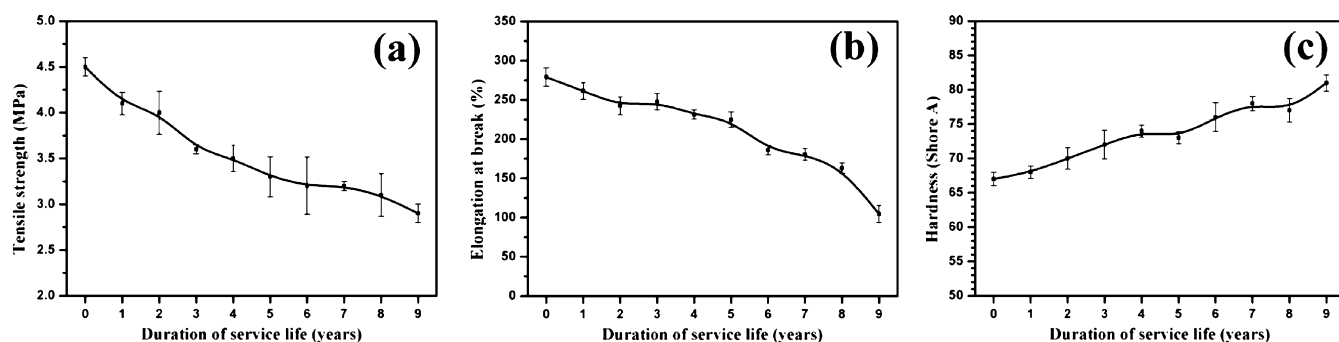


Figure 2. Variation in (a) tensile strength (TS), (b) EB, and (c) hardness (Shore A) of different working insulators.

System, Bangalore, India). The wavelength coverage of the UV source includes the whole UVB range and very small part of UVC. The distance between the high-intensity UV source (lamp) and the sample was kept fixed at 7 cm. Thermal aging was carried out up to 7 days at 150, 160, and 170 °C under dry heat in an aging oven. Neutralization time (24 h) was provided to all the aged samples, followed by the measurement of different properties. The average energy associated with incident UV rays determines the extent of polymer degradation and associated energy depends on wavelength. As mentioned earlier, sunrays contain UVA and UVB but UVA in higher percentage (90–95%). During the experiment, the UV light source (350–250 nm) used for accelerated UV aging mainly covers the UVB (315–280 nm) range coupled with small part of UVA (350–315 nm) and UVC (280–250 nm) radiations. This broad UV range can take care of detrimental effects of radiations from both sunrays and electrical discharge.

2.4. Characterizations. The mechanical properties were measured by using a Hounsfield universal testing machine (H10KS). The durometer type A instrument (Shore Instruments and MFG Co, INC, USA, CV-71200 CONVE-LOADER) was used to measure the hardness of different samples. An Agilent high-resistance meter (4339B) was used to measure the surface resistivity of different samples and was coupled with an Agilent resistivity cell (16008B). The static contact angles of different samples were measured using a goniometer (model no. 264 F4, Rame-Hart Instrument Co.). The measurement of dielectric properties was performed using a Novocontrol Alpha-A analyzer, Novocontrol Technologies, Germany. Surface morphology of the samples was analyzed by using scanning electron microscopy (SEM, ZEISS EVO 60, Carl ZEISS, Germany). Thermogravimetric analysis (TGA) was carried out using TGA Mettler Toledo (from Mettler Toledo Instruments) under a N₂ atmosphere from 45 to 700 °C at a heating rate of 20 °C/min.

All mechanical properties were studied from the edge portion of the polymer housing on dumbbell-shaped test specimens punched out from insulator samples in accordance with ASTM D 412.

3. RESULTS AND DISCUSSION

3.1. Change of Properties of Working Insulator Samples. **3.1.1. Change in Mechanical Properties.** The change in mechanical properties may be a good indication in service life prediction. A reduction in mechanical strength with the increase in service life is observed (Figure 2a). There is a slow but progressive degradation of the polymeric insulator cover compound. This is due to open-atmosphere aging, where UV radiations from sunlight and electrical discharge adversely

affect the matrix polymer. Other factors such as sand storm, acid rain, and bird pecking also damage the housing. All of these effects are cumulative and synergistic in nature.

The silicone polymer housing material exhibits a decrease in elongation at break (EB) (Figure 2b) and an increase in hardness (Figure 2c) during aging. In general, when polymers are subjected to aging, two types of chemical reactions take place in the system: the first is chain scission, that is, fragmentation of long polymeric chains into short fragments and the second is the cross-linking of fragmented chains through macroradical formation followed by recombination of these macroradicals, leading to the formation of three-dimensional networks with an increase in cross-link density.^{32,48} If the first process predominates, the net effect will be softening of the polymer product on aging. If the second process predominates, the net effect will be hardening of the polymer product with the increase in aging time. The probable mechanisms of chain scission and cross-linking of fragmented chains of the PDMS-based insulator under detrimental environmental conditions (especially under UV radiation) are shown in Figure 3. In fact, the natural aging process during service is a complex series of reactions. Apart from chemical degradation of PDMS, cover/housing surface damage (cracking and erosion) by sand storm, acid rain, and electrical discharge is also a likely phenomenon.^{30,42–47}

In the case of PDMS, the main polymeric chain of oxygen–silicone–oxygen (O–Si–O) is strong enough to resist UVA and UVB radiations but is affected by UVC, which may be accidentally generated for very short duration in the event of occasional electrical discharges such as plasma, corona, and dry-band arcing. Along with high-energy UV, some reactive species such as electrons and free radicals are formed during corona and plasma discharge, which can initiate main chain scission.^{65–67} However, duration of these electrical hazards is much shorter compared to that of sunlight exposure. Therefore, PDMS backbone chain scission is a relatively slow process during aging,³² whereas the cross-linking reaction is more predominant through the involvement of the methyl group attached to the silicone atom, which can be accomplished by normal UV rays present in sunlight. The reaction involving the methyl group (–CH₃) leads to the formation of cross-links. The combined effect of aerial oxygen, high-energy radiation from sun, and electrical discharges during environmental aging leads to photo-oxidative degradation of PDMS, as shown in Figure 3. The methyl groups convert to aldehydes, ketones, and carboxylic acids.^{68–70} Multiple reactions of degradation during environmental aging take place: chain scission, interchange of bonds, hydrolysis of siloxane and hydrocarbon groups, cross-linking of siloxane

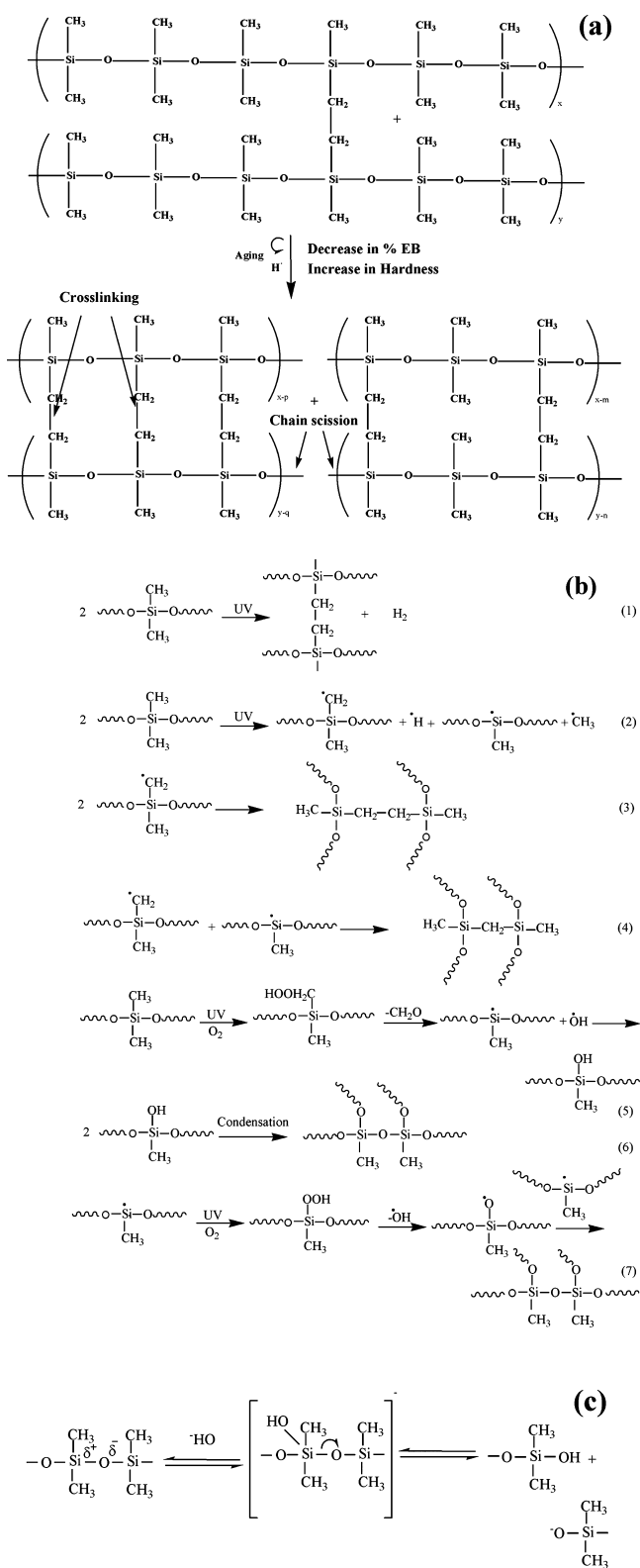


Figure 3. Schematic illustration of the mechanism of (a) chain scission and cross-linking of fragmented chains, (b) degradation, and (c) hydrolysis of the PDMS-based insulator under detrimental environmental conditions.

bonds through condensation, and carbon–carbon cross-linking are also possible.^{71–73} PDMS as such is a nonpolar polymer, but the polar nature of the C–Si bond due to electronegativity

difference makes the polymer chain susceptible to hydrolysis.^{74,75}

3.1.2. Change in Electrical Properties. It is expected that because of natural aging in an open atmosphere, the surface resistivity of the polymeric housing should change. The surface resistivity of the silicone housing material changes slowly with open atmospheric aging time (Figure 4a). The surface resistivity is found to decrease initially with aging period, but the change becomes marginal after 4–5 years. In fact, the surface resistivity change depends not only on the matrix polymer but also on the filler added to the system. These insulators contain ATH ($\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$) in large quantity,^{61,76–78} which itself is inorganic and insulating in nature, whereas the silicone elastomer on aging ultimately leads to silica formation on the surface of the insulators, which itself is a good electrical insulator. As a result, with aging, the surface resistivity change becomes almost marginal.

3.1.3. Change in Hydrophobicity. The surface hydrophobicities of different insulators were measured in terms of their contact angles. A decrease in hydrophobicity favors the formation of water droplets and water channels, leading to electrical discharge on the surface of the insulator. In fact, a large number of successive and repeated electrical discharges on the surface of the insulator over a short period of time cause failure of the insulator. PDMS-based polymeric insulators exhibit excellent hydrophobicity in fresh unused condition, where the material exhibits a contact angle around $110\text{--}115^\circ$ with respect to water droplets. However, with prolonged aging due to different detrimental effects and surface electrical discharge, there is a continuous reduction in surface hydrophobicity with time (Figure 4b). The rate of migration of LMW fraction from the bulk to the surface, which is responsible for the retention of surface hydrophobicity of the PDMS insulator, slows down with the increase in service life.^{27,51–55,79} The polymer PDMS during aging undergoes progressive cross-linking as revealed from a continuous increase in surface hardness and brittleness of the cover/housing. The increase in cross-link density hampers the LMW migration process because of the reduction in free volume. The migration of low-molar mass PDMS species to the surface is greatly impeded when the material is subjected to surface oxidation.^{73,80} Further progressive surface aerial oxidation during service converts some hydrophobic methyl groups ($-\text{CH}_3$) of PDMS to oxygen-containing hydrophilic groups such as aldehydes, ketones ($-\text{CHO}$, $>\text{C}=\text{O}$), and carboxylic acids ($-\text{COOH}$), and this may also contribute to the reduction in hydrophobicity. The reduction in hydrophobicity increases the chances of surface electrical discharge and ultimate failure of the insulator.

3.1.4. Change in Dielectric Properties. Dielectric properties such as dielectric constant and dielectric loss factor play an important role in the performance of high-voltage insulators (Figure 5a,b). The increase in the dielectric constant and loss factor will cause an enhancement of localized electrical field stress, leading to an increase in the chance of partial discharge under high voltage in the microvoids or defects generated in the insulator body during aging.^{32,81–84} This increase in loss factor with prolonged aging reveals the initiation of deterioration of the insulating material. The dielectric constant also shows some weak tendency to increase with aging time. The increase in dielectric properties may be due to the oxidative degradation of the polymer compound, absorption of moisture, or ionic contaminants in trace amount during normal

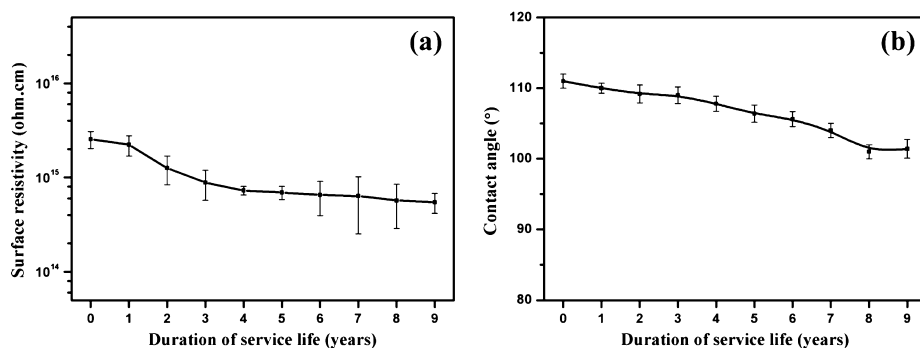


Figure 4. Change in (a) surface resistivity and (b) contact angle of different working insulators.

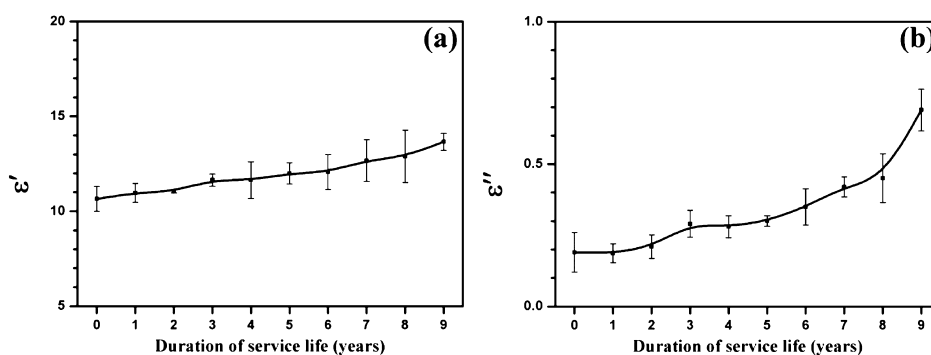


Figure 5. Variation in (a) dielectric constant and (b) dielectric loss at a 50 Hz frequency of different insulators.

aging in service. It may be expected that with further advancement of service life, some more changes in dielectric properties may be observed because of the increase in polar and ionic species in course of different reactions taking place. However, the increase in the degree of cross-linking will decrease the extent of polarization and hence lead to some decrease in dielectric properties. However, a very large change in dielectric properties may not be observed as ultimately PDMS converts to silica, which again is a good insulating material.

3.1.5. Surface Morphology. The analysis of surface morphology of the insulator housing can be effectively used as a tool for the measurement of extent of degradation during aging. However, a clear cut scale of surface roughness indicating the end of service life is yet to be established. However, it is clearly seen that with the increase in the service life, the surface quality of the silicone insulator progressively deteriorates (becomes more and more rough). This change in surface roughness can be detected by a scanning electron microscope and even by a normal optical microscope in many cases. In fact, the surface morphology of new samples can also provide some information about the quality of the elastomer compound used for housing as well as the molding process adapted.

The surface topologies of new samples (Figure 6a) reveal that the surfaces of polymeric insulators are more or less uniform and smooth. In fact, even for new samples of composite insulators, the surface morphology is found to be slightly rough. The SEM image of new samples also reveals the quality of the PDMS compound used for making the composite insulator. To improve resistance against surface electrical discharge, the PDMS compound contains a large amount of filler-like ATH (Al(OH)₃, commonly written as Al₂O₃·3H₂O). The proper dispersion of the filler in the

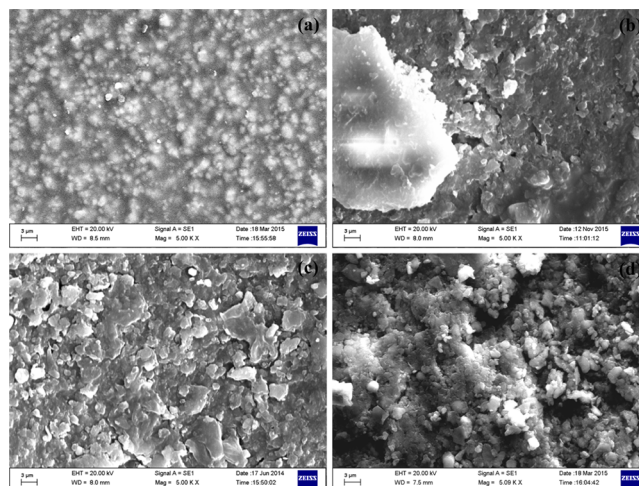


Figure 6. Surface morphology of (a) fresh sample and (b) 3 year, (c) 6 year, and (d) 9 year working composite insulators.

polymer matrix plays an important role in the quality of the silicone polymer compound. White spots throughout the surface reveal the presence of the filler, and the size of these clusters also varies, which signifies the level of dispersion obtained in the final compound. The molded elastomeric sheet has some fine roughness; this is mainly because it is filled with elastomeric composites having a high concentration of the particulate filler ATH. Further, if mold surfaces are not very smooth, they can give some rough impression on the insulator housing surface.

In fact, with the increase in aging period during prolonged service life, there is a continuous increase in surface roughness, exhibiting cracks and cut marks. For the new sample, such cracks are not visible. However, when the housing samples are

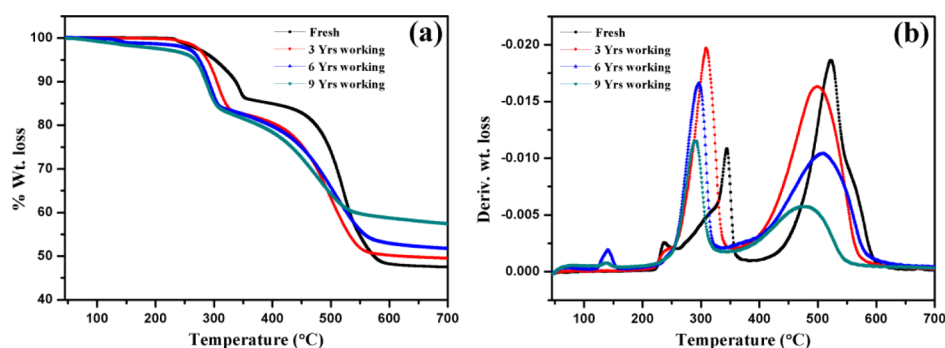


Figure 7. (a) TGA and (b) DTG curves of fresh and working insulators with different life periods (3, 6, and 9 years).

subjected to aging, there will be appearance of small cracks on the insulator surface. Small cracks initially develop progressively and grow into long and continuous cracks on the housing material.

Figure 6b reveals the SEM micrograph of the insulator housing subjected to 3 years of service. This is an in-service sample. The surface roughness for samples having 3 years of service life reveals deterioration started on the surface within 3 years of natural aging. With natural aging under an open atmosphere, the insulator housing surface exhibited a change of surface from relatively smooth to rough. In fact, the change in surface roughness for the sample subjected to only 3 years of aging is not very significant.

Figure 6c,d exhibits the silicone polymer insulator surface subjected to 6 and 9 years of service under an open atmosphere during operation in transmission lines. The cracks and cut marks are visible on the surfaces. With the increase in service life of these insulators, the surface roughness increases progressively as apparent for the insulator samples subjected to 9 years of service (Figure 6d). Thus, the surface topology can give some idea about service life. This reveals that the surface topology of the insulator housing made from the silicone polymer (PDMS) changes continuously with the increase in service life under an open atmosphere. Some surface roughness may also be due to the atmospheric erosion due to sand storm and electrical discharge during service. The degradation of the matrix polymer and consumption of the filler ATH during surface electrical discharge may also increase the surface roughness.

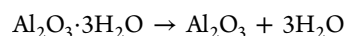
The PDMS insulator housing is exposed to environmental hazards such as UV radiations, ozone, and corona and plasma discharges. These detrimental factors in the presence of oxygen cause oxidation of the material surface, thereby converting the surface from hydrophobic to hydrophilic in nature. Along with oxidation, hydrolysis, main chain scission, and cross-linking reaction also take place. The increase in cross-link density of the insulator cover surface also contributes to its transformation from hydrophobic to hydrophilic character. The increased cross-link density results in the formation of a more rigid (glassy) and dense surface layer compared to the virgin surface. There is formation of oxygen-rich surface like SiO_X ($X > 2$) in aged insulator, when, $X = 2$ in case of virgin material. This oxygen-rich highly cross-linked surface layer is rigid and prone to crack easily under natural stress. The surface cracking is a long-term process and leads to degradation of the insulator.^{65,85}

3.1.6. Thermogravimetric Analysis. Figure 7a,b shows the TGA and differential TGA (DTG) curves of fresh and working

insulators with different life periods (3, 6, and 9 years) in service.

TGAs of fresh (unaged) and working (not failed) samples from service reveal that there are two stages of decomposition for the PDMS-based insulator housing compounds. These housing compounds contain a large amount of ATH to improve resistance against dry-band discharge.^{76,77}

The first stage of decomposition starts at a temperature of 226–227 °C for working and new samples because of the dehydration of ATH, where weight loss is due to firmly bonded water of hydration.^{86–88}



It is interesting to note that initiation temperatures of decomposition for different samples are more or less the same. The peak temperature for the first stage of decomposition is the temperature at which the maximum degradation has taken place. It can be seen that the peak temperature shifts toward lower temperature as the service life of the composite insulator increases (Table 1). The second stage of degradation, however,

Table 1. TGA of Different Insulators

sample	peak deg. temp. (°C)	% wt loss at the first stage	% wt loss at the second stage	% residue content
fresh	344 & 523	14	38.5	47.5
3 yrs working	309 & 498	16	34.5	49.5
6 yrs working	296 & 508	16	32.5	51.5
9 yrs working	291 & 479	16	26.5	57.5

starts at different temperatures for the new unused sample and working samples with different age profiles. It is noteworthy that initiation of the second stage degradation is taking place at lower temperatures when the service life of the composite insulator increases. The second stage of decomposition is due to the breakdown of the polymer matrix (PDMS).

The second stage of degradation of composite insulators can also be related to their service life. On an average, it can be said that both initiation temperature and peak temperature for the second stage of decomposition shift toward lower temperatures as the service life of the composite insulator increases. Because of the increase in service life of the composite insulator, the insulator housing compounds are exposed to different types of environmental hazards along with a number of nonfatal electrical discharges. Both electrical discharge and UV radiation have a detrimental effect on the housing polymer and are reflected in the lowering of second stage decom-

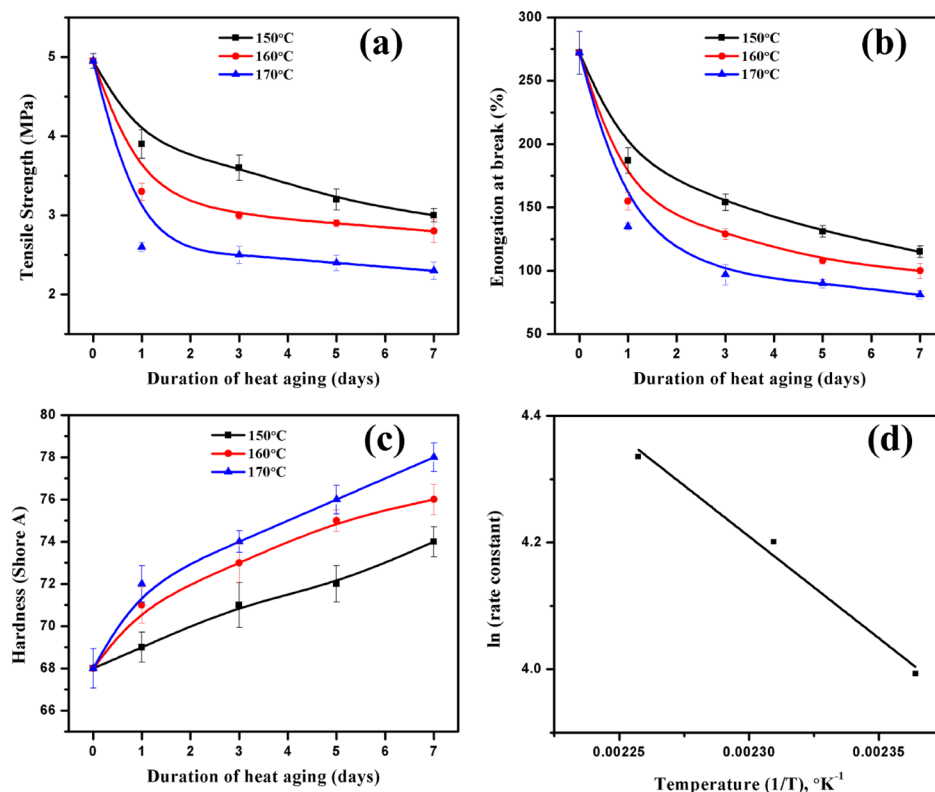


Figure 8. Change in (a) TS, (b) EB, (c) hardness, and (d) rate of deterioration of EB under accelerated thermal aging.

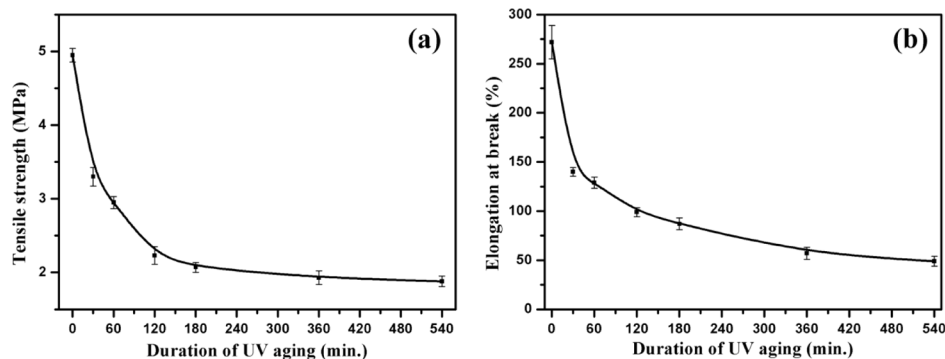


Figure 9. Change in (a) TS and (b) EB under accelerated UV aging.

position temperature with the increase in service life due to an increase in radiation exposure time and an increase in the number of electrical discharges encountered during specified periods of service. In fact, during surface electrical discharge due to a significant increase in temperature, both degradation of the matrix polymer and dehydration of the ATH-like filler present in the compound can happen.^{44,89–92} Therefore, it may be concluded that the second stage decomposition temperature measured through TGA for a housing material is related to its service life.

3.2. Accelerated Thermal Aging of the PDMS Insulator. Accelerated aging tests were also carried out on the insulator compound to compare normal aging and accelerated aging and to understand the main detrimental factor that plays the most dominant role in aging of the PDMS-based insulator compound. One standard insulator compound was taken and subjected to accelerated aging, and different property variations are monitored.

3.2.1. Change in Mechanical Properties. The PDMS compound shows marginal change in properties during accelerated heat aging carried out at temperatures as high as 140 °C. To get appreciable change in properties due to thermal aging, the aging temperature is increased to 150 °C and beyond. The variations of mechanical properties for different time durations at aging temperatures of 150, 160, and 170 °C are presented in Figures 8a and 9b. It can be seen that the rate of decrease in TS as well as EB is quite fast initially up to 24 h (1 day); thereafter, the decrease in TS as well as EB becomes relatively slower compared to the initial aging period. The main chain of PDMS consists of a very stable bond (Si–O–Si), which is less affected during thermal aging.³² However, the pendent methyl groups (–CH₃) along the chain are susceptible to thermal oxidation. In fact, the process of degradation is initiated from the decomposition of pendent groups mainly consisting of methyl (–CH₃) and very few vinyl groups (–CH₂=CH₂–), which may be present in the system. As the Si–C bond is weaker than the Si–O bond, it may be

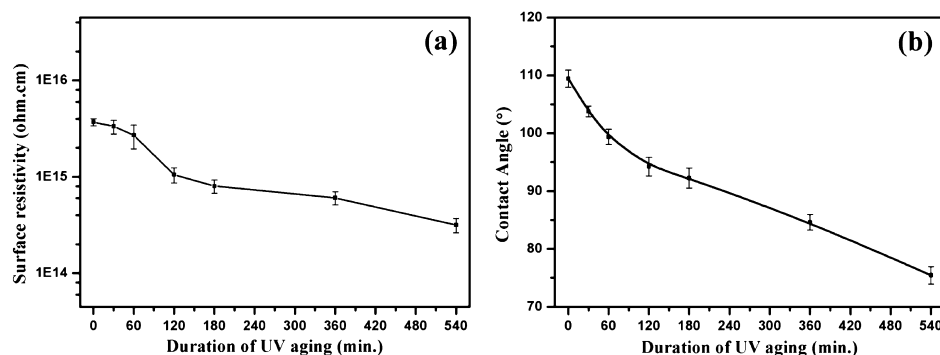


Figure 10. Change in (a) surface resistivity and (b) hydrophobicity under accelerated UV radiation.

thought that degradation of the polymer starts from the organic moiety $-\text{CH}_3$, which ultimately affects the main chain. After the initial degradation of surface layer of matrix polymer, perhaps there is formation of some thermally stable silicate layers over the polymer matrix, which retards further thermo-oxidative process. The progressive reduction of EB (Figure 8b) and the increase in hardness (Figure 8c) reveal that both chain scission and cross-linking processes are operative in the system during high-temperature thermal aging.

Thus, during thermal aging, the rate of polymer degradation can be calculated by drawing a tangent to the curve of EB versus aging time. The rate is again temperature-dependent and was calculated at different aging temperatures. The activation energy for aging can be calculated using the standard Arrhenius plot (Figure 8d). The activation energy thus calculated from the Arrhenius equation was found to be $2.7 \times 10^4 \text{ J mol}^{-1} \text{ K}^{-1}$.

3.3. Accelerated UV Aging of the PDMS Insulator.

3.3.1. Change in Mechanical Properties. Polymeric weather sheds are used to protect composite insulators in service. These polymeric weather sheds should have some mechanical properties to perform their service. Loss of mechanical properties with aging is an important factor to be considered for ensuring adequate service life. Open atmosphere temperature generally varies from subzero to as high as $50 \text{ }^\circ\text{C}$ in tropical regions and $51.5 \text{ }^\circ\text{C}$ in tropical deserts in India.⁹³ In fact, the surface temperature can go easily beyond $50 \text{ }^\circ\text{C}$. The maximum temperature of service may not be very high in general, but prolonged exposure to sunrays for several years may cause slow and continuous degradation of chemical, mechanical, and electrical stresses. However, the housing material may be exposed to a much higher temperature well beyond $170 \text{ }^\circ\text{C}$, the highest aging temperature for a very short duration during electrical discharges.^{44,89–92}

Heating due to direct sunlight exposure in tropical or desert regions is one of the main environmental stresses that influence the performance of PDMS insulators.⁹⁴ Further electrical discharges occurring on housing surface in the event of corona, plasma and dry band arcing may result substantially high increase in surface temperature for very short time duration. Oxidative degradation of PDMS in the presence of atmospheric oxygen increases both O/C and O/Si molar ratios for the aged housing surface compared to the original compound.^{6,37,72,95} The intensity of UV rays experienced by the insulators depends on climatic and geographical conditions and clock time. UVA radiation with a wavelength of 330 nm can impart 398 kJ/mol, which is sufficient to break the Si–C bond (a bond strength of 301 kJ/mol) but not enough to break

the Si–O bond (a bond strength of 443 kJ/mol), which can be broken by UV radiations with a wavelength $\leq 267 \text{ nm}$.⁹⁶ This level of energy is available from UVC radiation. There is also another source of UV radiation, which occurs accidentally during electrical discharges such as plasma, corona, and dry-band arcing on the housing surface. Its intensity is high but duration is short, as the electrical discharge occurs very close to the insulator, is not filtered, and may contain high-energy UVC to affect backbone chains. As stated earlier, a number of nonfatal discharges may occur during the service life of an insulator before it becomes totally ineffective. Sand storm erosion and polymer hydrolysis by rain and acid rain can also cause polymer degradation. However, detrimental activities of different environmental and service hazards are synergistic and cumulative in nature. Therefore, overall degradation of the PDMS housing material in service is a combined effect of all detrimental factors mentioned.

Figure 9a,b shows the change of TS and EB, respectively, under accelerated UV aging. Both TS and EB decrease with the increase in UV exposure time. However, the initial drop in properties is found to be quite high, especially in the case of EB. However, with further increase in time, the drop in both properties is comparatively less. These changes in properties are due to the overall degradation of PDMS under UV exposure.

3.3.2. Change in Electrical Properties. The reduction of surface resistivity under UV aging has a technical importance regarding the performance of the composite insulator. It is working under high voltage; dry-band discharge may take place because of the reduction of surface resistivity.

Figure 10a shows the change in surface resistivity under accelerated UV aging. It is found that the surface resistivity decreases initially with increase in the time period of accelerated UV aging. However, as seen in the case of the silicone insulator exposed to open-atmosphere aging, the surface resistivity of the accelerated UV-aged insulator compound also exhibits a marginal change beyond a certain period of accelerated aging, for example, after 150 min of aging. This indicates that polymer degradation in an open atmosphere under sunlight and electrical discharge shows a trend slightly similar to that of degradation under accelerated UV aging. Therefore, it may be concluded that UV radiation present in sunlight and electrical discharges plays an important role in insulator aging during service.

3.3.3. Change in Hydrophobicity. The change in hydrophobicity under accelerated UV aging is shown in Figure 10b. The exposure to high-intensity UV radiation adversely affects the surface hydrophobicity of the insulator; in fact, the

hydrophobic surface changes to a hydrophilic surface. The accelerated aging under high-intensity UV radiation reduces the tendency of migration of LMW PDMS molecules to the insulator surface. During UV aging, the % EB reduces and hardness increases, which shows that the sample undergoes both chain scission and a high degree of cross-linking, thereby reducing the matrix free volume. This free-volume reduction hampers LMW migration from the bulk to the surface.

3.3.4. Surface Morphology. The surface morphology plays an important role in the performance of the insulator.^{36,38,69,80,97} With aging, if there is formation of any cracks and/or debris, these cracks and debris may accumulate pollutants, salts, and carbon particles from the environment and create conductive deposits on the insulator surface. These external foreign materials further absorb/collect moisture, leading to the formation of a thin conductive layer causing electrical discharge on the insulator housing surface.

Figure 11 shows the change in surface morphology under UV aging. It was found that with the increase in aging time, the

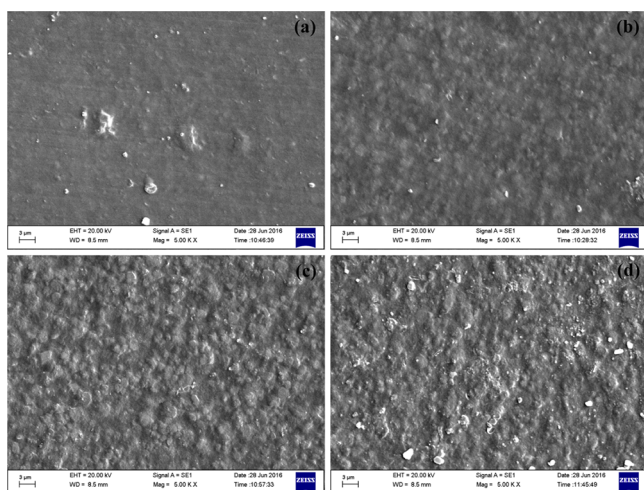


Figure 11. Change of surface morphology of (a) unaged and UV-aged samples: UV aging for (b) 3 h, (c) 6 h, and (d) 9 h.

surface roughness also increases. After 9 h of accelerated UV aging (Figure 11d), it was also found that polymer chains on the surface degraded leaving behind some exposed filler particles. These surface filler particles are less strongly bonded with the main body of the housing. These filler particles can absorb atmospheric moisture, causing electrical discharge.

3.4. Lifetime Estimation of a High-Voltage Insulator Subjected to Natural Aging during Service through MATLAB Modeling. Ceramic or glass insulators used for power transmission lines have a long service life often more than 50 years. However, though polymeric insulators exhibit superiority in many respects, they are expected to give relatively shorter service life. As these materials are being used only in the recent past, their expected life is yet to be confirmed. Outdoor polymeric insulators used on railway tracks should provide long service life and should be replaced before failure without affecting the train service. Therefore, the estimation of approximate service life for this product is very important.

One of the aims of the present investigation is to estimate the lifetime of silicone rubber (PDMS) composite insulators using material properties. In this study, an effort has been made to predict approximate lifetime based on two key

properties: (1) % EB and (2) hydrophobicity measured in terms of contact angle.

3.4.1. Change in % EB Due to Natural Aging. Lifetime prediction in terms of residual elongation (retained elongation after aging) for elastomeric components is well known and generally done for engineering products and electrical cable materials.^{98–100} Working insulators of different service lives were collected, and their EB was measured (Figure 12). EB

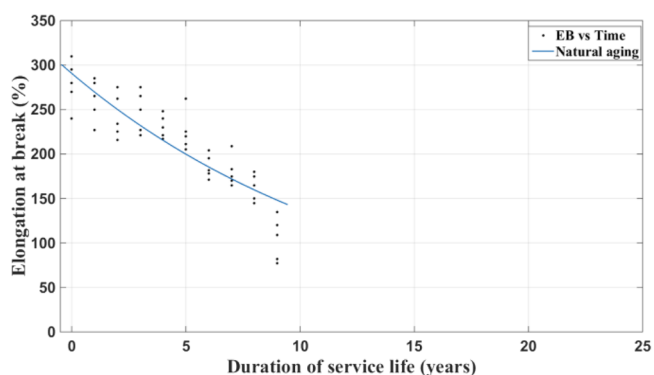


Figure 12. Change of EB (% EB) with the duration of service life (years).

decreases with service life, and the time to reach residual minimum EB of 50% has been calculated mathematically using MATLAB programming (equation fitting). The time taken to reach 50% residual elongation in the sample was calculated whose original EB was around 279%. The extrapolated time to reach residual EB was calculated based on a mathematical expression (eq 1).

$$y = f(x) = ae^{-bx} \quad (1)$$

where y stands for the properties (EB) and x stands for the time. From MATLAB software calculation, a and b are two constants in the expression, whose values are 290.7 and 0.07492, respectively. The estimated time to reach minimum 50% EB for the PDMS insulator in service is ~ 23.5 years.

3.4.2. Change in Hydrophobicity Due to Natural Aging. Service life estimation is also done based on the hydrophobicity measurement in terms of contact angle with a limiting value of 90° . The decrease of surface hydrophobicity leads to an increase in the probability for coalescences of water droplets and water channels, thereby facilitating surface discharge, and a large number of successive and repeated electrical discharges over a short period of time may lead to failure of the insulators. Polymeric insulators based on PDMS exhibit excellent hydrophobicity in the new sample (unaged) when the sample contact angle with respect to water droplets is on the order of $110\text{--}115^\circ$. However, with increase in aging time and electrical discharges, there is a reduction in hydrophobicity, which is reflected through the reduction in contact angle. As per the normal standard, a surface that exhibits a contact angle $\geq 90^\circ$ with respect to water droplets is considered as hydrophobic in nature. The minimum residual contact angle for the aged insulator has been fixed as 90° . However, for practical service condition, any PDMS insulator with surface hydrophobicity measured in terms of contact angle $\geq 90^\circ$ may still provide satisfactory service life even for a few more years.

On the basis of these criteria from the contact angle measurement on different working insulators with various service life are plotted against time, and the time to reach the minimum contact angle of 90° is estimated from the extrapolation of this plot using MATLAB software and a similar mathematical equation (eq 1) (Figure 13), where y

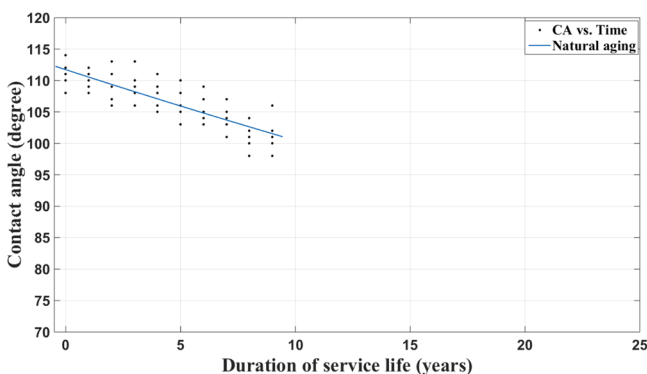


Figure 13. Change in contact angle with the duration of service life (years).

represents the properties (contact angle) and x is the time (service life). Moreover, a and b are constants, and their values are 111.7 and 0.01062 respectively. If the limiting value of y is kept 90° , then the approximate service life was found to be ~ 20 years.

3.5. Service Life Estimation from Accelerated Aging Test of a High-Voltage Compound Material. Lifetime estimation of the insulator compound subjected to natural aging in service has been done using MATLAB. Similarly, lifetime estimation of the PDMS insulator compound subjected to the accelerated aging process has also been done to compare natural aging and accelerated aging processes.

As done in the previous case, lifetime estimation through accelerated aging has been done based on the change in EB and hydrophobicity measured in terms of contact angle. It is to be mentioned here that the laboratory accelerated aging process is exclusively based on exposure of the sample to high-intensity UV radiation for different time intervals, followed by the measurement of residual properties of the compound. As the degradation process is quite fast under high-intensity UV radiation, the exposure time of the sample to UV radiation has been limited to a maximum of 9 h. The same limiting value of EB (50% residual EB) and contact angle (90°) for the end of service life has been used to determine the end limit for lifetime.

3.5.1. Change in % EB Due to Accelerated UV Aging. Accelerated aging tests are carried out under high-power UV to check the detrimental effect on the polymer housing. A high-power UV source provides faster degradation of PDMS samples. The UV aging was performed for different time durations up to 9 h to calculate the time required for drop in EB (residual EB) $\approx 50\%$ is estimated (Figure 14). The values were fitted to the standard equation (eq 2) using MATLAB software. The service life calculated under accelerated UV aging is found to be around 7 h 33 min.

$$y = f(x) = ae^{-bx} + ce^{-dx} \quad (2)$$

where x represents the time duration of UV aging and y denotes the properties (% EB). Moreover, a , b , c , and d are

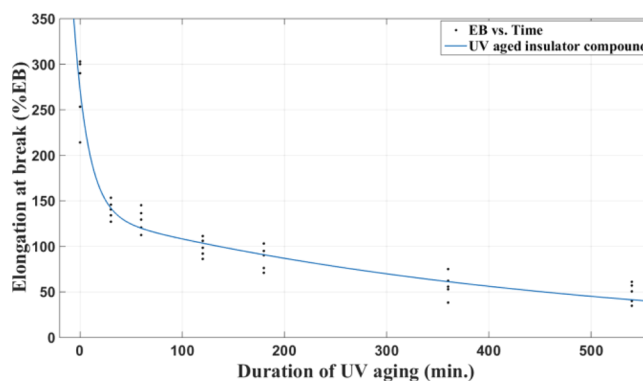


Figure 14. Change in EB (% EB) with time under accelerated UV aging.

constants, and their values are 137.5, 0.07123, 134.5, and 0.002182, respectively.

3.5.2. Change in Hydrophobicity Due to Accelerated UV Aging. The change in surface hydrophobicity due to UV aging can also be used as a criterion for predicting service life. It was observed that the contact angle decreases with the time duration of accelerated UV aging (Figure 15). The limiting

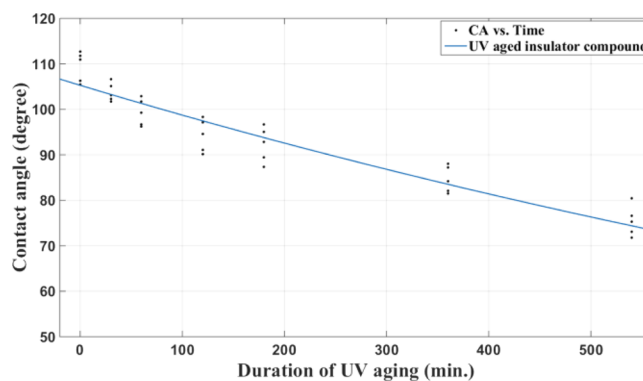


Figure 15. Change in contact angle with time under accelerated UV aging.

contact angle for the hydrophobicity test was kept at 90° . The service life from contact angle was also estimated using MATLAB programming (eq 1). The service life estimated from accelerated UV aging is found to be 4 h 4 min, where y represents the properties (contact angle) and x denotes the time duration of accelerated UV aging. Moreover, a and b are two constants, and their values are 105.3 and 0.0006429, respectively.

The variation of EB against UV exposure or accelerated aging is presented in Figure 14. It can be seen that EB reduces with UV exposure time and the limiting value of EB (50% residual EB) is attained around 7 h 33 min of aging under high-intensity UV radiation. The surface contact angle reduces with aging time, and the limiting value of contact angle (90°) attained is around 4 h 4 min. The surface hydrophobicity measured in terms of contact angle plays a crucial role in the electrical discharge phenomenon for high-voltage insulators. Under wet climatic conditions, isolated water droplets may form on the insulator surface, which does not help in electrical discharge under high voltage. However, continuous loss of hydrophobicity aids in the formation of a continuous water line

through coalescence of a number of droplets, providing an easy path for electrical discharge.

It is important to note here that the average service life obtained from accelerated UV aging under high-intensity UV radiation is significantly less than that of samples subjected to natural aging, especially when hydrophobicity is considered as a variable factor. This reveals that perhaps the mechanism of degradation under high-intensity UV radiation is different from that under low-intensity UV radiation available from sunrays. The extent of degradation is also substantially high when the sample is subjected to high-intensity UV radiation for a shorter time compared to actual insulators under the natural aging process under normal sunlight during their service.

4. SUMMARY AND CONCLUSIONS

A slow but steady deterioration of normal properties occurs for polymeric insulators during service. From the natural aging process, lifetime prediction can be done from variation of EB and change in hydrophobicity. The lifetime estimated from EB is found to be around 23–24 years with a limiting residual EB value of 50%, whereas when it is measured from the change in hydrophobicity, the average service life is around 20 years, with a limiting contact angle value of 90°.

However, in real-life situation, if the contact angle reduces below 90°, it does not make the insulator surface highly hydrophilic and sensitive to electrical discharge under wet conditions. In fact, these aged insulators still can provide some more years of service life. The estimation of service life from the contact angle measurement has certain practical limitations: attainment of equilibrium in contact angle measurement is rather difficult. There is a loss of hydrophobicity due to different kinds of aging processes such as electrical discharge, UV radiation, heat aging, and high-intensity rain during service life. However, there is a regain of hydrophobicity for PDMS insulators, which is a time-dependent process as discussed earlier, and the regain process slows down with service life (aging time). Therefore, estimation of service life from EB is more reliable compared to that from contact angle measurement.

The probable service life estimated from accelerated aging conditions under high-temperature and high-power UV radiation is substantially less than that obtained from natural aging. The comparison of results obtained from natural aging and accelerated aging reveals that these two degradation processes are governed by two different mechanisms. However, both accelerated aging tests under high-temperature and high-intensity UV can provide useful information about rate of aging and service life.

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