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Performance Evaluation of 230 kV Polymer Insulators in the Coastal Area of Saudi Arabia

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ABSTRACT This article investigates the technical performance of 230 kV field-aged composite insulators in the coastal region of Saudi Arabia. Two insulator samples removed from the 230 kV line after 20 years of service are assessed at KFUPM High Voltage Lab (KHVL). Different assessment techniques, such as visual inspection, contact angle, surface pollution severity, electrical withstand, and material characterization are utilized to evaluate the insulator performance. Equivalent salt deposit density (ESDD) and non-soluble deposit density (NSDD) techniques are used for the surface pollution severity measurements. Clear views of surface changes and surface hydrophobicity conditions are displayed. Scanning electron microscope (SEM), energy dispersive x-ray spectrometry (EDX), and Fourier-transform infrared spectroscopy (FTIR-IR) techniques are utilized for the material characterization. The visual inspection reveals small and big cracks in the insulator sheds. Hard breakable portion areas, many shed cuts, changed color areas, and whitish parts are visually noticed in the insulator surface. Such changes confirm the aging condition effect of the insulator units. Furthermore, the samples are subjected to laboratory clean fog tests to check the electrical performance of the samples. Informative results are given for the current condition and performance for the 20-years, field-aged insulators. Additionally, the experimental results are presented for the rest of the insulator life period. Utilization of the existing line insulators has been evaluated. Finally, discussions and recommendations for the future handling of the insulators at the 230 kV line are highlighted.

INDEX TERMS High voltage insulator, silicon rubber insulator, flashover, materials evaluation.

I. INTRODUCTION

High voltage (HV) insulators are essentially used to provide the electrical insulation and mechanical support of a transmission lines hardware. The electrical performance of the composite insulators is normally affected by the environmental conditions such as wind speed, wind direction, rainfall, relative humidity, ultraviolet (UV) radiation, ambient temperature, adhesive soluble contaminants, and moisture contents [1]. The source and degree of the contamination, wind direction, particles adhesiveness, and insulator design can be considered as self-cleaning ways [1]. For example, heavy rains may wash off the insulator surface. However, both light rains and high relative humidity increase the moisture amount in the contamination and can lead to flashover [2], [3]. For high polluted areas like the coastal regions of Saudi Arabia, the insulator pollution becomes a very decisive factor in the transmission line system's reliability. Through the long periods of using different ceramic insulators, such as porcelain and glass, extensive washing programs were adapted to improve the insulator performance. Such troubling situations prompted using the silicone rubber composite insulators (SiR) in the transmission line system of Saudi Electricity Company (SEC), especially at the eastern operating area, to combat the pollution-caused outages [4], [5]. SiR is giving a very promising performance at 115 kV and 230 kV transmission systems [6]. The excellent pollution performance of SiR is mainly attributed to the surface hydrophobicity by preventing the formation of continuous polluted water film over the insulator surface [6].

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The characteristics, behavior and performance of SiR composite insulators (organic material) might be timely changed due to the environmental, mechanical, and electrical stresses. Solar radiation (especially UV), rain, corrosive atmosphere, marine and industrial pollution, and oxides of nitrogen are examples of environmental aspects. Depending on the shape of the insulating parts, terminal metal fitting, shedding material surface condition, and presence and distribution of pollution layers, electrical stresses -such as local electric field at the composite insulator surface - can be very intense [7]–[9]. Electrical surface tracking can be initiated by dry band arcing or current flow concentration. It is considered as an irreversible degradation that could be caused by the formation and development of electrically surface conducting paths [10]–[12]. It may occur on the air contacted surfaces or the contacting points between different insulating materials.

Similarly, when a composite insulator is polluted and wet, dry band arcing leads to some surface erosion. The erosion rate depends on the housing material and its fillers [13]. In addition, shallow surface traces can occur on composite insulators that have experienced partial arcs. These traces do not have detrimental effects if they are nonconductive. Surface aging may take the form of a whitish deposit on the surface during weathering. This behavior is termed as 'Chalking' [14]. Some weathering polymers induce a surface hardening, which becomes brittle, usually in a very small thickness (0.01mm to 0.1mm) and show micro-fractures like treeing. This treeing is very likely caused due to several involved interfaces. The performance evaluation of HV composite insulators has been extensively presented and evaluated [15]–[20]. The electrical and material properties of 15 years in-service 400 kV- polymer coastal insulators were assessed [15], [16]. The material aging was evaluated using many techniques, such as visual observation, hydrophobicity analysis, EDX, and FTIR for materials characterization. Additionally, the flashover test and leakage current (LC) monitoring techniques were used to evaluate the electrical performance of the insulator. Results revealed that the tested insulators suffered from the non-uniform aging on the surface of sheds and rods [16]. The non-invasive online monitoring techniques such as infrared and ultraviolet imaging, and heat propagation techniques were used to evaluate the polymer insulator performance [17]. High internal temperature of the insulator causes polymer degradation, however, a well-designed corona ring reduces the temperature gradients and corona activities [17]. In [18], the polymer insulators were investigated using hydrophobicity analysis, LC monitoring, chemical composition, and surface microstructure tests.

Different artificial and naturally polluted samples were tested for 2, 5, 10, and 15 years in service. Results showed that the hydrophobicity of the field-aged insulators declines from HC1 for 2-year service to HC5 for 15-year service. In addition, with aging, LC is increased due to the surface conductivity expansion. Moreover, surface microstructure analysis showed that many micro-pores and polar chemical groups are formed on the insulator surface with aging. In [19], LC technique was employed to estimate the contamination level and hydrophobicity. The wavelet transform was used to correlate the LC with contamination level and hydrophobicity. While both detection of the dry band arcing beginning and correlating the average value of LC with composite insulator surface damage were investigated [20]. It has been found that the average level of both fundamental and third harmonic component of LC is well correlated with the different damage degrees of non-ceramic insulators surface.

In [21] for composite insulators, collected from hot and humid area, a comprehensive study on the aging characterization and life span prediction was presented for 391 samples. The insulators were used in the field between 3 and 22 years. Both electrical erosion resistance and mechanical property were the core aging factors affecting the life span of the insulators. In addition, the mechanical properties of insulators were highly affected by the migration of white carbon black, compared with the effect of electric field. Furthermore, the authors recommended replacing gradually the insulators which were in the field more than 19.2 years. In [22], an evaluation of field-aging effects on the insulating materials (EPDM and VMQ/HCR) of 150KV costal composite suspension insulators after the same service life of 17 years has been conducted. The resistance against tracking, erosion and chalking was investigated. The results showed that the field-aging was more severe for the EPDM housing material. In addition, the chalking was more severe close to the insulator fitting ends. In [23], a potential decay measurement on specimens of in-service HVDC aged composite insulator sheds were done to evaluate the insulation material degradation. The authors found that these measurements could be used for determining the degree of the material degradation. Due to birds nesting activity, the flashover effect on a 150 kV suspension SiR equipped with arcing horns has been studied [24]. Visual inspection showed that arcing caused an excessive damage to the arcing horns. However, there were non-critical effects on the insulator housing. In addition, the hydrophobic properties of the housing material found a different degradation extent due to differently structured materials and contamination levels [24], [25].

In this article, a comprehensive study is considered as a part of superior investigation to conduct and determine a viable methodology for evaluating and eventually predicting the aging characteristics of the existing SiR insulators in wide varieties of atmospheric conditions. The performance of the collected insulator samples is tested using the following electrical, chemical, and material evaluation techniques:

I. Visual inspection
II. Hydrophobicity classification per STRI Guide 92/1
III. Electrical testing
IV. Measurement of equivalent salt deposit density of pollution (ESDD)
V. Measurement of non-soluble deposit density of pollution (NSDD)

VI. Conduct material characterization evaluation using the following techniques:
   a. Scanning Electron Microscopy (SEM)
   b. Energy Dispersive X-Ray Spectroscopy (EDX)
   c. Fourier Transform Infra-Red Spectroscopy (FTIR-IR).

II. INSULATOR SAMPLES

The two insulator samples removed from a 230 kV transmission line near the coast of Saudi Arabia at the Arabian Gulf after 20 years of service are tested. This 230 kV line extended through the coastal Kingdom area and is located 2 to 4 km away from the sea. The insulator did not record any tripping events for the whole service period. However, heavy corona and scintillations were reported. The details of the two insulators are shown in Table 1 and Fig. 1a. The two field samples were brought to the High Voltage Laboratory (KHVL) of King Fahd University of Petroleum & Minerals (KFUPM). For optimal usage of the field insulator samples at the HV Lab and to conduct all required tests, each unit was subdivided into different sectors as explained in Fig. 1b. Ranging from visual inspection to highly advanced material characterization sophisticated techniques, various tools and techniques have been addressed to understand the insulator aging from its early inception to the ultimate failure.

III. VISUAL INSPECTION

The two SiR composite insulator units were received wrapped in plastic sheets at KHVL. The samples were visually checked, recorded, numbered, and photographed, as shown in Figs. 2 & 3. Both units show surface cracks in many sheds and portions of the cores, housing, sever erosion in some areas, dryness and surface brittleness of many sheds, color change, and sheds deformations. The insulator shows surface moderate pollution deposits, which may be due to transportation. The insulator units are still mechanically sound and there is no breakage or cuts in the core and end fittings.

IV. HYDROPHOBICITY

Hydrophobicity levels have been checked at KHVL as per STRI approach. It is clearly noticed that the insulator surface hydrophobicity is HC6 as shown in Fig. 4, which indicates the loss of hydrophobicity from the insulator surface.

V. ELECTRICAL TESTS

Using the test procedures, electrical testing has been conducted for the field insulator samples at KHVL [1]. the test procedures shown in Fig. 5 are presented as follows:

The insulator string unit is placed in the fog chamber and energized with the targeted voltage.

1. Steam fog is injected to the fog chamber at a rate of $0.074\ kg/h/m^3$.
2. After 20 minutes, the voltage is increased step by step. At each step, the voltage is increased by a 10% level for 5 minutes until a flashover occurs.

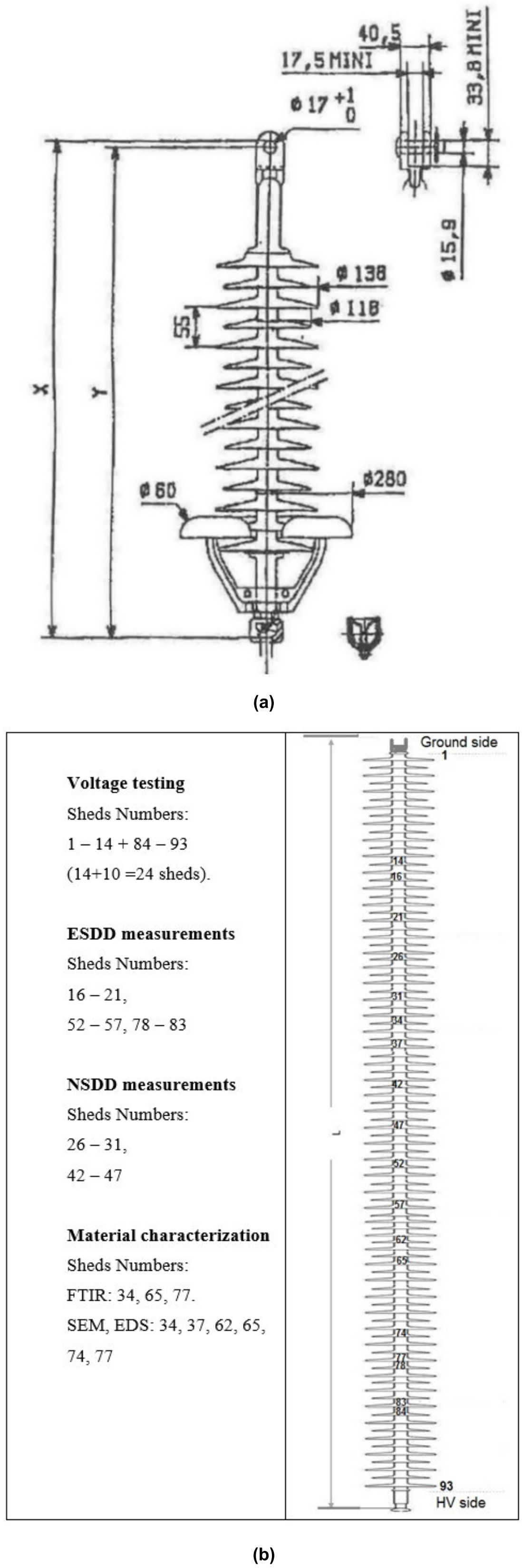


FIGURE 1. (a) Insulator sample details, (b) The SEC field insulator sample for testing.

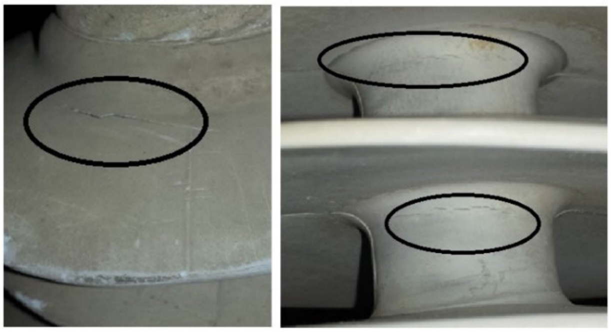


FIGURE 2. Insulator surface cracks.

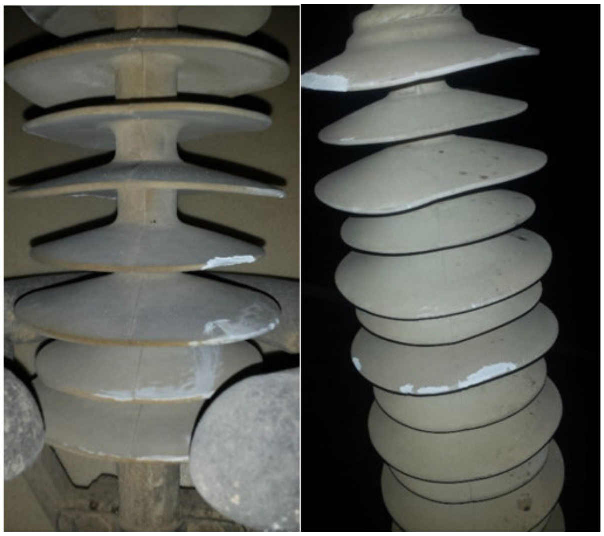


FIGURE 3. Surface dryness, erosion, cracks, deformed sheds, medium surface deposits and color changes in the insulator.

FIGURE 4. Surface hydrophobicity of the insulator units, HC6.

3. The withstand voltage will be determined as the one step lower voltage than flashover voltage.

The electrical test has been conducted on the portion of the 24 sheds insulator to accommodate the facilities limitations of the HV test as shown in Fig. 6. It has been prorated

TABLE 1. Insulators details.

Line info.	About 2 to 4 km from sea
Tower Structure.	Double circuit
Voltage level	230 kV
Manufacturer	SEDIVER Insulators, 1995
Sample Type	ARMOURSIL Suspension insulator (SiR polymer)
Creepage distance	46 mm/kV
Number of sheds	93
Insulator spacing X	2833mm
Shed spacing	55mm
Socket fitting complies with	ANSI 52-5
Arcing distance	2537 mm
Leakage distance ± 2%	10647mm
Total tested leakage distance	2744 mm
Approximate weight with ring	16.7kg
Dry Low frequency flashover voltage	895 kV
Wet Low frequency flashover voltage	820 kV
Positive Critical impulse flashover voltage	1530 kV
Negative Critical impulse flashover voltage	1550 kV
Specified mechanical load	120 KN
Specified mechanical Routine test load	60 KN

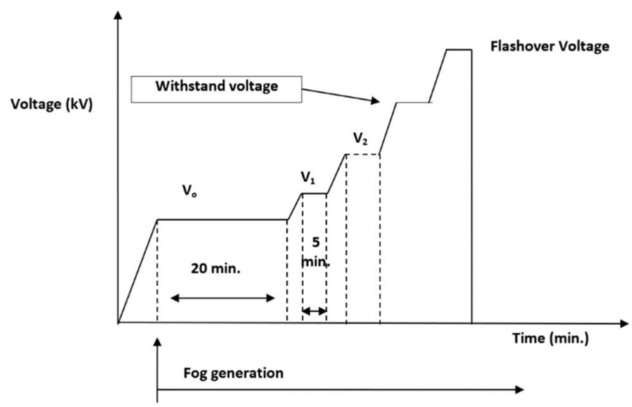


FIGURE 5. Withstand Voltage Test as per NGK testing approach.

linearly to calculate the withstand voltage for each unit based on the creepage distance ratio. The initial voltage of 100 kV is selected based on our experience with similar types of insulators. The results are shown in Table 2. Both units showed similar results.

VI. POLLUTION LEVEL MEASUREMENTS

The pollution sample was removed from the selected sheds of the insulator samples for Equivalent Salt Deposit Density (ESDD) and Non-Soluble Deposit Density (NSDD) levels measurements. In addition, deposit samples have been investigated for chemical analysis.

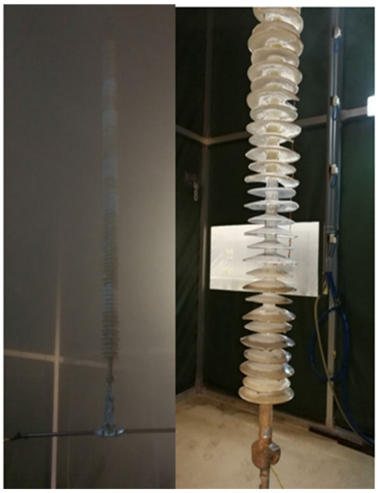


FIGURE 6. Electrical testing Chamber of the field insulator unit.

TABLE 2. Electrical test results for field insulator unit #1.

No	Voltage Level (KV)	Time duration (Min.)	Comments Tested portion: 24 out of 93 sheds	
1.	100	20	Starting voltage for 20 minutes	
2.	110	5	Voltage step =10 kV	
3.	120	5	Voltage step =10 kV	
4.	130	5		
5.	140	5		
6.	15	5		
7.	160	5		
8.	170	5	Withstand Voltage	
9.	180	45 sec	Flashover	
Withstand Voltage (kV) for the tested portion				170 kV
Withstand Voltage (kV) for the whole unit				659.6 kV

TABLE 3. ESDD results for the insulators.

No.	Insulator description	ESDD (mg/cm^2)
1	Insulator #1	0.260
2	Insulator # 2	0.234

A. ESDD LEVELS

Careful removals of the deposits from portions of the insulators have been carried out at KHVL. The surface areas of the SiR insulator have been calculated. The results are shown in Table 3.

B. NSDD LEVELS

Sample deposits of the insulator contaminates have been checked to measure the non-soluble parts of the deposits. Results are shown in Table 4.

VII. MATERIAL AGING EVALUATION

For different sample materials of the insulator units, SEM, EDX, and FTIR-IR instruments and analytical facilities have been utilized to evaluate the aging conditions of samples at KHVL.

TABLE 4. NSDD results for the insulators.

No.	Insulator description	NSDD (mg/cm^2)
1	Insulator #1	0.855
2	Insulator # 2	0.464

A. SEM/EDX ANALYSIS

Twelve specimens sectioned from the various insulator sheds have been used for characterization using SEM/EDX analysis at the material characterization lab at KFUPM, (Model #: JEOL JSM 6610LV). For insulator #1, six specimens have been labelled as 1-34, 1-37, 1-62, 1-65, 1-74 and 1-77. While for insulator # 2, another six specimens have been labelled as 2-34, 2-37, 2-62, 2-65, 2-74 and 2-77. Each specimen has been obtained from a different shed. The shed specimens have been retrieved from the insulator samples. As expected, the shed specimens were laden with desert sand and dust. Silicone rubber material generally degrades over the time while being subjected to outdoor conditions such as heat, humidity, dust, and industrial pollutants. To evaluate the kinds of changes associated with the aging process of SiR as manifested at the top layers of the sample surfaces, special imaging facilities have been utilized to obtain the surface conditions and the chemical analysis of the surface material using sophisticated techniques, namely scanning electron microscope (SEM), and energy dispersive x-ray spectrometer (EDX), (Oxford Instruments XMax-50 SSD).

The aim of this study is to determine the degree of degradation and decomposition of the SiR material due to the outdoor exposure. The procedures of the compositional analysis have been performed and described by Gorur *et al.* [26], [27]. To remove the dust and sand settled over the specimen surfaces, gently washing with soap and ultrasonic cleaning have been performed for 15 minutes. The specimen surfaces have been coated with platinum (Pt) to reduce the charging effects and to improve the imaging in the scanning electron microscope. Due to the polymer surface coating, the (Pt) peaks in the EDX spectra have been observed. The specimens have been examined using JEOL JSM 6610LV scanning electron microscope. Secondary electron imaging (SEI) has been used to study the surface morphology at an accelerating voltage of 20 kV. Elemental analysis has been performed at different accelerating voltages ranging from 3kV to 9 kV using an energy dispersive X-ray spectrometer (EDX) fitted with an ultra-thin window. EDX spectra has been obtained at 9 kV for each analyzed specimen. Low molecular weight (LMW) polymer chains at the insulator surface are responsible for its hydrophobicity.

Aging of insulators leads to the depolymerization and depletion of these chains at the surface. The insulating property of silicone rubber material is degraded. LCs increase

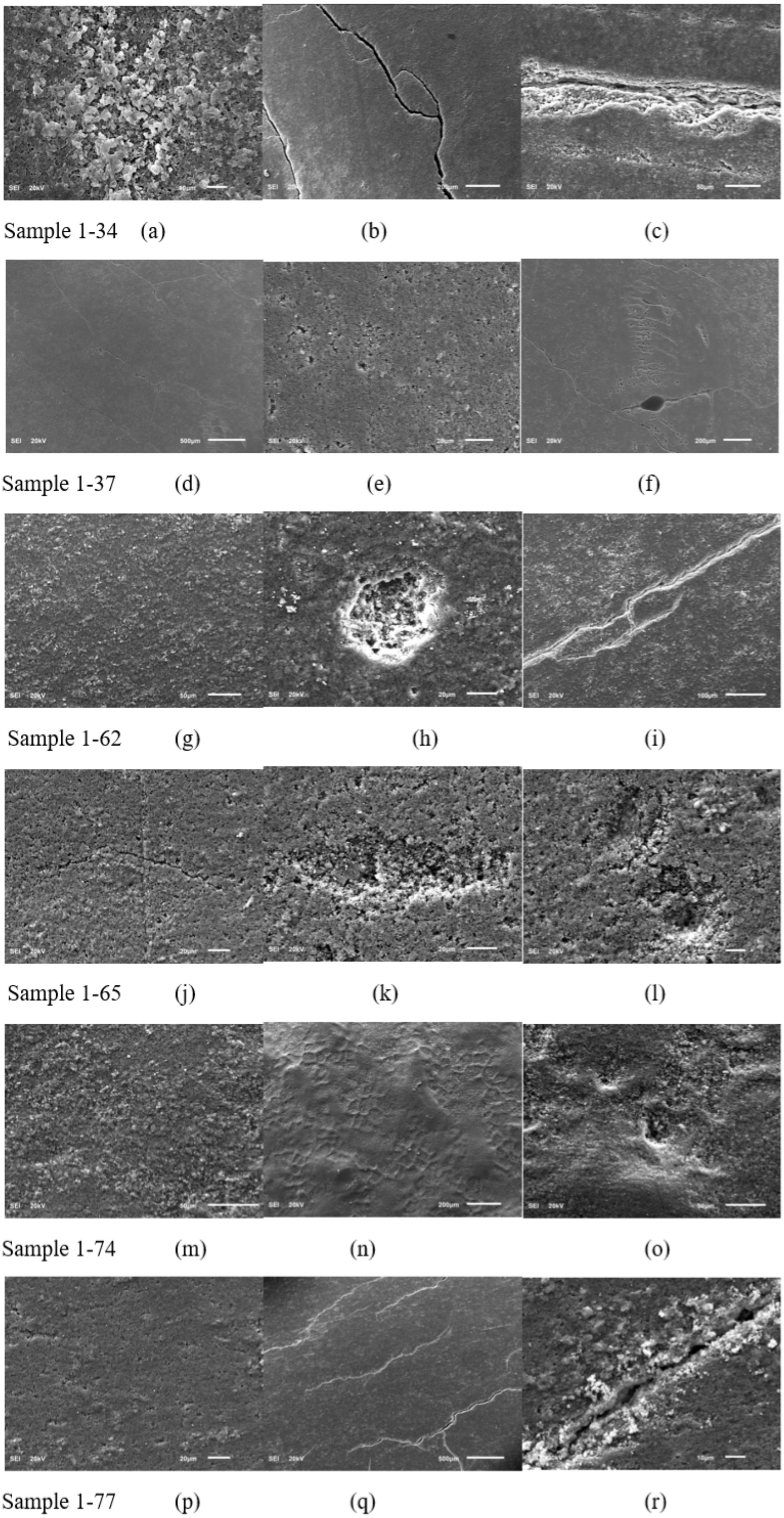


FIGURE 7. SEM Imaging: Specimens 1-34, 1-37, 1-62, 1-65, 1-74 and 1-77.

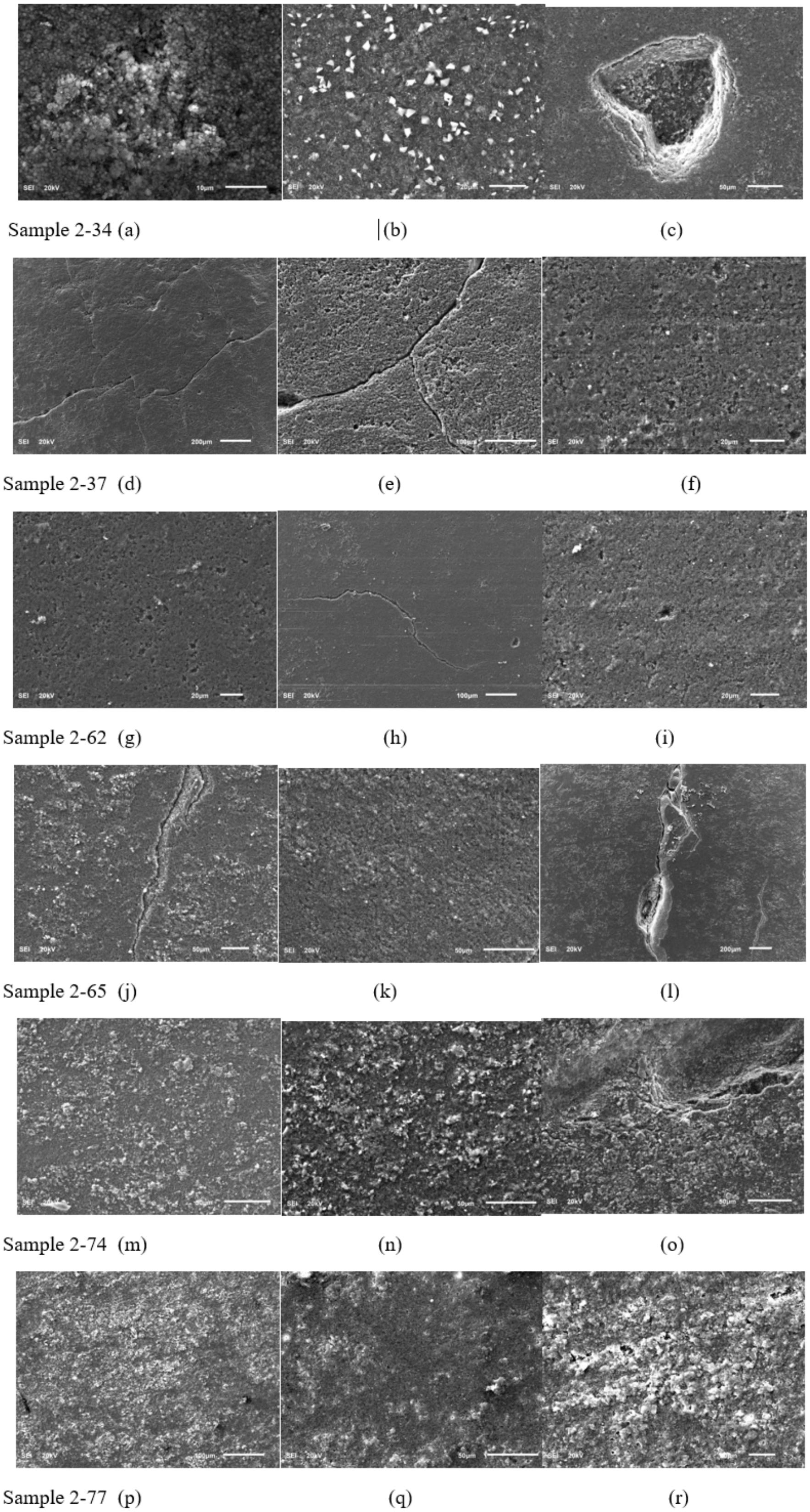
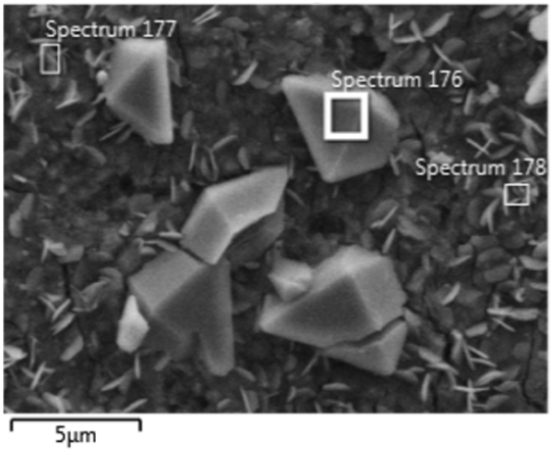
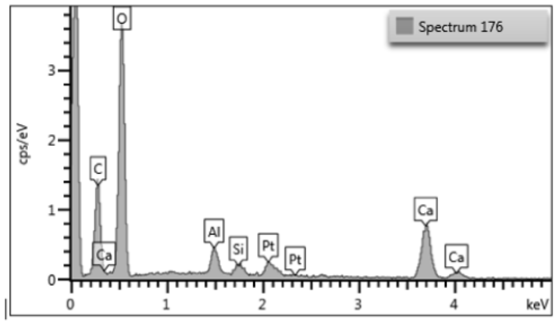


FIGURE 8. SEM Imaging: Specimens 2-34, 2-37, 2-62, 2-65, 2-74 and 2-77.



(a)



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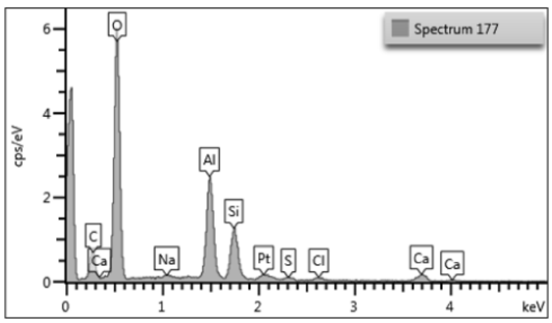

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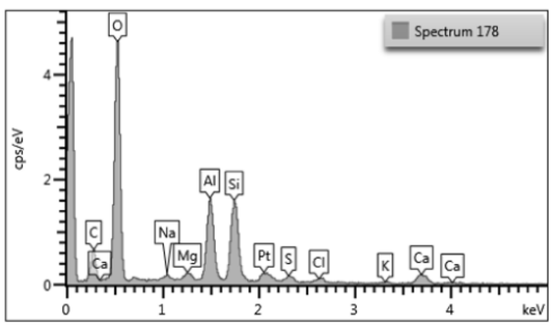

(d)

FIGURE 9. (a) Secondary electron (SEM) image showing coarse Ca-rich faceted particles and thin Al-rich flakes. The (b, c, d) EDX spectra obtained from these particles.

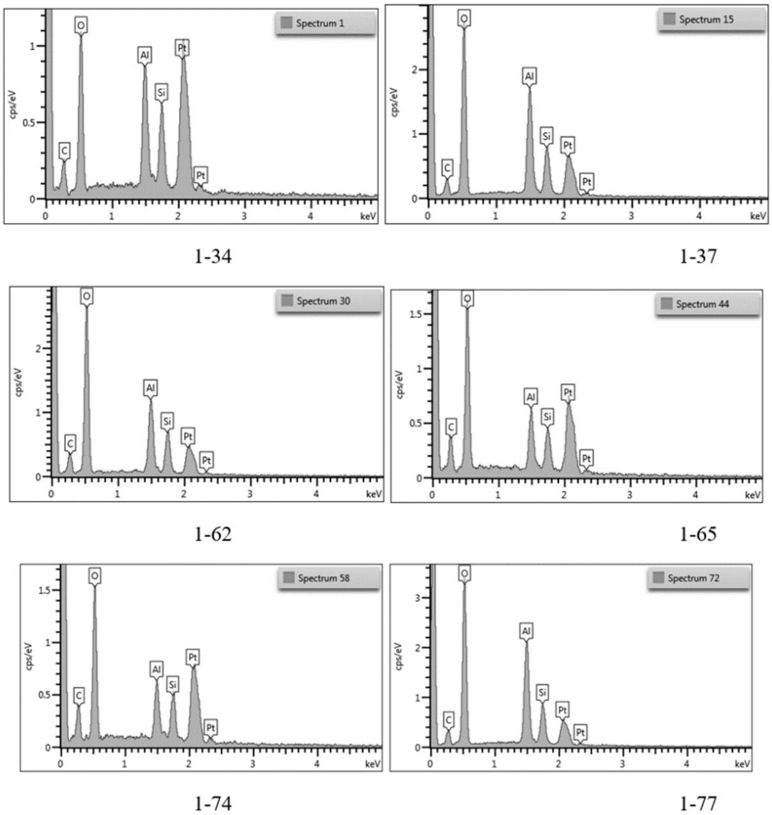

FIGURE 10. EDX spectra obtained from shed specimens of Insulator No. 1 at beam energy of 9 keV.

if the initial hydrophobic surface becomes hydrophilic due to the depletion of LMW polymer chains at the surface, which can be caused by dry band arcing. Permanent material surface changes affect the insulator degradation over the time [26]–[28]. These changes reduce the quantity of the LMW polymer chains and increase the LCs [26]. This quantity reduction of LMW chains decreases the Si/Al ratios. Therefore, the field insulator is expected to depict lower Si/Al ratios compared to the unused/virgin samples. Additionally, aging increases the surface roughness of the insulator, clusters the filler particles and reduces the tracking and erosion resistance [26]. Materials degradation spreads from layer to layer. During the aging process, the dry band arcs remove the top layers and undergo the below layers. Alumina trihydrate (ATH) has been added as a filler material to SiR to improve their tracking and erosion resistance. Degree of roughness and elemental constitution of the polymer surface associated with the insulator electrical properties can be used to evaluate the insulator material. The SEM/EDX has been used to study the associated changes with the aging process of SiR by examining the morphology and analyzing the chemical composition of the top surface layers of the specimens.

Insulator #1: SEM Imaging for Specimens 1-34, 1-37, 1-62, 1-65, 1-74 and 1-77:

The secondary electron (SEM) images are shown in Fig. 7. All six shed specimens obtained from insulator #1 exhibit a coarse and rough surface morphology suggestive of extensive surface damage. The roughness of the top surface layers is obvious throughout all specimens, signifying widespread material degradation. Evidence of uniform smooth morphology generally observed in the unused specimens or that of localized patches of smooth area seen in partially degraded insulators was not detected on any of the specimens observed. The surface exhibited large voids, rougher patches, and long deep cracks at the specimen surface. These cracks have been observed in all specimens, as clear signs of surface damage.

Insulator #2: SEM Imaging for Specimens 2-34, 2-37, 2-62, 2-65, 2-74 and 2-77:

Secondary electron (SEM) images obtained from insulator #2 illustrated at Fig. 8 exhibit coarse rough morphology indicative of the surface degradation. Cracks and voids are apparent in all specimens. Coarse faceted particles enriched in Ca are observed in specimen No. 2-34, as shown in Fig. 9a. Additionally, sharp fine flakes rich in Al can be observed in the background as depicted in Fig. 9a. Fig. 9 (b, c, d) illustrates an obtained EDX spectra for various locations shown in Fig. 9a. These filler additives occasionally become apparent once the surrounding matrix of polymer disintegrates. It signifies the polymer aging.

In summary, the surface morphology of all specimens belonging to both insulators shows evidence of roughness, large cracks and coarse voids, which are indicative of severe

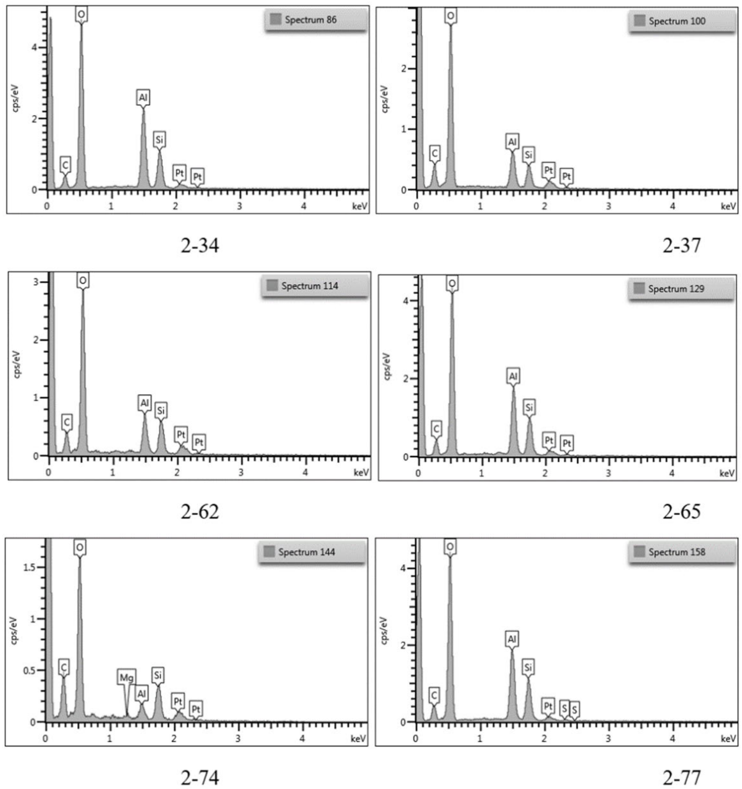

FIGURE 11. EDX spectra obtained from shed specimens of Insulator No. 2 at beam energy of 9 keV.

TABLE 5. Si/Al composition ratios obtained from shed specimens.

Insulator #	Shed #	3kV	4 kV	5 kV	6 kV	7 kV	8 kV	9 kV
New sample		13:3	11:41	5:72	3.85	2.92	2.56	2.19
Insulator #1	34	3.012	2.183	1.605	1.203	0.882	0.888	0.809
	37	2.299	1.678	1.187	0.933	0.766	0.612	0.560
	62	2.904	1.673	1.792	1.160	0.921	0.796	0.722
	65	2.773	1.901	1.633	1.312	1.126	1.081	0.843
	74	6.216	1.258	1.265	1.269	1.063	1.083	0.984
	77	1.314	1.425	0.909	0.695	0.558	0.531	0.479
Insulator #2	34	3.089	1.793	1.278	0.906	0.734	0.680	0.578
	37	1.573	2.467	1.258	1.150	1.009	0.779	0.741
	62	2.725	3.257	2.000	1.779	1.500	1.238	1.050
	65	3.169	2.267	1.500	1.124	0.983	0.741	0.670
	74	3.123	3.381	1.822	3.207	2.019	3.186	2.726
	77	3.404	1.871	1.294	1.077	0.910	0.763	0.691

surface degradation. Evidence of clustering of filler particles is found in one of the specimens which points toward aging process.

Energy Dispersive X-ray Spectroscopy (EDX) for Specimens 1-34, 1-37, 1-62, 1-65, 1-74 and 1-77, and Specimens 2-34, 2-37, 2-62, 2-65, 2-74 and 2-77:

Energy dispersive x-ray spectroscopy (EDX) has been performed at different accelerating voltages ranging from 3 to 9 kV. For insulators # 1 and # 2. The EDX spectra have been obtained as shown in Figs. 10 and 11, respectively. Moreover, the obtained Si/Al ratios using the elemental EDX analysis are presented in Table 5. Through the entire range of beam energies (3-9 keV), the Si/Al ratios show a considerable variation with respect to new sample indicating an absence of a protective Si-rich LMW chains in the bulk of the polymer insulator. Lack of a high Si/Al ratio indicates degradation or rough surface. It is exactly the same conclusion that came with the SEM imaging. The depletion of LMW polymer

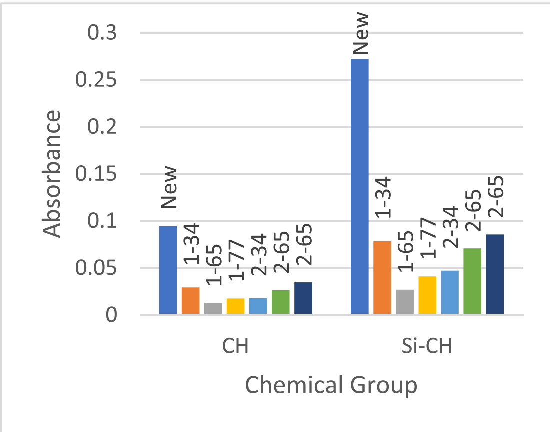

FIGURE 12. Absorbance level comparison for chemical groups.

TABLE 6. FTIR Absorbance levels of insulators at various frequencies in wavenumbers.

Insulator /Shed number	Absorbance at 2960 cm^{-1}	Absorbance at 1260 cm^{-1}
New sample	0.94473952	0.27205229
Insulator 1-34	0.02923484	0.078365539
Insulator 1-65	0.012691326	0.026872146
Insulator 1-77	0.017593071	0.041006335
Insulator 2-34	0.017955021	0.047159143
Insulator 2-65	0.026318081	0.070785496
Insulator 2-77	0.034751249	0.085551059

chains allows the contamination at the surface to absorb water and form a thick water film. This has led to reduce the surface resistance and increase the LC.

At a beam energy of 3 keV, the beam penetration into the specimen is the lowest and it increases when the beam energy increases. In addition, the beam penetration depth provides an elemental information from the top layers of the surface. The obtained Si/Al composition ratios are low (2-3.4 wt%) for all specimens. Furthermore, LMW polymer chains that presented at the surface which are rich in Si are consumed due to the degradation.

B. FTIR-IR ANALYSIS

Insulator samples have been submitted to The Central Analytical Laboratory at KFUPM to study the aging effects on six polymeric insulators after being exposed under different conditions. The samples were analyzed using FTIR (Nicolet 370) spectrometer with DTGS detector. The analysis was conducted with Smart Orbit high-performance diamond single-bounce ATR accessory. The used IR range was 4000 cm^{-1} to 400 cm^{-1} with a resolution of 4 cm^{-1}. A constant pressure was set for all the samples. The spectra were analyzed for the following regions:

a) Wave number @2960 cm^{-1} for the CH chemical group
b) Wave number @1260 cm^{-1} for the Si-CH chemical group

The results of the samples analyzed by the FTIR technique are shown in Table 6. Comparing with the new sample, the absorbance levels decreased in the above-mentioned regions, as when a sample undergoes decomposition due to aging or exposure to the environmental conditions. Moreover, the absorbance intensities of Insulator samples (1 and 2) decreased at 2960 cm^{-1}, and 1260 cm^{-1} respectively. Both had lower absorbance intensities compared to the new sample, as presented in Fig. 12. This indicates that Insulators samples (1 and 2) underwent degradation compared to the new one [21].

VIII. CONCLUSION

In this article, the performance of naturally field-contaminated insulator samples is tested using various electrical, chemical, and material evaluation techniques at KFHVL. The visually checked samples show surface cracks in several sheds and core housing portions, severe erosion in some areas, dryness and surface brittleness of many sheds, color changes, and shed deformations. The hydrophobicity tests and contact angle measurements indicate that the insulator surface hydrophobicity is HC6. The results of the material characterization techniques confirm the erosion and surface deterioration of the insulator sheds. For the two insulators, the ESDD and NSDD results display surface medium pollution deposits, which could be attributed partially to transportation of the samples. The samples did not show any breakage or cuts in the insulator core and end fittings. Moreover, from the electrical test, the insulators still have an excellent pollution performance. The insulators electrical performance is quite accepted because of the superior performance of the composite insulators. However, it is recommended to create a program to check all similar insulators of the same age and consider replacement based on the overall assessment. Finally, the continual service monitoring of the insulator can provide further correlation of surface structure/chemistry and its hydrophobicity.

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