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Aging Process Evaluation Method of Silicone Rubber in Composite Insulators in Natural Environmental Experiment Station

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ABSTRACT In this paper, silicone rubber on composite insulators from three different manufacturers with an operating duration between 1 and 10 years were sampled. In order to investigate the law of diminishing performance of these samples in aging process, widely adopted aging process evaluation test methods such as Hydrophobicity test, Water absorption test were performed. Based on test results, parameters significantly correlated with operating time were obtained by means of correlation calculation. Finally, considering the differences of parameter values among three manufacturers, the relative decrease value (denoted as w) of parameters was proposed as a unified standard and the equivalent equations between w and operating time were established for predicting lifespan of composite insulators in high altitude area. Test results indicate that parameters including saturated water absorption ratio δ_s, the relative content of Si and O elements (X_{Si} and X_O) are significantly correlated with operating time, and these three parameters can be used to characterize aging degree of composite insulators. Besides, for the relative error σ_1 between theoretical operating time calculated by the equivalent relationship obtained in this paper and actual operating time is less than 20%, within the allowable error range of engineering practice, this equation can be applied to predict the operating time of composite insulators from three manufacturers in future research.

INDEX TERMS Composite insulators, aging properties, equivalent relationship, aging characterization.

I. INTRODUCTION

Since the 1960s, composite insulators were widely used in power transmission line systems [1]–[4]. As operating time went by, most composite insulators lost their hydrophobicity and allowed cracks and voids appearing in the superficial material of silicone rubber, resulting in pollution flashover and ice flashover accidents [5]–[8].

Over the past few years, scholars carried out plenty of researches to evaluate aging process properties of composite insulators. In literature [9]–[11], researchers evaluated the aging properties of composite insulators in aging process through measuring hydrophobicity in the superficial material of silicone rubber. In literature [11]–[12], images captured by Scanning Electron Microscope (SEM) were used to analyse the aging degree of composite insulators in aging process.

On this basis, some researchers proposed one or several parameters concluded from research results to characterize aging degree of composite insulators. In literature [12]–[14], Static Contact Angle (CA) method and FTIR method were employed to evaluate aging properties of composite insulators with different aging time, and parameters static contact angle and absorption peak altitude of main functional groups were proposed to characterize aging degree of composite insulators of the same manufacturer. In literature [15], aging properties of 391 composite insulators were evaluated through testing contamination, hydrophobicity, porosity analysis and so on of samples, and parameters such as the equivalent salt deposit density (ESDD), static contact angle (CA), porosity were proposed to establish the lifespan prediction model of silicone rubber in composite insulators.

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FIGURE 1. Aging environments of composite insulators in a high altitude area experimental station.

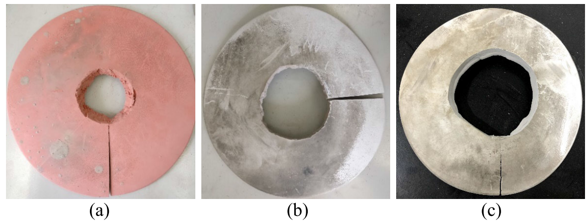

FIGURE 2. Silicone rubber rings from composite insulators. (a) Samples from Factory A. (b) Samples from Factory B. (c) Samples from Factory C.

TABLE 1. Samples of composite insulators with different aging years.

Operating time/year	Manufacturer		
	A	B	C
1	A_1	B_1	C_1
3.5	A_2	B_2	C_2
6	A_3	B_3	C_3
8	A_4	B_4	C_4
10	A_5	B_5	C_5

According to the current research of studying aging characterization of composite insulators, parameters such as static contact angle, hardness, images captured by SEM were commonly accepted [16]–[17]. However, due to the ignorance of the great influence of different compositions on aging process properties of composite insulators in aging process, the accuracy of the equivalent relationship obtained in most research is doubtful.

This work described in this paper was focused on establishing the equivalent equation where operating time of composite insulators from different manufacturers in high altitude area can be predicted widely. The main contents in this paper were divided into three parts. Sample, experimental setups and procedure of test methods such as CA method and Water absorption test method for different composite insulators are shown in Section 2. Results and analysis of aging process properties including physical, chemical and electrical properties of composite insulators are shown in Section 3. In Section 4, the correlation calculation of parameters of aging process properties for different composite insulators are shown in Part *A*, while the aging process evaluation method and verification are shown in Part *B*.

II. SAMPLE, EXPERIMENTAL SETUPS AND TEST PROCEDURE FOR DIFFERENT AGING COMPOSTIE INSULATORS

A. SAMPLE

In this research, composite insulators from three different manufacturers (denoted as A, B, C) exposed in natural environmental experiment station located in XueFeng mountain of Hunan province (as shown in Figure 1) for 1 – 10 years, were sampled, as shown in Table 1.

In order to evaluate the aging process properties of silicone rubber in composite insulators, silicone rubber rings were cut off from composite insulators, as shown in Figure 2.

B. EXPERIMENTAL SETUPS AND TEST PROCEDURE

Based on previous research [18], several widely accepted methods which can be used to evaluate aging process properties were employed for composite insulators from different manufacturers aged for different years.

1) PHYSICAL PROPERTIES

a: CA (STATIC CONTACT ANGLE) METHOD

Static contact angle in the superficial material of silicone rubber was measured through DropMeter A-100P. CA test criterion is based on IEC/TS 62073 - 2003 [19], where CA test results are divided into two parts. In this standard, if static contact angle of samples is more than 90 °, silicone rubber is regarded as hydrophobic material; on the contrary, silicone rubber is regarded as hydrophilic material. Three samples from the same insulator were selected, and each sample was tested for six times. The average of test results, denoted as θ_{av}, was obtained for comparing the hydrophobicity between composite insulators aged for different years.

b: WATER ABSORPTION TEST METHOD

Water absorption test of samples was performed in a bucket, as shown in Figure 3. In Figure 3, TH is a hygrothermograph placed on the wall of the bucket to ensure the temperature constant in 20 ± 3 ° and the humidity constant in 100%. Samples were placed on a glass plate which is 10 cm above the deionized water surface. In preparation, all samples should be dried until the quality of samples (denoted as m_0) no longer decreased in air dry oven, where temperature was constant in 40 °.

When testing, the measuring process was divided into three stages. The first stage is 0 – 8 hours of experiment, in which the sample quality was tested every 1 hour. Sample quality of composite insulators was tested every 8 hours within 8 - 40 hours of the second stage. And during the last 168 hours, sample quality was tested every 24 hours. The ratio of water absorption, denoted as σ_t, could be obtained, as shown in Eq. (1).

$$\sigma_t = \frac{m_t - m_0}{m_0} \times 100\% \tag{1}$$

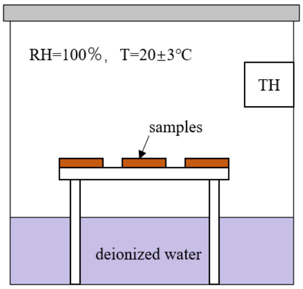

FIGURE 3. Water absorption testing device.

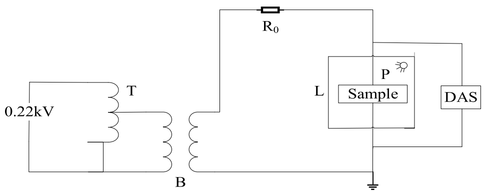

FIGURE 4. Schematic diagram of the AC test circuit.

where, m_t is sample quality in tth hour, g; m_0 is the original sample quality, g.

2) CHEMICAL PROPERTIES

a: FTIR (FOURIER TRANSFORM INFRARED SPECTROSCOPY) METHOD

The ALPHA Fourier infrared spectrometer produced by Bruker Company was used in infrared spectral measurement of samples. Absorption peak altitude of main functional groups ranged from 500 cm^{-1} to 4000 cm^{-1} were obtained for comparing chemical properties of composite insulators aged for different years in ATR mode.

b: XPS (X-RAY PHOTOELECTRON SPECTROSCOPY) METHOD

In order to further study chemical properties of composite insulators, X-ray photoelectron spectroscopy(XPS) was carried out in this research by ESCALAB 250Xi energy dispersive system, and relative content of main elements was obtained.

3) ELECTRICAL PROPERTIES

a: Salt-fog flashover test method

In this paper, salt-fog flashover test was carried out in testing hall of Chongqing University. The power is supplied by the YDJ-5/50 AC testing transformer, of which the frequency is 50 Hz. The test circuit is shown in Figure 4, where B is the voltage regulator, T is the test transformer, R_0 is the protective resistance, L is artificial fog chamber, P is ultrasonic water mist generator, DAS is voltage measuring system, Sample is the silicone rubber with the size of 6 cm×4 cm. Electrodes were installed on both sides of the sample to meet the test requirement DLT 859 - 2004 [20], as shown in Figure 5.

Before the test, all samples were cleaned with anhydrous ethanol and water so that all traces of dirt were removed. Then

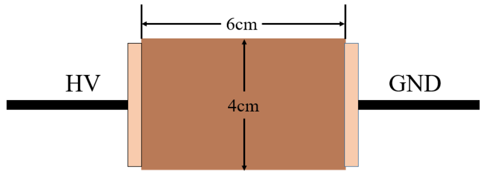

FIGURE 5. Diagram of the samples.

samples were left to dry indoors for 24 hours to avoid dust and other pollution.

According to DLT 859 - 2004 [20], the concentration of salt-fog in this study is 1000 μS/cm, and samples should be wetted in salt-fog environment for 15 minutes to meet the test requirements. When testing, the uniform boosting method was adopted, in which applied voltage increases uniformly until flashover occurred. To enhance the accuracy of test results, three pieces of the sample from the same manufacturer with the same operating time were selected and each for three repeated tests, and the average value of flashover voltage was obtained to compare electrical properties between composite insulators aged for different years. The average flashover voltage U_f, the voltage gradient E_L and the relative standard deviation error $\sigma\%$ are calculated as follow:

$$U_f = \frac{\sum_{i=1}^{N} U_i}{N} \tag{2}$$

$$E_L = \frac{U_f}{d} \tag{3}$$

$$\sigma\% = \sqrt{\frac{\sum_{i=1}^{N}(U_i - U_f)^2}{N-1}} \cdot \frac{100\%}{U_f} \tag{4}$$

where, U_i is an applied flashover voltage, kV; N is total number of tests; U_f is the average flashover voltage, kV; E_L is the voltage gradient, kV/cm; d is the arc development path of samples, $d = 6$ cm in this paper; $\sigma\%$ is the relative standard deviation error.

III. TEST RESULTS AND ANALYSIS OF AGING PROCESS PROPERTIES OF COMPOSITE INSULATORS

A. PHYSICAL PROPERTIES

1) HYDROPHOBICITY

Due to excellent hydrophobicity of silicone rubber, composite insulators with silicone rubber as shed has good anti-pollution performance. With an increase of operating time, anti-pollution performance of samples becomes worse, which leads to an increase of possibility of pollution flashover. To study this phenomenon, CA test method was adopted, and test results were shown in Table 2.

Table 2 presents the following:

(i) In initial, loss and recovery phase, change regularities of static contact angle are similar. With the increase of operating time, static contact angle of composite insulators in three phases gradually decreases in aging process.

TABLE 2. Hydrophobicity test results on samples in aging process.

Phases	Initial Phase			Loss Phase			Recovery Phase		
Aging time/year	A	B	C	A	B	C	A	B	C
1	110.9	110.7	110.6	84.3	82.1	81.2	105.8	106.3	111.6
3.5	108.8	106.7	104.8	83.4	79.3	79.9	102.1	103.3	105.7
6	102.7	102.6	99.7	82.9	77.4	76.1	100.6	102.1	94.1
8	94.8	93.3	92.2	81.1	70.1	72.9	92.2	95.3	91.8
10	87.6	84.6	80.8	78.1	70.6	68.7	85.5	86.4	83.1

(ii) The hydrophobicity of samples in initial, loss and recovery phase is different. In Table 2, static contact angles of composite insulators from three manufacturers are all above 90 ° within 8 years, which indicates that these composite insulators are still in good condition and can be regarded as hydrophobic material according to IEC/TS 62073 - 2003 [19]. Compared with the static contact angles in initial phase, static contact angles in loss phase decrease by 10.8% - 26.5%, which leads to a decrease of hydrophobicity of samples and these composite are all regarded as hydrophilic material according to IEC/TS 62073 - 2003 [19]. After drying indoors for 24 hours, static contact angle of samples in recovery phase is similar to that in initial phase and it indicates that the hydrophobicity of samples recovers to the state of the initial stage.

2) WATER ABSORPTION TEST

With the increase of operating time, more cracks appear in the superficial material of composite insulators, which leads to the increase of water absorption performance of samples. After absorbing water, the physical, chemical and electrical properties of silicone rubber will change. Besides, water is the key factor which affects the performance of silicone rubber. In this paper, the water absorption test was performed to analyze the relationship between the water absorption of composite insulators and operating time. The relationship between the ratio of water absorption σ_t and water absorption time was shown in Figure 6.

Figure 6 presents the following:

(i) The change regularities of the water absorption ratio σ_t of composite insulators from three manufacturers with testing time are similar, which are mainly divided into three parts including 0 - 8 hours, 8 - 40 hours and 40 - 240 hours. In 0 - 8 hours, due to the dry state of silicone rubber, water absorption speed of samples is the fastest; In 8 - 40 hours, with the increase of water content, the water absorption speed slows down; In 40 - 208 hours, the water content in silicone rubber reaches saturation, and water absorption speed is the slowest at this stage.

(ii) In the same humidity environment, there are some differences of the water absorption speed among composite insulators aging for different years. With the increase of operating time, the water absorption speed of composite insulators gradually increases. For example, the water absorption ratio of samples aged for 1, 6 and 10 years from Factory A at

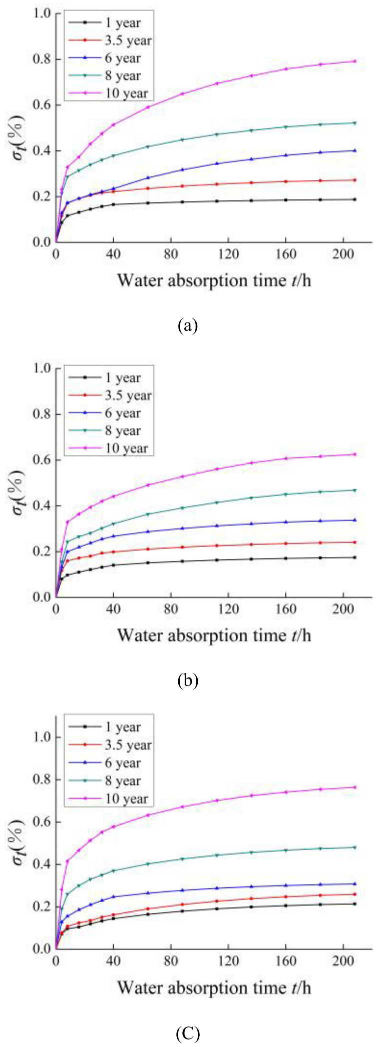

FIGURE 6. Water absorption regularity of samples of composite insulators in aging process. (a) Samples from Factory A. (b) Samples from Factory B. (c) Samples from Factory C.

8 hour is 0.088%, 0.173% and 0.329% respectively; Besides, the water absorption ratio at 40 hour is 0.134%, 0.235% and 0.517% respectively; Finally, the water absorption ratio at 208 hour is 0.172%, 0.401% and 0.791% respectively.

The differences of compositions in composite insulators from different manufacturers will result in the differences in the water absorption speed of samples. Thus, the method, comparing the water absorption ratio of different samples at a certain time cannot reflect the differences in the water

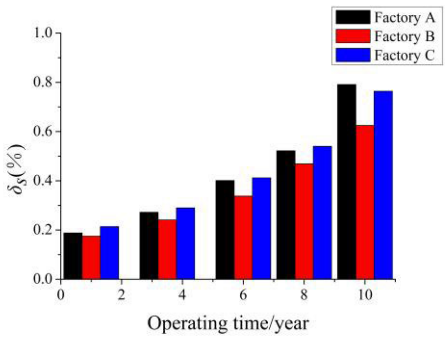

FIGURE 7. Saturated water absorption ratio of samples in aging process.

TABLE 3. Key absorption peaks of silicone rubber in FTIR analysis.

Functional groups	Wavenumber/cm^{-1}
O-H	3700-3200
CH_3(C-H)	2960
C-H	1440-1410
Si-CH_3(C-H)	1270-1255
Si-O-Si(Si-O)	1100-1000
O-Si(CH_3)$_2$-O(Si-O)	840-790
Si(CH_3)$_3$	800-700

absorption performance of composite insulators accurately. In this paper, the saturated water absorption ratio δ_s was proposed in this paper as the parameter to characterize the water absorption performance of composite insulators, and results of δ_s of samples from three manufacturers are shown in Figure 7.

In Figure 7, the increase of operating time leads to an gradually accelerating increase of the saturated water absorption ratio of composite insulators. Through comparing δ_s of samples, it can be found that the saturated water absorption ratio of samples from Factory A aged for 3.5, 6, 8, 10 years is 0.59, 1.35, 2.95, 3.63 times that of samples aged for 1 year. The increase trend of the saturated water absorption ratio of samples from Factory A gradually accelerates with an increase of operating time. And the saturated water absorption ratio of samples from other two manufacturers all follows this change regularity.

B. CHEMICAL PROPERTIES

1) FTIR TEST

Fourier transform infrared spectroscopy (FTIR) has been widely adopted in material analysis to obtain an infrared spectrum of absorption of samples. Key absorption peaks corresponded to functional groups in silicone rubber material are listed in Table 3 and test results of main functional groups of samples from Factory A, B and C are shown in Figure 8–10 respectively.

Figure 8–10 present the following:

(i) The main functional groups of samples from three manufacturers are consistent, and there are no new key functional groups appearing in the superficial material of samples in the aging process.

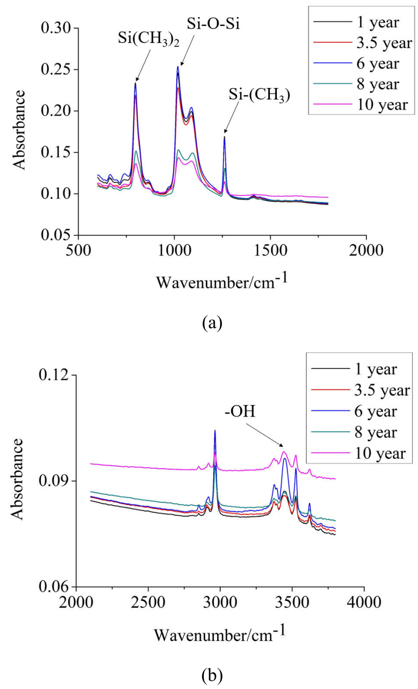

FIGURE 8. FTIR analysis results of samples from Factory A in aging process. (a) Wavenumber between 500 ∼ 2000 cm^{-1}. (b) Wavenumber between 2000 ∼ 4000 cm^{-1}.

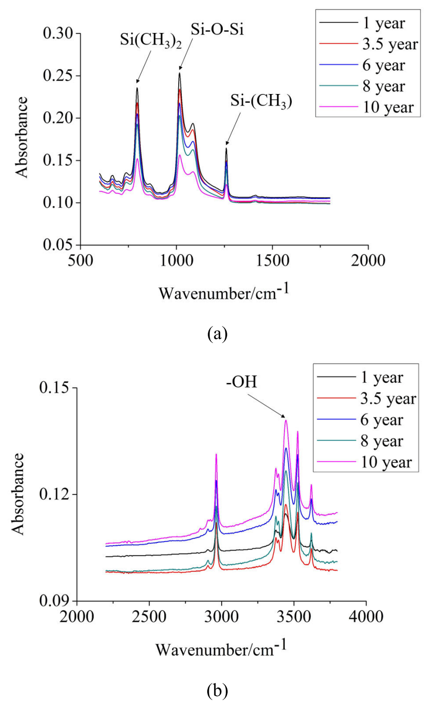

FIGURE 9. FTIR analysis results of samples from Factory B in aging process. (a) Wavenumber between 500 ∼ 2000 cm^{-1}. (b) Wavenumber between 2000 ∼ 4000 cm^{-1}.

(ii) With the increase of operating time, it leads to a decrease of the absorption peak altitude of Si-O-Si at wavenumber 1100 ∼ 1000 cm^{-1} and Si-(CH_3)$_2$ at wavenumber 840 ∼ 790 cm^{-1} as well as an increase of the absorption peak altitude of –OH at wavenumber 3700 ∼ 2800 cm^{-1}.

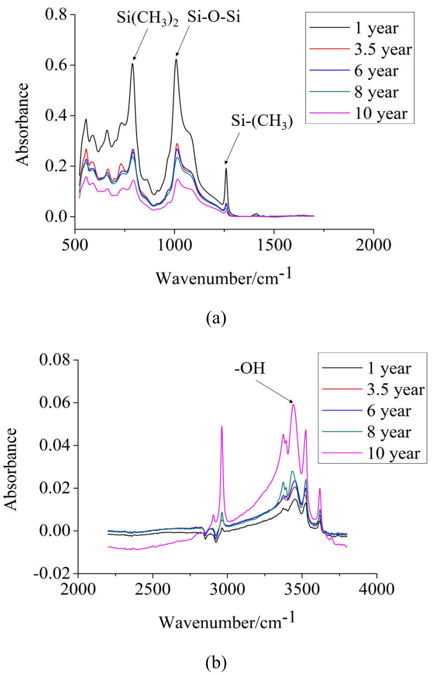

FIGURE 10. FTIR analysis results of samples from Factory C in aging process. (a) Wavenumber between 500 ∼ 2000 cm^{-1}. (b) Wavenumber between 2000 ∼ 4000 cm^{-1}.

TABLE 4. Results of *H* of composite insulators in aging process.

Operating time/year	*H*		
	Factory A	Factory B	Factory C
1	0.9681	0.9302	0.9664
3.5	0.9569	0.9304	0.9400
6	0.9588	0.9259	0.9381
8	0.9529	0.9232	0.9260
10	0.9429	0.9097	0.9276

However, due to the different compositions of composite insulators from three manufacturers, analyzing differences of absorption peaks altitude between typical functional groups cannot reflect changes of chemical properties of composite insulators. In previous research, researchers indicate that the ratio of the absorption peak altitude of Si-O-Si to C-H can reflect the relative content of its side bond, which is the key reason for the changes of chemical properties in aging process [21]. In this paper, the ratio (denoted as H) of Si-$(CH_3)_2$ absorption peak altitude to Si-O-Si absorption peak altitude is used to characterize aging degree of composite insulators, and test results of H of samples from three manufacturers are shown in Table 4.

2) XPS TEST

In order to further study the chemical properties of composite insulators in aging process, XPS test method was employed in this paper to analyze the relative content of main elements of composite insulators. Test results of Si, C, O, Al, Fe and Pt elements of samples from three manufacturers are shown in Table 5–7.

TABLE 5. The relative content of main elements of samples from factory A in aging process.

Samples	Si(%)	C(%)	O(%)	Al(%)	Fe(%)	Pt(%)
A_1	21.88	47.17	28.17	2.49	0.18	0.11
A_2	21.3	47.01	28.99	2.4	0.18	0.12
A_3	20.49	46.18	30.8	2.18	0.23	0.12
A_4	19.33	44.56	32.94	2.82	0.22	0.13
A_5	18.11	44.09	34.79	2.65	0.23	0.13

TABLE 6. The relative content of main elements of samples from factory B in aging process.

Samples	Si(%)	C(%)	O(%)	Al(%)	Fe(%)	Pt(%)
B_1	22.71	45.74	29.3	2	0.12	0.13
B_2	21.86	44.86	30.8	2.14	0.14	0.2
B_3	21.21	43.11	33.1	2.27	0.14	0.17
B_4	20.09	41.71	35.93	1.94	0.17	0.16
B_5	19.18	40.83	37.74	2	0.12	0.13

TABLE 7. The relative content of main elements of samples from factory C in aging process.

Samples	Si(%)	C(%)	O(%)	Al(%)	Fe(%)	Pt(%)
C_1	22.51	41.85	30.77	4.54	0.06	0.27
C_2	21.75	40.19	32.72	5.15	0.06	0.13
C_3	20.88	38.62	35.36	4.83	0.05	0.26
C_4	19.64	36.44	38.48	5.06	0.13	0.25
C_5	18.62	36.23	40.22	4.62	0.07	0.24

Table 5–7 presents the following:

(i) With the increase of operating time, the relative content of Si and C elements in the superficial material of samples from three manufacturers gradually decrease, which results in the decrease of Si-O-Si and Si-$(CH_3)_2$ absorption peak altitude in aging process.

(ii) With the increase of operating time, the relative content of O element in the superficial material of samples from three manufacturers gradually increases, which leads to an increase of –OH absorption peak altitude in aging process.

(iii) With the increase of operating time, there are few changes in the relative content of Al, Fe and Pt elements, which indicates that the factor aging in high altitude area will not cause the relative content of elements such as Al, Fe and Pt to change in aging process.

C. ELECTRICAL PROPERTIES

1) SALT-FOG FLASHOVER TEST

In this paper, the salt-fog flashover test was carried out to analyze the change regularity of salt-fog flashover voltages with the increase of operating time, and test results are shown in Table 8.

Table 8 presents the following:

(i) With the increase of operating time, salt-fog flashover voltage of samples from three manufacturers gradually decreases. For samples from Factory A, salt-fog voltage of samples at 3.5, 6, 8 and 10 year is 13.71, 13.23, 12.40 and 11.42 kV respectively, which decrease by 3.86%,

TABLE 8. Test results of salt-fog flashover voltage of samples in 1000μS/cm environment in aging process.

Operating time(year)	Factory A			Factory B			Factory C		
	U_f(kV)	σ(%)	E_L(kV/cm)	U_f(kV)	σ(%)	E_L(kV/cm)	U_f(kV)	σ(%)	E_L(kV/cm)
1	14.3	4.0	2.4	15.1	2.2	2.5	13.9	3.3	2.3
3.5	13.7	4.1	2.3	14.6	4.5	2.4	13.3	4.9	2.2
6	13.2	3.5	2.2	14.2	4.1	2.4	12.8	2.3	2.1
8	12.4	2.1	2.1	12.1	3.8	2.0	11.2	2.1	1.9
10	11.4	3.5	1.9	10.6	3.2	1.8	10.0	4.8	1.7

TABLE 9. Aging parameters of samples from three manufacturers.

No.	Aging parameters	Test methods
1	θ_{av}	Static contact angle of the surface of samples in initial phase
2	δ_S	Saturated water absorption ratio of samples
3	H	The ratio of $Si\text{-}(CH_3)_2$ absorption peak altitude to Si-O-Si absorption peak altitude
4	X_{Si}	Relative content of Si element of samples
5	X_C	Relative content of C element of samples
6	X_O	Relative content of O element of samples
7	U_{y1}	Salt-fog flashover voltage of samples in 1000µs/cm

7.22%, 13.04%, 19.9% compared with samples at 1 year in 1000 μs/cm salt-fog environment.

(ii) With the increase of operating time, E_L of samples gradually decreases, but they are all within the range where composite insulators can maintain excellent electrical performance. For samples aged for 10 years from three manufacturers, salt-fog voltages of A_5, B_5 and C_5 are 1.90, 1.76 and 1.67 kV/cm respectively.

IV. AGING PROCESS EVALUATION METHOD OF COMPOSITE INSULATORS

A. CORRELATION PARAMETERS ANALYSIS OF AGING PROCESS PROPERTIES FOR COMPOSITE INSULATORS

In Section 3, aging properties of samples from three manufacturers are measured through CA test method, Water absorption test method, FTIR method, XPS method and Salt-fog flashover test. Through analyzing test results of aging effects, some parameters which can be used to characterize aging degree are concluded and listed on Table 9.

In this section, Person correlation analysis calculation was employed and the correlation coefficient r was proposed to analyze the correlation between these parameters and operating time.

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(t_i - \bar{t})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(t_i - \bar{t})^2}} \quad (5)$$

where, x_i is the aging characterization parameters of ith sample; t_i is aging year of ith sample; $\bar{x}$ is the mean value of aging characterization parameters of samples aged for different years; $\bar{t}$ is the mean value of operating time of samples aged for different years.

Besides, T-test was employed to verify the significance of the correlation coefficient r of samples from three manufacturers and the results of T-test were denoted as α.

$$T = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \sim t(n-2) \quad (6)$$

where, if $\alpha > 0.05$, it indicates that two variables are irrelative with each other; if $0.01 < \alpha \leq 0.05$, it indicates that two variables are correlated; if $\alpha \leq 0.01$, it indicates that two variables are significantly correlated.

The correlation calculation results of aging characterization parameters are shown in Table 10.

Based on test results of correlation analysis, the conclusion that parameters including static contact angle θ, saturated water absorption ratio of samples δ_S, the relative content of Si, C and O element are significantly correlated with operating time. Besides, parameter U_{y1}(salt-fog flashover voltage of samples in 1000 μs/cm) is correlated with operating time.

Meanwhile, the partial correlation method was employed to test the independence of these significantly correlated parameters, and operating time is taken as control variable. The analysis method is similar to that of correlation calculation between different parameters. If the significance of the independent hypothesis $\alpha > 0.05$, the hypothesis is true and two variables are non-independent variables; Otherwise, these two parameters are independent with each other. The calculation results are listed on Table 11–13.

TABLE 10. Correlation between operating time and aging parameters of samples.

Parameters	Factory A		Factory B		Factory C		Correlation
	r	α	r	α	r	α	
θ	-0.972	0.0055	-0.972	0.0075	-0.975	0.0055	Significant negative correlation
δ_S	0.963	0.0095	0.963	0.0045	0.969	0.0065	Significant positive correlation
H	-0.929	0.0225	-0.929	0.0515	-0.910	0.0325	Irrelevance
X_{Si}	-0.979	0.0045	-0.979	0.0015	-0.990	0.0015	Significant negative correlation
X_{C}	-0.955	0.0115	-0.987	0.0015	-0.985	0.0025	Negative correlation
X_{O}	0.982	0.0035	0.982	0.0015	0.994	0.0015	Significant positive correlation
U_{y1}	-0.978	0.0045	-0.978	0.0185	-0.963	0.0095	Negative correlation

TABLE 11. The calculation results of the independence of significantly correlated parameters of factory A.

Parameters	$\alpha(\theta)$	$\alpha(\delta_S)$	$\alpha(X_{Si})$	$\alpha(X_O)$
$\alpha(\theta)$	0	0.192	0.033	0.003
$\alpha(\delta_S)$	0.192	0	0.103	0.234
$\alpha(X_{Si})$	0.033	0.103	0	0.052
$\alpha(X_O)$	0.003	0.234	0.052	0

TABLE 12. The calculation results of the independence of significantly correlated parameters of factory B.

Parameters	$\alpha(\theta)$	$\alpha(\delta_S)$	$\alpha(X_{Si})$	$\alpha(X_O)$
$\alpha(\theta)$	0	0.024	0.037	0.184
$\alpha(\delta_S)$	0.024	0	0.117	0.222
$\alpha(X_{Si})$	0.037	0.117	0	0.221
$\alpha(X_O)$	0.184	0.222	0.221	0

TABLE 13. The calculation results of the independence of significantly correlated parameters of factory C.

Parameters	$\alpha(\theta)$	$\alpha(\delta_S)$	$\alpha(X_{Si})$	$\alpha(X_O)$
$\alpha(\theta)$	0	0.028	0.158	0.669
$\alpha(\delta_S)$	0.028	0	0.162	0.623
$\alpha(X_{Si})$	0.158	0.162	0	0.215
$\alpha(X_O)$	0.669	0.623	0.215	0

Based on calculation results in Table 11–13, parameters except static contact angle θ and relative content of C element are all independent with each other, and these parameters including saturated water absorption ratio δ_S, the relative content of Si and O elements (X_{Si} and X_O) can be used in characterizing aging degree of composite insulators in aging process.

B. AGING PROCESS EVALUATION METHOD AND VERIFICAITION

In previous research, some scholars proposed some parameters to analyze aging degree of composite insulators from one single manufacturer. Due to the influence of different compositions of composite insulators from three manufacturers to the initial value of parameters, it is difficult to conclude the methods where aging degree of composite insulators from different manufacturers can be characterized quantitatively.

In this paper, although the initial values of each characterization parameter are different among samples from different manufacturers, the change regularity of parameters is similar with the increase of time and the aging degree of composite insulators can be characterized by the relative decrease value compared with the initial value of parameters. The relative decrease value (denoted as w) compared with the initial value was proposed as a unified standard to characterize the aging degree of composite insulators from different manufacturers.

$$w = \frac{x_t - x_1}{x_1} \times 100\% \tag{7}$$

where, x_t is the value of parameters at tth year; x_1 is the initial value of parameters at 1 year.

The results of w of parameters including δ_S, X_{Si} and X_O are shown in Table 14–16.

TABLE 14. The change regularity of the saturated water absorption ratio δ_S.

Operating time/year	Factory A		Factory B		Factory C	
	δ_S	w(%)	δ_S	w(%)	δ_S	w(%)
1	0.188	0	0.175	0	0.214	0
3.5	0.272	45.1	0.241	37.7	0.29	35.5
6	0.401	113.9	0.338	93.1	0.412	92.5
8	0.522	178.4	0.469	168	0.54	152.3
10	0.791	321.9	0.625	257.1	0.764	257

TABLE 15. The change regularity of the relative content of Si element X_{Si}.

Operating time/year	Factory A		Factory B		Factory C	
	X_{Si}	w(%)	X_{Si}	w(%)	X_{Si}	w(%)
1	21.89	0	22.71	0	22.51	0
3.5	21.30	-2.67	21.86	-3.74	21.75	-3.38
6	20.49	-6.37	21.21	-6.61	20.88	-7.24
8	19.33	-11.67	20.19	-11.10	19.64	-12.75
10	18.11	-17.25	19.18	-15.54	18.62	-17.28

TABLE 16. The change regularity of the relative content of Si Element X_O.

Operating time/year	Factory A		Factory B		Factory C	
	X_O	w(%)	X_O	w(%)	X_O	w(%)
1	27.67	0	29.30	0	30.77	0
3.5	27.99	4.30	30.80	5.12	33.72	6.34
6	28.8	11.31	33.11	12.99	35.36	14.92
8	32.44	19.05	35.93	22.63	38.48	25.06
10	34.79	25.73	37.74	28.81	40.22	30.72

TABLE 17. Aging parameters significantly correlated with operating time of composite insulators in aging process.

Operating time/year	w_1(%)		
	δ_S	X_{Si}	X_O
1	0	0	0
3.5	39.43	-3.26	5.25
6	99.83	-6.74	13.07
8	166.23	-11.84	22.25
10	278.67	-16.69	28.42

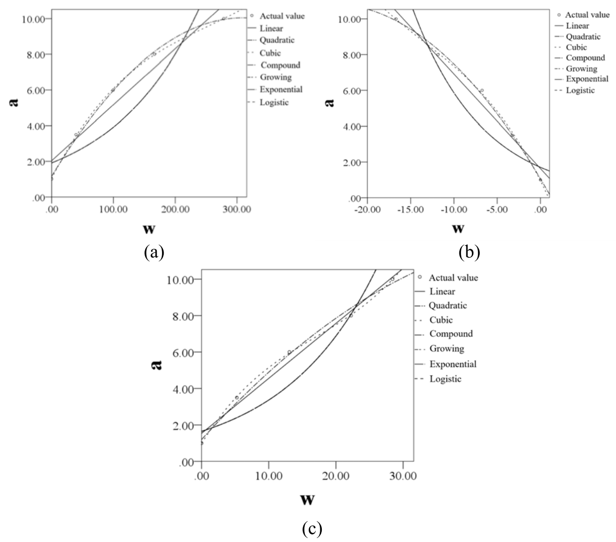

FIGURE 11. The estimated regression calculation of parameters with operating time. (a) δ_S (b) X_{Si}. (c) X_O.

In order to establish the equivalent relationship between w of parameters significantly correlated with operating time and operating time, the median (denoted as w_1), which can reflect the centralization trend of parameter in mathematical statistics, was proposed to represent the decreasing trend of parameters from different manufacturers at the same aging year. The results of w_1 of relative decrease values are listed on Table 17.

In this paper, SPSS, a data processing software, is used to perform the estimation regression calculation of w of parameters including δ_S, X_{Si} and X_O with operating time, and calculation results are shown in Figure 11.

Figure 11 presents that the cube of w of parameters fits well with operating time, which can be used to obtain the equivalent relationship between these parameters and operating time as follow:

$$\begin{cases} y = 0.0000005x_1^3 - 0.0003x_1^2 + 0.0768x_1 + 0.9995 \\ y = -0.0007x_2^3 - 0.0349x_2^2 - 0.9322x_2 + 0.9396 \\ y = 0.0005x_3^3 - 0.0238x_3^2 + 0.6131x_3 + 0.9786 \end{cases} \quad (8)$$

where, x_1 is the w of saturated water absorption ratio δ_S; x_2 is the w of the relative content of Si element X_{Si}; x_3 is the relative content of O element X_O; y is the operating time.

In this paper, σ_1 is defined as the relative error between the actual operating time y and theoretical operating time y_1. Results of σ_1 of different parameters are shown in Table 18–20.

$$\sigma_1 = \frac{|y - y_1|}{y} \times 100\% \quad (9)$$

TABLE 18. The error of operating time based on δ_S between theoretical value and actual value in aging process.

Operating time/year	σ_1(%)		
	Factory A	Factory B	Factory C
1	0.05	0.05	0.05
3.5	11.40	0.14	3.71
6	9.90	0.79	1.13
8	0.11	2.43	6.20
10	13.13	5.88	5.90

TABLE 19. The error of operating time based on X_O between theoretical value and actual value in aging process.

Operating time/year	σ_1(%)		
	Factory A	Factory B	Factory C
1	6.04	6.04	6.04
3.5	8.77	13.56	6.25
6	5.96	3.39	2.08
8	2.22	0.70	7.73
10	2.28	3.75	2.39

TABLE 20. The error of operating time based on X_{Si} between theoretical value and actual value in aging process.

Operating time/year	σ_1(%)		
	Factory A	Factory B	Factory C
1	2.14	2.14	2.14
3.5	8.15	1.74	15.33
6	6.81	0.38	8.14
8	6.53	5.74	15.82
10	4.86	8.44	18.48

Table 18–20 presents that the relative error σ_1 of parameters including saturated water absorption ratio δ_S, the relative content of Si element X_{Si} and the relative content of O element X_O is less than 20%, which is within the allowable error range of engineering practice. In future research, when initial and current values of parameters including δ_S, X_{Si} and X_O have been obtained, operating time of composite insulators from these three manufacturers can be predicted by the Eq.(8).

V. CONCLUSION

This paper studies the aging properties of composite insulators aging in natural environmental experiment station through physical, chemical and electrical tests in aging process and explores aging characterization parameters based on test results. Considering the differences resulting from different components of three manufacturers, the relative decrease value (denoted as w) compared with the initial value was proposed as a unified standard, and the equivalent relationship significantly correlated parameters and operating time can be obtained based on the parameter w. The main conclusions are as follows:

(1) With the increase of operating time, the change regularity of aging properties of composite insulators from three manufacturers is similar in aging process: when the operating time increases, it will lead to an increase of the hydrophobicity, the relative content of O element and salt-fog flashover voltage of samples, and a decrease of the relative content of Si and C elements.

(2) Through calculating the correlating relationship between operating time and aging characterization parameters concluded from results of aging affects tests, it indicates that parameters including saturated water absorption ratio δ_s, the relative content of Si and O elements (X_{Si} and X_O) are significantly correlated with operating time. And these three parameters can be used to characterize aging degree of composite insulators from three manufacturers.

(3) The relative decrease value (denoted as w) of aging characterization parameters compared with the initial value was proposed as a unified standard to establish the equivalent relationship between aging parameters and operating time, and it turns out that the cube of w of parameters fits well with operating time by means of the estimation regression calculation.

(4) In this paper, the equivalent relationship between w of parameters and operating time was established. Through the verification, it turns out that the relative error σ_1 between theoretical operating time based on w of parameters including saturated water absorption ratio δ_S, the relative content of Si element X_{Si} and the relative content of O element X_O and actual operating time is less than 20%, which is within the allowable error range of engineering practice. Therefore, operating time of composite insulators from these three manufacturers aging in high altitude area can be predicted by the equivalent relationship obtained in this paper in the future research.

(5) The results and conclusions of this study are based on the samples exposed in high altitude area. In this case, whether the aging process evaluation method is applicable to other areas needs further verification and research.

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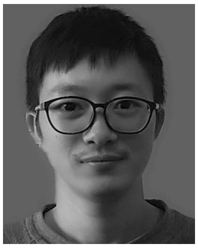

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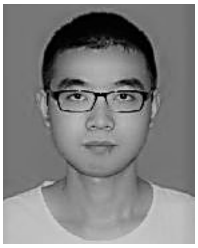

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