Effect of Ultraviolet—A Radiation on Alicyclic Epoxy Resin and Silicone Rubber Used for Insulators

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Abstract: Compared with the high-temperature vulcanized silicone rubber (HTVSR) insulator, the alicyclic epoxy resin insulator has higher hardness and better bonding between the core and the sheath. This makes the latter very promising in the coastal area of Southern China. Outdoor insulators are often subjected to high intensity of ultraviolet (UV)-A radiation. The influence of UV-A radiation is significant for alicyclic epoxy resin insulators. To help address the concern, the surface of two kinds of samples, namely the alicyclic epoxy resin insulator and HTVSR insulator, with UV-A aging time was characterized by tests of scanning electron microscope (SEM), X-ray photoelectron spectroscopy (XPS), and Fourier transform infrared spectroscopy (FTIR). The operation properties (mechanical properties, hydrophobicity) for outdoor insulators were also analyzed. It was found that the appearance color of the alicyclic epoxy resin has changed greatly, and there is a certain degree of fading. The mechanical properties of the alicyclic epoxy resin are maintained well and, the hydrophobicity decreases gradually. For silicone rubber, the appearance color change of silicone rubber is smaller, and the mechanical properties of silicone rubber decreased greatly. In addition, although the hydrophobicity of silicone rubber decreased gradually, it is still better than that of alicyclic epoxy resin. Both materials have broken chemical bonds, but the degree is relatively light, which meets the requirements of insulators for outdoor operation.

Keywords: alicyclic epoxy resin; hygrothermal environment; silicone rubber; ultraviolet-A radiation

1. Introduction

As an indispensable part of power transmission lines, insulators play an important role in mechanical support and electrical insulation. China began to develop composite insulators in the 1980s. Under the background of large-scale pollution flashover in the 1990s, composite insulators were widely used in China’s power transmission system for their excellent anti-pollution performance and easy maintenance [1–3]. Since then, high-temperature vulcanized silicone rubber (HTVSR) insulators have been used for more than 40 years [4–6]. However, silicone rubber, influenced by the inorganic fillers and its characteristic, is soft and vulnerable to external forces such as strong wind and birds peck, because of its characteristics of large molecular spacing and weak molecular interatomic forces [7–10]. When the mandrel is exposed to air, it suffers from the action of light, moisture, pollution, and mandrel mechanical performance degradation. In that case, it could lead to malignant accidents such as fracture of insulator string [11,12]. In order to solve these problems, some researchers brought forward a solution by replacing the insulating material of silicone rubber with alicyclic epoxy resin.

Insulators run outdoors all around the year. Long-term exposure to ultraviolet light will lead to photooxidation degradation of molecular materials. After aging, the mechanical
strength, surface hydrophobicity, and other macroscopic properties of insulating materials may change obviously. Ultraviolet light can be divided into ultraviolet (UV)-A, UV-B, and UV-C according to its wavelength. UVA stands for long wavelength in ultraviolet light with a wavelength between 400 nm and 315 nm. Most UVB and almost all UVC shortwave UV light are blocked by the atmosphere. However, due to the wavelength, 98% of UVA can pass through the earth’s atmosphere and reach the ground. Therefore, most of the UV light that reaches the earth’s surface is UVA [13].

Li carried out UV-A aging of silicone rubber materials for 1000 h [14]. The test result showed that with the increase of UV aging time, the tensile strength, elongation at break, volume resistivity, and surface resistivity of silicone rubber materials decreased while the hardness gradually increased. In addition, the breakdown strength first decreased and then increased. Gao compared the UV aging resistance of modified alicyclic epoxy material and silicone rubber material and found that although the UV aging resistance of modified alicyclic epoxy resin is slightly lower than that of silicone rubber materials, it still meets the requirements of outdoor insulation [15].

The ultraviolet aging mechanism of organic insulating materials has been studied in many works of the literature [16–19]. Under the action of UV aging, the chain segment fracture degradation process of organic insulating materials may occur. In this process, photooxidation and photodegradation reactions will cut the chemical bonds with low bond energy in organic insulating materials. Because of this reaction, the generated free radicals will undergo further oxidation and a certain degree of re-crosslinking reaction will occur between the severed chemical bonds. As a new type of insulator, the aging performance of alicyclic epoxy insulators needs to be compared with silicone rubber insulators to test their reliability after the operation.

Therefore, the UV aging resistance of alicyclic epoxy resin materials is studied in this paper. The alicyclic epoxy resin materials are exposed to UVA under the UV lamp and then taken out after different aging times. The tensile strength, tensile elongation, hydrophobic, scanning electron microscopy (SEM), Fourier infrared spectrum, and X-ray photoelectron spectroscopy were conducted to study the aging mechanism. Meanwhile, its aging resistance performance was compared with silicone rubber insulating material.

2. Experimental Works
2.1. Materials

The alicyclic epoxy resin samples used in this paper are made by an automatic pressure gel molding process by a manufacturer [20–22]. The formula and process of the test sample are the same as that of the 110 kV alicyclic epoxy insulator sheath produced by the manufacturer, and the HTVSR sample is produced by Dalian Insulator Group Co., Ltd. (Dalian, China). The basic chemical structures of the materials studied are shown in Figure 1.

(a) Polydimethylsiloxane  
(b) Alicyclic epoxy resin

Figure 1. The chemical structure of materials: (a) HTVSR; (b) alicyclic epoxy resin.
2.2. Methods

2.2.1. UV-A Aging Process

In this paper, the UV-A aging test was carried out with a UV aging test chamber produced by Esry Instrument Technology Co., LTD (Guangdong, China), as shown in Figure 2. The xenon lamp emitted a continuous spectrum from short-wave UV to infrared radiation. In order to simulate natural UV radiation reaching the earth's surface, the short-wave UV radiation below 300 nm of light was blocked to generate the UV radiation mainly composed of UV-A radiation [12,23]. The radiation distance between the radiation source and the specimens is 20 cm. The infrared light with low photon energy can heat the sample surface by radiation although the bonds in silicone rubber will not be broken. Therefore, the temperature was controlled by regulating the airflow of a fan. During the experiment, UV irradiance was set to 0.76 W/m². Moreover, the exposure period was set to 8 h dry irradiation and 4 h dark condensation. In these periods, the temperature was controlled at 60 °C during irradiation and 50 °C during condensation. The distance between the test sample and the lamp is 50 ± 3 mm. The surfaces of epoxy resin and HTVSR samples with different shapes are wiped clean with anhydrous ethanol and non-woven cloth. After that, the samples were placed on the test rack of the UV aging chamber for the UV aging test. The aging time was 0 h, 120 h, 240 h, 600 h, and 1000 h, respectively. In Guangdong, China, the natural solar irradiation is about 4234.62 MJ/m², of which the ultraviolet light that can reach the ground accounts for about 1%. The wavelength distribution of type 1A (UVA–340) fluorescent ULTRAVIOLET lamp in standard GB/T 16422.3—2014 is as follows: 

\[
290 \geq \lambda \geq 320 \text{ accounts for } 5.4\%, \quad 320 > \lambda \geq 360 \text{ accounts for } 38.2\%, \quad 360 > \lambda \geq 400 \text{ accounts for } 56.4\%.
\]

Based on these data, it can be calculated that 1000 h of UV aging is equivalent to 4 years of natural UV irradiation in Guangdong.

![Figure 2. The UV aging test chamber.](image)

2.2.2. Scanning Electron Microscope

To compare the surface change after UV-A radiation, the microtopography of specimens was imaged by SEM (JSM–6460, JEOL, Peking, China) at 500× magnifications with an applied voltage of 5 kV. Since both HTV and alicyclic epoxy resin are insulating materials, they were sputter-coated with gold before the experiment.

2.2.3. Mechanical Characterization

In this study, tensile properties were tested according to ISO 37:2017 with an electronic tension test machine made by Machine Equipment Co., Ltd., (Shanghai, China) [24–26]. In accordance with ISO 37:2017, the samples were dumbbell-shaped with a thickness of 2 mm and a test length of 25 mm. The experiment was conducted with a tensile speed of 500 mm/min. Five samples of each formula were tested for the above-mentioned mechanical properties and the median value was used. For tensile properties, the stress–strain curves corresponding to the median value of tensile strength were illustrated.
2.2.4. Hydrophobicity and its Transfer Characteristics

In polluted regions, good hydrophobicity is desired to prevent pollution flashover accidents. Referring to IEC 61109:2008, the static contact angle was tested to evaluate the hydrophobicity and its transfer characteristics [27]. The dimension of the specimens is 120 mm × 50 mm × 6 mm. The sample surface was wiped with absolute ethanol to make sure that it was clean. Then, samples were placed in a dustproof container for 24 h at a temperature of 20 ± 5 °C. After that, the sample surface was contaminated with NSSD of 0.5 mg/cm² (diatomite) and ESSD of 0.1 mg/cm² (NaCl) using the quantitative brushing method. For each formula, three contaminated samples were prepared and the static contact angles of five points were measured for each sample. The final static contact angle is calculated by the average of 15 samples.

2.2.5. Fourier Transform Infrared Spectroscopy

The internal functional groups in silicone rubber can be analyzed by FTIR due to its detection depth from several micrometers to tens of micrometers. In this paper, a Tensor 27 Spectrometer (Bruker Optics, Germany) was used to measure the characteristic peaks of silicone rubber in the spectral range from 4000 to 500 cm⁻¹. The FTIR data were recorded in attenuated total reflection mode.

2.2.6. X-ray Photoelectron Spectroscopy

The material composition of the sample surface was analyzed by XPS with detection depth ranging from several nanometers to tens of nanometers [28]. In this study, the elemental composition and chemical state of the alicyclic epoxy resin surface and HTV silicone rubber surface subjected to UV-A radiation were analyzed by XPS (PHI Quantro SXM, ULVAC–PHI Co., Japan). The incidence angle and receiving angle were 54.7° and 90°, respectively.

3. Results and Discussion

3.1. Appearance Analysis and SEM Studies

Figure 3 shows the visual changes of alicyclic epoxy resin and silicone rubber materials with different UV aging times. The aging times for the samples are 0, 120, 240, 600, and 1000 h from left to right. With the increase of UV-A aging, white spots are observed on the surface of both samples. Thus, the surface color can reflect the aging time of both materials to some degree. Nevertheless, both insulating materials did not experience severe and obvious damage on the surface color during the experiment time. To further compare the variations in appearance with color changes, the average gray levels of the appearance pictures after different aging times are also calculated as shown in Figure 3. The calculated results illustrate that the average gray levels of both materials decrease with aging time. From the perspective of the average gray level, HTVSR experienced a more obvious change.

The appearance changes were imaged by SEM at 500× magnifications as shown in Figure 4. With the increase of UV-A aging time, holes and cracks of different sizes gradually appeared on the surfaces of both materials, and the surface roughness gradually increased. The reason for this observation is that some chemical bonds with weak bond energy in alicyclic epoxy resin and silicone rubber materials break. This leads to the destruction of macromolecular network structure and degradation of materials to a certain extent and the increase of surface defects. At the same time, the precipitation of Al(OH)₃ and other fillers can also be observed due to the damage of matrix materials.

Figure 5 shows the cross-section of alicyclic epoxy resin and HTV silicone rubber after 1200 h UV-A radiation. From the microstructures of the cross-section images at 500× magnification, it can be observed that both samples have a relatively loose texture on the margin, and the interface between the matrix and fillers is obvious. This is ascribed to the UV-A radiation on the sample surface. It can lead to the breakage of the chemical bonds and the destruction of the macromolecular network structure. However, the microstructures in the inner side of the sample are not affected by the UV-A radiation.
Figure 3. The appearance changes of two samples after different aging times: (a) The average gray level of the alicyclic epoxy resin sample; (b) the average gray level of the HTVSR sample.

Figure 4. Cont.
Figure 4. SEM of two samples with different UV-A aging times.

- Alicyclic epoxy resin – 240 h
- HTV silicone rubber – 240 h
- Alicyclic epoxy resin – 600 h
- HTV silicone rubber – 600 h
- Alicyclic epoxy resin – 1000 h
- HTV silicone rubber – 1000 h

Figure 5 shows the cross-section of alicyclic epoxy resin and HTV silicone rubber after 1200 h UV-A radiation. From the microstructures of the cross-section images at 500X magnification, it can be observed that both samples have a relatively loose texture on the margin, and the interface between the matrix and fillers is obvious. This is ascribed to the UV-A radiation on the sample surface. It can lead to the breakage of the chemical bonds and the destruction of the macromolecular network structure. However, the microstructures in the inner side of the sample are not affected by the UV-A radiation.
3.2. Mechanical Characterization with UV-A Aging Time

Tensile and elongation at break of both samples are shown in Figures 6 and 7. It can be observed that as the aging time increases, the tensile strength of alicyclic epoxy resin is enhanced. Conversely, the tensile strain property becomes inferior to the specimen without aging though it increases after 120 h UV-A aging time. In terms of HTVSR, with the increase of aging time, both properties are slightly lower than the sample without UV-A radiation. When the aging time is 1000 h, the elongation at break of HTVSR material and alicyclic epoxy resin decreases by 32.89% and 13.63%, respectively. Moreover, the tensile strength of silicone rubber material decreases by 13.63% after 1000 aging as shown in Figure 6. On the contrary, the tensile strength of alicyclic epoxy resin increases by 22.58% after the 1000 h aging test.

The peak strain energy density was measured to analyze the mechanical properties of the two materials. It is calculated by the area surrounded by the material stress–strain curve. The physical significance of peak strain energy density is the mechanical energy consumed when the material is stretched to fracture stress per unit volume, which can be used to evaluate the toughness and impact resistance of the material.

Figure 5. Cross-section images after 1200 h UV-A radiation: (a) Alicyclic epoxy resin; (b) HTV silicone rubber.
When the aging time is 1000 h, the elongation at break of HTVSR decreases gradually from 60% to 46.36%. The tensile strength of silicone rubber material decreases by 13.63% after 1000 h aging as shown in Figure 6. On the contrary, the tensile strength of alicyclic epoxy resin increases by 22.58% after 1200 h UV-A aging. However, the peak strain energy density of HTVSR decreases gradually from 429 J·m$^{-3}$ to 184 J·m$^{-3}$. However, the peak strain energy density of alicyclic epoxy resin decreases by 32.89% and 13.63%, respectively. Therefore, the peak strain energy density of HTVSR decreases gradually with aging time as shown in Figure 8. It increases slightly at first and then decreases after 100 h aging. Overall, the effect of UV-A radiation on the mechanical properties of HTVSR materials is more significant than it is on alicyclic epoxy resin. From the point of view of mechanical properties, alicyclic epoxy resin shows better UV aging resistance.

![Figure 6](image6.png)

**Figure 6.** Tensile and elongation at break of two samples: (a) alicyclic epoxy resin; (b) HTVSR.

![Figure 7](image7.png)

**Figure 7.** Comparison of mechanical properties of two samples at different UV-A aging time: (a) tensile stress; (b) elongation at break.

With the increase of UV-A aging time, the peak strain energy density of HTVSR decreases gradually. However, the peak strain energy density of alicyclic epoxy resin shows a fluctuating trend as shown in Figure 8. It increases slightly at first and then decreases after 100 h aging. Overall, the effect of UV-A radiation on the mechanical properties of HTVSR materials is more significant than it is on alicyclic epoxy resin. From the point of view of mechanical properties, alicyclic epoxy resin shows better UV aging resistance.

![Figure 8](image8.png)

**Figure 8.** Comparison of the peak strain energy density of two samples at different UV-A aging time.
3.3. Hydrophobicity Analysis with UV-A Aging Time

Without UV-A radiation, the static contact angle of alicyclic epoxy resin is 109°, while that of the silicone rubber material is 115°, as shown in Figure 9. The static contact angle of the silicone rubber material is larger than that of the alicyclic epoxy material, indicating that silicone rubber material has better hydrophobicity properties. This can be explained by the fact that the silicone rubber material is wrapped with methyl groups on both sides of the molecular main chain and the methyl groups have strong hydrophobicity. However, the alicyclic epoxy resin material contains more polar groups. This makes it inferior to silicone rubber in terms of hydrophobicity.

![Figure 9. Static contact angle at different UV-A aging times of two samples.](image)

Generally, the static contact angles of both materials decrease with the increasing UV-A aging time, and it is about 5° of decrease after 1000 h radiation. During the UV-A aging process, part of the groups on the surface of two materials are oxidized and polar molecules are generated. At the same time, the Si–C bond of the side chain of HTV silicone rubber material is also cut off, and the methyl group is reduced. All these reasons contribute to the increase of the molecular polarity of both materials and the decrease of hydrophobicity.

3.4. FTIR Analysis of Samples with UV-A Aging Time

FTIR analysis was conducted to illustrate the surface change of chemical structure and composition of alicyclic epoxy and silicone rubber materials which are the decisive factors of their macroscopic properties after being subjected to UV-A radiation. The main functional groups and characteristic absorption peaks of the two materials are shown in Tables 1 and 2. Figures 10 and 11 show Fourier transform infrared spectra of alicyclic epoxy resin and silicone rubber materials respectively after different UV-A aging times.

| Table 1. The wavenumbers corresponding to the main chemical bond in alicyclic epoxy resin. |
|-----------------------------------------------|
| **Chemical Bond** | **Wavenumbers (cm⁻¹)** |
| --- | --- |
| –OH | 3700–3200 |
| C–H (in –CH₃) | 2970–2920 |
| C=O | 1770–1680 |
| C–O–C | 1081 |

| Table 2. The wavenumbers corresponding to the main chemical bond in HTV silicone rubber. |
|-----------------------------------------------|
| **Chemical Bond** | **Wavenumbers (cm⁻¹)** |
| --- | --- |
| –OH | 3700–3200 |
| Si–O (in Si–O–Si) | 1100–1000 |
| Si–(CH₃)₂ | 840–790 |
Figure 10. FTIR analysis of alicyclic epoxy resin samples at different UV-A aging times.

As shown in Figure 9, for alicyclic epoxy resin samples, the content of –OH near 3700–3200 cm$^{-1}$ increases gradually as UV-A aging time increases, which indicates that a growing body of groups carry out oxidation reaction. Meanwhile, the content of C–H near 2970–2920 cm$^{-1}$ and C–O–C near 1081 cm$^{-1}$ gradually decreases. Furthermore, the content of C=O near 1770–1680 cm$^{-1}$ shows a fluctuating trend as it increases first and then decreases.

As for HTV silicone rubber, with UV-A aging time increasing, the contents of –OH and Si–O–Si near 3700–3200 cm$^{-1}$ and 1100–1000 cm$^{-1}$ increase gradually while the contents of Si–C near 840–790 cm$^{-1}$ decrease. After UV-A radiation, the characteristic peaks of Si–O–Si shifted to a higher wavenumber. That is relevant to the oxidation reaction. To be more
specific, the methyl group on the side chain is cut off and the Si–O–Si is built due to the crosslinking reaction.

![FTIR analysis of HTV silicone rubber at different UV-A aging times.](image)

3.5. XPS Analysis of Samples with UV-A Aging Time

Figures 12–15 show the effects of UV-A radiation on the surfaces of alicyclic epoxy resin and HTV silicone rubber with XPS analysis. In both kinds of materials, the Si, C, and O are dominant elements and their contents and position of binding energy were investigated. Based on the corrected peak area and sensitivity factor of each element, the relative percentage contents of Si, O, and C elements were calculated by normalization and the results are illustrated in Table 3.

Table 3. Comparison of the position of peak binding energy and contents of three elements of both samples after 1000 h UV-A aging time.

| Sample                  | Aging Time(h) | Si     | C      | O      | C/O   |
|-------------------------|---------------|--------|--------|--------|-------|
| Alicyclic epoxy resin   | 0             | 102.70 | 285.10 | 533.10 | 19.8  | 54.9  | 25.3  | 2.17  |
|                         | 1000          | 102.62 | 285.02 | 531.42 | 18.9  | 55.0  | 26.1  | 2.12  |
| HTV silicone rubber     | 0             | 101.16 | 285.16 | 531.56 | 21.5  | 53.2  | 25.3  | 2.10  |
|                         | 1000          | 101.22 | 285.22 | 531.62 | 23.3  | 50.2  | 26.5  | 1.89  |
**Figure 12.** The XPS result of alicyclic epoxy resin samples.

**Figure 13.** Peak fitting of C in alicyclic epoxy resin samples.

**Figure 14.** The XPS result of HTV silicone rubber samples.
As for HTVSR, UV-A radiation cleaves the methyl group on the side chain and activates fracture to a certain extent, resulting in material deterioration. The bond energies of C–H and C–O are 332 kJ/mol and 326 kJ/mol, both are less than the energy of the UV-A ultraviolet photon from the alicyclic epoxy resin molecule. In addition, the bond energies of C–C and C–O are 332 kJ/mol and 326 kJ/mol, both are less than the energy of the UV-A ultraviolet photon from the alicyclic epoxy resin molecule. For alicyclic epoxy resin, the reaction as shown in Figure 16 may occur when it suffers from UV-A aging. The C–H bond in the alicyclic epoxy resin is oxidized, which increases the content of –OH in the outer layer, and consequently the shielding effect is enhanced. For the alicyclic epoxy resin, the binding energy positions of the three main elements shift to a lower binding energy region, indicating that they bonded with more elements with low electronegativity after UV-A aging. Another reason is the loss of filler silica on the surface (tens of nanometers, the detection depths of XPS instruments). As for HTVSR, UV-A radiation cleaves the methyl group on the side chain and activates the crosslinking reaction, leading to more electronegative oxygen atoms bonded with silicon atoms.

3.6. Possible UV-A Degradation Mechanism with UV-A Aging

The macroscopic and microscopic properties of alicyclic epoxy resin and HTV silicone rubber materials are decreased by UV-A aging, and complex bond breaking, crosslinking, and oxidation reactions occur on the surface of materials, as illustrated in Figures 16 and 17. For alicyclic epoxy resin, the reaction as shown in Figure 16 may occur when it suffers from UV-A radiation. The C–H bond in the alicyclic epoxy resin is oxidized, which increases the content of O element, C–O bonds, and C=O bonds in the molecule, while decreasing the content of C–H bonds. At the same time, under the combined actions of UV light and water, the ester bond will undergo a hydrolysis reaction, which increases the content of –OH in the alicyclic epoxy resin molecule. In addition, the bond energies of C–C and C–O are 332 kJ/mol and 326 kJ/mol, both are less than the energy of the UV-A ultraviolet photon which is 352 kJ/mol. Thus, C–C and C–O–C bonds in alicyclic epoxy resin molecules fracture to a certain extent, resulting in material deterioration.
As the aging time increases, the hydrophobicity of both alicyclic epoxy resin and HTV silicone rubber decreases. HTV silicone rubber material shows a better UV-A aging resistance than alicyclic epoxy resin material. UV-A aging results in the oxidation of C–H in alicyclic epoxy resin and silicone rubber materials, and an increase in O element and C–O content. Meanwhile, C–O–C and C–C bonds in alicyclic epoxy resin materials and Si–C bonds in silicone rubber materials are cleaved, which led to the destruction of the macromolecular network structure and the degradation of materials to a certain degree. This resulted in an increase in surface defects.

**4. Conclusions**

In this study, the surface appearances, mechanical properties, and hydrophobicity of alicyclic epoxy resin and HTV silicone rubber subjected to different UV-A aging times are investigated and compared. It is found that the visual color of alicyclic epoxy resin changes obviously and a certain degree of fading phenomenon occurs after UV-A 1000 h aging test. However, the color of HTV silicone rubber is almost the same. In terms of mechanical properties, alicyclic epoxy resin behaves better than HTV silicone rubber after the UV-A aging test. As for alicyclic epoxy resin, tensile strength increases, and the elongation at break decreases. From the XPS and FTIR results, it is found that the interactions between fillers and the matrix become loose in both materials whereas the degree of crosslinking in the HTV matrix increases after UV-A aging. As the aging time increases, the hydrophobicity of both alicyclic epoxy resin and HTV silicone rubber decreases. HTV silicone rubber material shows a better UV-A aging resistance than alicyclic epoxy resin material. UV-A aging results in the oxidation of C–H in alicyclic epoxy resin and silicone rubber materials, and an increase in O element and C–O content. Meanwhile, C–O–C and C–C bonds in alicyclic epoxy resin materials and Si–C bonds in silicone rubber materials are cleaved, which led to the destruction of the macromolecular network structure and the degradation of materials to a certain degree. This resulted in an increase in surface defects.

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References
1. Zhang, H.; Yang, H.; Shentu, B.; Chen, S.; Chen, M. Effect of titanium dioxide on the UV-C ageing behavior of silicone rubber. *J. Appl. Polym. Sci.* 2018, 135, 46099. [CrossRef]
2. Tong, Y.; Liu, H.; Chen, A.; Guan, H.; Kong, J.; Liu, S.; He, C. Effect of surface chemistry and morphology of silica on the thermal and mechanical properties of silicone elastomers. *J. Appl. Polym. Sci.* 2018, 135, 46646. [CrossRef]
3. Li, Z.; Yin, F.; Cao, B.; Wang, L.; Shao, S.; Farzaneh, M. Pollution flashover performance of RTV coatings with Partial Damage. *Int. J. Electr. Power Energy Syst.* 2020, 121, 106102. [CrossRef]
4. Yin, F.; Liu, P.; Mei, H.; Wang, L.; Li, L.; Farzaneh, M. The shed hole influence on the electrical performance of composite insulator. *IEEE Access* 2020, 8, 217447–217455. [CrossRef]
5. Liu, Y.; Gao, Y.; Wang, J.; Li, S. Rapid development of silicone rubber composite insulator in China. *High Volt. Eng.* 2016, 42, 2888–2896.
6. Jia, Z.; Ma, G.; Zhu, Z.; Wang, X.; Guan, Z. Deformation and stress concentration of composite insulator in strong wind. *High Volt. Technol.* 2015, 41, 602–607.
7. Meng, X.; Mei, H.; Zhu, B.; Yin, F.; Wang, L. Influence of pollution on surface streamer discharge. *Electr. Power Syst. Res.* 2022, 212, 108638. [CrossRef]
8. Zhang, S.; Cheng, L.; Liao, R.; Liu, Y.; Wang, X.; Wang, T.; Fu, J. Process Improvement to Restrain Emergency Heating Defect of Composite Insulator. *IEEE Trans. Dielectr. Electr. Insul.* 2022, 29, 446–453. [CrossRef]
9. Cheng, L.; Liu, Y.; Chen, R.; Zhang, S.; Liao, R.; Yang, L.; Wang, T. Method for predicting the water absorption of external insulating silicone rubber. *IEEE Trans. Dielectr. Electr. Insul.* 2022, 29, 1242–1250. [CrossRef]
10. Cheng, L.; Liu, Y.; Chen, R.; Zhang, S.; Liao, R.; Yang, L.; Wang, T. Method for predicting the water absorption of external insulating silicone rubber. *IEEE Trans. Dielectr. Electr. Insul.* 2022, 29, 1242–1250. [CrossRef]
11. Sun, Z.; Li, Z.; Zhang, J.; Fu, M. Analysis on bird pest of composite insulators for 1000 kV AC transmission line and its counter measures. *Power Syst. Technol.* 2009, 33, 52–54.
12. Shi, Q. Study on the UV Aging Characteristics of HTV Silicone Rubber Material Under Different Humidity. Master’s Thesis, North China Electric Power University, Beijing, China, 2014.
13. Li, G. Study on the Influence of UV Aging on Mechanical and Electrical Properties of HTV Silicone Rubber. Master’s Thesis, Kunming University of Science and Technology, Kunming, China, 2015.
14. Gao, H. Study on Aging Properties of Polymer Composites Insulators. Master’s Thesis, Xi’an Polytechnic University, Xi’an, China, 2019.
15. Andersson, J.; Gubanski, S.M.; Hillborg, H. Properties of interfaces in silicone rubber. *IEEE Trans. Dielectr. Electr. Insul.* 2007, 14, 137–145. [CrossRef]
16. Hedir, A.; Moudoud, M.; Lamrous, O.; Rondot, S.; Jbara, O.; Dony, P. Ultraviolet radiation aging impact on physicochemical properties of crosslinked polyethylene cable insulation. *J. Appl. Polym. Sci.* 2020, 137, 48575. [CrossRef]
17. Qin, Y. Study on UV Irradiation Characteristics and Aging Mechanism of HTV Silicone Rubber for UHV Power Transmission. Master’s Thesis, Kunming University of Science and Technology, Kunming, China, 2013.
18. Ehsani, M.; Borsi, H.; Gockenbach, E.; Bakshandezeh, G.R.; Morshedian, J. Modified silicone rubber for use as high voltage outdoor insulators. *Adv. Polym. Technol.* 2005, 24, 51–61. [CrossRef]
19. Liu, Y.; Wang, Q.; Lv, F.; Liang, Y. Influence of UV radiation on HTV silicon rubber performance. *High Volt. Eng.* 2010, 36, 2634–2638.
20. Liu, Y.; Lin, Y.; Wu, K.; Fan, H.; Wang, L. Analysis and Optimization on Non-uniformity of Temperature Distribution in Hydrophobic Cycloaliphatic Epoxy Resin Insulators during the Curing Process. *IEEE Trans. Dielectr. Electr. Insul.* 2021, 28, 1810–1818. [CrossRef]
21. Liu, Y.; Lin, Y.; Wang, Y.; Wu, K.; Cao, B.; Wang, L. Simultaneously improving toughness and hydrophobic properties of cycloaliphatic epoxy resin through silicone prepolymer. *J. Appl. Polym. Sci.* 2022, 139, e52478. [CrossRef]
22. Liu, Y.; Lin, Y.; Cao, B.; Wu, K.; Wang, L. Enhancement of polysiloxane/epoxy resin compatibility through an electrostatic and van der Waals potential design strategy. *Polym. Test.* 2022, 117, 107820. [CrossRef]
23. *ASTM D 2240–81*. Test for Rubber Property—Durometer Hardness, Annual Book of ASTM Standards. ASTM: West Conshohocken, PA, USA, 1982.
24. *ISO 37*: Rubber, Vulcanized or Thermoplastic—Determination of Tensile Stress-Strain Properties. ISO: Geneva, Switzerland, 2017.
25. ISO 34–1; Rubber, Vulcanized or Thermoplastic—Determination of Tear Strength—Part 1: Trouser, Angle, and Crescent Test Pieces. ISO: Geneva, Switzerland, 2015.

26. IEC 61109; Insulators for Overhead Lines—Composite Suspension and Tension Insulators for A.C. Systems with a Nominal Voltage Greater than 1000 V—Definitions, Test Methods, and Acceptance Criteria. ISO: Geneva, Switzerland, 2008.

27. Guang, X. Modern Material Analysis and Testing Technology; China University of Mining and Technology Press: Xuzhou, China, 2013.

28. Chen, C.; Jia, Z.; Wang, X.; Lu, H.; Guan, Z.; Yang, C. Micro characterization and degradation mechanism of liquid silicone rubber used for external insulation. *IEEE Trans. Dielectr. Electr. Insul.* 2015, 22, 313–321. [CrossRef]