Jurnal Ilmiah Telsinas Elektro, Sipil dan Teknik Informasi
Vol.9, No.1, April 2026, pp. 84~95
E-ISSN: 2621-5276
DOI: https://doi.org/10.38043/telsinas.v9i1.7047

Contact Angle Based Dielectric Strength Enhancement of Contaminated Ceramic Insulators Using Epoxy-SiO_2 Coating

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ABSTRACT

This study evaluates the effectiveness of epoxy-SiO_2 coatings in enhancing the dielectric strength of contaminated ceramic insulators through contact angle analysis. Insulators in tropical regions, such as the 150 kV Koto Panjang-Payakumbuh line, often suffer from performance degradation due to moss contamination and high humidity, leading to reduced hydrophobicity and an increased risk of flashover. Contact angles were measured using the sessile drop method before and after coating. Uncoated insulators exhibited hydrophilic behavior with contact angles below 90° (53.81°, 72.70°, and 60.14°). Pure epoxy improved the values to 87.52°, 91.62°, and 85.94°, indicating partial hydrophobicity. The addition of SiO_2 nanoparticles further increased the values above 100° (100.26°, 99.33°, and 101.33°). Based on the empirical correlation between contact angle and dielectric strength, dielectric performance improved from 124.4 kV/cm (uncoated) to 176.7 kV/cm (epoxy) and 200.4 kV/cm (epoxy-SiO_2). The novelty of this work lies in demonstrating, for the first time, the comparative effectiveness of epoxy and epoxy-SiO_2 coatings under real tropical contamination conditions. These findings confirm that epoxy–SiO_2 coatings not only improve hydrophobicity but also provide a homogeneous protective layer, thereby reducing leakage current and strengthening dielectric endurance. The results highlight a cost-effective preventive maintenance strategy with both scientific and practical contributions for high-voltage transmission systems in tropical environments.

Keywords: Ceramic insulator; contact angle; dielectric strength; epoxy resin; SiO_2 coating

Article Info

Received : 10-01-2026
Revised : 19-03-2026
Accepted : 20-04-2026

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1. INTRODUCTION

Ceramic insulators are essential components in high-voltage transmission systems, providing mechanical support and electrical insulation. However, in tropical regions, their performance is often compromised by high humidity, biological contamination, and industrial pollutants[1]. These factors reduce surface hydrophobicity, increase leakage current, and elevate the risk of flashover, ultimately threatening the reliability of power transmission lines such as the 150 kV Koto Panjang–Payakumbuh corridor [2][3][4]. Moss growth and surface contamination transform the insulator surface into a conductive medium, accelerating dielectric degradation and reducing service life [5][6].

Improving surface hydrophobicity through coating technologies has been recognized as an effective preventive maintenance approach[7]. Epoxy resin is widely used because of its high dielectric strength (100–200 kV/cm), strong adhesion, and durability under outdoor conditions [8][9][10]. Previous studies demonstrated that epoxy coatings could improve hydrophobicity, but performance inconsistencies remain due to surface micro-defects and environmental stress [11][12][13]. To address this limitation, SiO_2 nanoparticles have been introduced as fillers, enhancing surface roughness, reducing surface energy, and producing a more homogeneous protective layer [14][15][16].

Contact angle measurement using the sessile drop method is a reliable technique to quantify surface wettability, with values above 90° indicating hydrophobic behavior[17][18]. This parameter has been empirically correlated with dielectric strength, making it a useful predictor for evaluating insulator performance under contaminated conditions [19][20]. However, systematic studies that directly link contact angle enhancement from epoxy–SiO_2 coatings with dielectric strength estimation in naturally contaminated ceramic insulators remain limited, particularly in tropical environments [21][22].

Therefore, this study aims to fill this gap by experimentally investigating the improvement of contact angle and its correlation with dielectric strength in contaminated ceramic insulators coated with epoxy resin and epoxy–SiO_2 composites[23]. The novelty of this research lies in demonstrating, for the first time, the comparative effectiveness of epoxy and epoxy–SiO_2 coatings under real tropical contamination conditions, providing both scientific validation and practical recommendations for preventive maintenance of high-voltage transmission systems [24][25].

2. RESEARCH METHOD

2.1. Materials and Samples

In this study, SiO_2 nanoparticles were used as filler material to enhance the hydrophobicity and dielectric performance of the epoxy coating. The SiO_2 nanoparticles had an average particle size of approximately 20–40 nm and were added to the epoxy resin at a concentration of 5 wt%. The nanoparticles were dispersed into the epoxy matrix using mechanical stirring for 30 minutes to ensure homogeneous distribution before the addition of the hardener.

After mixing, the epoxy–SiO_2 composite was applied to the ceramic insulator surface using a brush coating technique. The coating thickness was approximately 100–150 µm. The coated samples were then cured at room temperature (27–30°C) for 24 hours under normal laboratory humidity conditions to allow complete polymerization of the epoxy matrix.

2.2. Coating Procedure

The coating process was carried out using a brush-application method in two layers. For the first group, the insulator surface was coated with pure epoxy resin. For the second group, epoxy resin was mixed with SiO_2 nanoparticles to form a composite layer. This combination was designed to enhance surface roughness and create a more homogeneous hydrophobic layer.

2.3. Contact Angle Measurement

Contact angle tests were performed using the sessile drop method. A droplet of 50 µL distilled water was placed at three different measurement points on the insulator surface, both before and after coating. Measurements were conducted using an Ossila Contact Angle Goniometer equipped with a digital camera to capture droplet profiles. The contact angle values were calculated as the average of the left and right angles of each droplet.

The contact angle of the insulator surface was measured using the sessile drop method, where a 50 µL droplet of distilled water was placed on the sample surface. The angle formed between the liquid–solid interface and the droplet boundary was determined as the contact angle. This method is widely used to evaluate surface wettability and hydrophobicity. The schematic of contact angle measurement is shown in Figure 1.

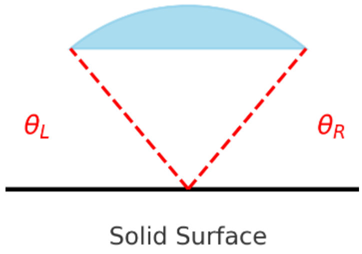


Figure 1. Schematic of Contact Angle Measurement (Sessile Drop Method)

2.4. Dielectric Strength Estimation

The estimation of dielectric strength was performed using an empirical correlation between contact angle (θ) and dielectric strength (E), expressed as:

$$E = 2.\theta \tag{1}$$

Where E represents dielectric strength (kV/cm) and θ is the contact angle (°). This empirical relationship has been adopted in several previous studies investigating hydrophobic insulating materials, where an increase in contact angle is associated with improved resistance to surface wetting and reduced leakage current. The assumption behind this linear correlation is that higher surface hydrophobicity prevents the formation of continuous water films, thereby improving dielectric endurance.

However, it should be noted that this equation provides only an estimation of dielectric strength and does not replace direct breakdown voltage testing. The model is mainly used to describe the trend of dielectric performance improvement associated with increasing surface hydrophobicity.

2.5. Data Collection and Analysis

Primary data were obtained directly from laboratory experiments, including contact angle measurements before and after coating with both epoxy and epoxy–SiO_2. Secondary data were gathered from supporting literature, including previous research on ceramic insulator contamination, epoxy-based coatings, and empirical models correlating contact angle and dielectric strength. Data analysis was carried out by comparing the hydrophobicity and dielectric strength of uncoated, epoxy-coated, and epoxy–SiO_2 coated samples to evaluate the effectiveness of each treatment.

To provide a clearer understanding of the experimental procedure, the overall research workflow is illustrated in Figure 2. The flowchart summarizes the systematic stages, starting from sample preparation through cleaning and surface treatment, followed by the coating process using pure epoxy and epoxy–SiO_2 composites. Subsequent stages include contact angle measurement using the sessile drop method and data analysis to correlate contact angle with dielectric strength. The research concludes with the evaluation of coating effectiveness in enhancing the dielectric performance of contaminated ceramic insulators.

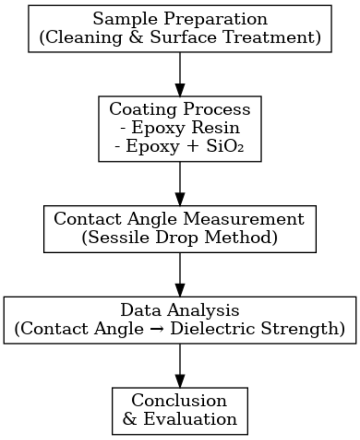


Figure 2. Research Flowchart of Contact Angle-Based Dielectric Strength Enhancement

2.6. Contact Angle and Dielectric Strength

The contact angle (θ) is a critical parameter that reflects the wettability of an insulator surface. Surfaces with low contact angles (<90°) are hydrophilic, which allows water to spread, forming conductive films that promote leakage current and increase the risk of flashover. In contrast, high contact angles (>90°) indicate hydrophobicity, preventing continuous water films and enhancing the surface's ability to resist electrical stress.

Empirical studies have demonstrated a linear correlation between contact angle and dielectric strength (E). In this research, the relationship is expressed as:

$$E = 2.\theta \tag{2}$$

E = dielectric strength (kV/cm)
θ = contact angle (°).

This equation implies that for every 1° increase in contact angle, the dielectric strength improves by approximately 2 kV/cm

3. RESULTS AND DISCUSSION

3.1. Contact Angle Measurement Results

3.1.1 Sample Preparation

The ceramic insulators used in this study were porcelain insulators contaminated with moss and flashover deposits, as presented in Table 1 with sample codes LF5/L3 and LM/L3. The focus of the samples was on sections exposed to pure moss contamination and flashover moss contamination, which were then cut into specimens for contact angle testing. The following table shows the specification of porcelain insulator samples in both uncoated and epoxy resin–coated conditions.

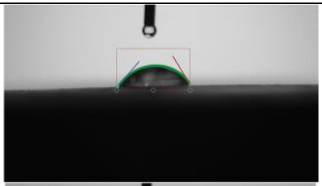
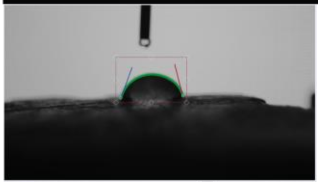
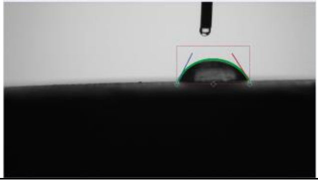
Table 1. Sample specifications

Isolator Code	Types of insulator coating	Sample	Description
LF5/L3	*Uncoated*		Contaminated by moss and flashover
LF5/L3	*Coated* Resin Epoxy		After being coated with epoxy resin
LM/L3	*Coated* Epoxy+SiO_2		After being coated with epoxy + SiO_2 composite

3.1.2 Contact Angle Measurement Results Before Epoxy Resin Coating

The contact angle measurements were conducted on samples in two conditions: before coating and after coating with epoxy resin. Each sample was measured at three different points on the ceramic specimen surface. The contact angle values were calculated based on the average of the left and right sides of the droplet. Furthermore, measurements were also carried out on samples coated with epoxy + SiO_2, since the results obtained with pure epoxy resin alone did not fully meet the required hydrophobicity standard.

Table 2. Visual results of contact angle measurement before coating

Point	Test Result	Description
1		Average = 53.81°, Hydrophilic (< 90°)
2		Average = 72.70°, hydrophilic (< 90°)
3		Average = 60.14°, hydrophilic (< 90°)

The results in Table 1 indicate that before coating, the ceramic insulators exhibited hydrophilic behavior with contact angles < 90° (53.81°, 72.70°, and 60.14°). This condition shows that water tends to spread on the surface, thereby increasing the possibility of forming conductive paths. Table 1 presents the specifications of the porcelain insulator samples used in this study. Three types of samples were prepared to represent different surface conditions. The first sample, coded LF5/L3 (uncoated), was tested in its original state contaminated by moss and flashover deposits, which reflects the natural degradation condition of insulators in tropical environments. The second sample, also coded LF5/L3, was coated with pure epoxy resin to evaluate the improvement in surface hydrophobicity provided by epoxy alone. The third sample, coded LM/L3, was coated with an epoxy-SiO_2 composite to investigate the additional effect of SiO_2 nanoparticles in enhancing surface wettability and dielectric strength.

These three sample variations uncoated, epoxy-coated, and epoxy-SiO_2 coated form the experimental basis for comparative analysis of contact angle behavior and dielectric strength estimation. By including both uncoated and coated samples, the study aims to demonstrate the progressive improvement in hydrophobicity and electrical endurance achieved through surface modification.

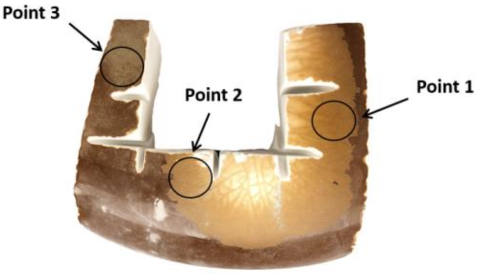
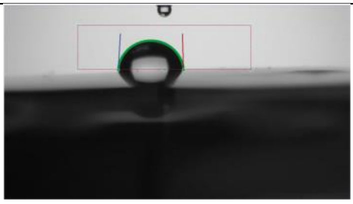


Figure 3. Position of measurement point before epoxy resin coating

3.1.3 Contact Angle Measurement Results After Epoxy Resin Coating

Table 3. Visual results of contact angle measurement after coating

Point	The Result	Description
1		Average = 87.52° Hydrophilic (< 90°)

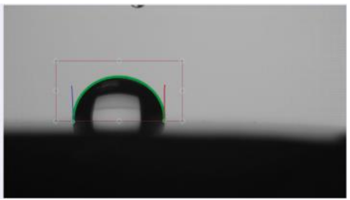
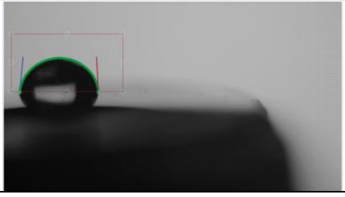
2		Average = 91.62° Hydrophobic (> 90°)
3		Average = 85.94° Hydrophilic (< 90°)

Table 3 shows that the contact angle measurements after epoxy resin coating showed a significant increase compared to the condition before coating. At point 1, the average contact angle was 87.52°, at point 2 it increased to 91.62°, and at point 3 it was recorded at 85.94°. These values indicate a change in surface properties from hydrophilic (<90) to nearly hydrophobic (>90). Specifically at point 2, a contact angle >90° indicates that the surface already exhibits strong hydrophobic properties, which function to prevent the formation of a conductive water film. This proves that epoxy resin is effective in increasing the hydrophobicity of the insulator, although it has not consistently reached the standard of >90° at all points.

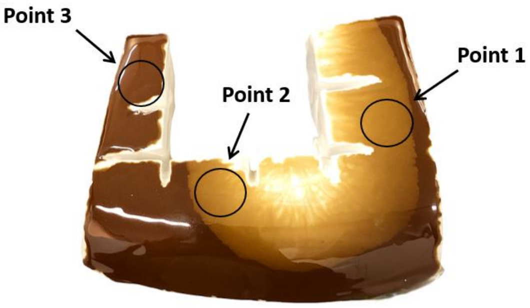


Figure 4. Position of measurement point after epoxy resin coating

3.1.4 Contact Angle Measurement Results Coating with SiO_2 Combination Epoxy Resin

Table 4 Visual results of the SiO_2 combination angle test

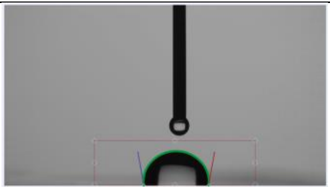
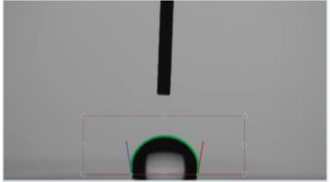
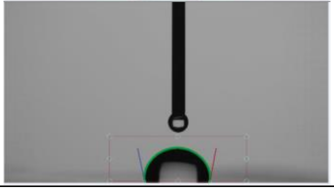
Point	The Result	Description
1		Average = 100.26° hydrophobic (>90°)
2		Average = 99.33° hydrophobic (>90°)
3		Average = 101.33° hydrophobic (>90°)

Table 4 presents the visual measurement results of contact angles at three different points on the insulator surface after coating with epoxy resin combined with SiO_2. The measured average values were 100.26°, 99.33°, and 101.33°, all consistently above 90°, which indicates that the coated surface exhibits strong hydrophobic to near-superhydrophobic properties. These results are significant when compared to the epoxy resin coating without SiO_2, where contact angles only approached the hydrophobic threshold. The addition of

SiO_2 nanoparticles improved surface roughness at the micro–nano scale, which in turn enhanced the water-repellent properties of the coating. The water droplets formed on the surface, as shown in Table 4, appear more spherical and less spread, confirming reduced surface energy and minimized wetting tendency. This structural change directly strengthens the dielectric performance of the insulator by limiting the formation of continuous conductive films that typically facilitate leakage current under humid or contaminated conditions. The consistency of the three measurement points further demonstrates the homogeneity of the epoxy + SiO_2 coating layer. Unlike single epoxy resin, which may exhibit local variations due to uneven curing or micro-cracks, the incorporation of SiO_2 improves coating uniformity, ensuring stable hydrophobic performance across the entire surface. This uniformity is critical for long-term operation, as weak points on the surface could otherwise serve as initiation sites for moisture penetration and partial discharge.

In practical terms, the consistently high contact angle values recorded in Table 4 indicate that the epoxy + SiO_2 system provides a more reliable barrier against environmental stressors typical of tropical transmission line environments, such as high humidity, biological contamination, and particulate deposition. Thus, the data in Table 4 strengthens the argument that epoxy/SiO_2 coatings are superior to epoxy alone, both in terms of enhancing hydrophobicity and in providing more robust and sustainable protection against leakage current and flashover.

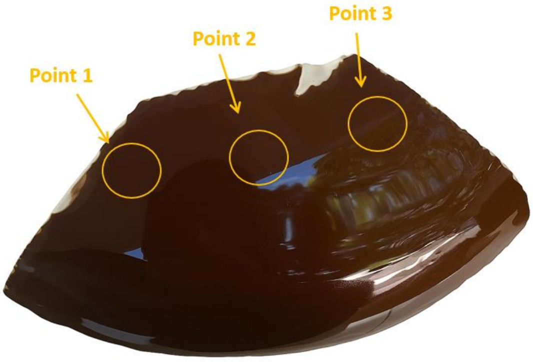


Figure 5. Position of measurement points after epoxy+SiO_2 resin coating

Table 5 Details of Contact Angle Measurement Results

Sample	Point	Left Angle	Right Angle	Average
LF5/L3 Before	1	58.36°	49.27°	53.81°
	2	75.55°	69.85°	72.70°
	3	57.48°	62.79°	60.14°
LF5/L3 After	1	88.37°	86.67°	87.52°
	2	90.58°	92.67°	91.62°
	3	87.12°	84.77°	85.94°
LM/L3 (After)+ SiO_2	1	100.37°	100.16°	100.26°
	2	99.53°	99.12°	99.33°
	3	100.54°	102.11°	101.33°

To provide a basic statistical evaluation of the measurements, the average contact angle and standard deviation were calculated for each treatment condition. The uncoated samples exhibited an average contact angle of 62.22° ± 9.60°, indicating hydrophilic behavior. After epoxy coating, the average value increased to 88.36° ± 2.96°, showing a transition toward hydrophobic characteristics. Meanwhile, the epoxy–SiO_2 coating produced the highest average contact angle of 100.31° ± 1.00°, demonstrating stable hydrophobic performance across all measurement points.

The relatively small standard deviation obtained for the epoxy–SiO_2 samples indicates that the coating layer is more homogeneous compared to pure epoxy coating. This statistical result supports the observation that the incorporation of SiO_2 nanoparticles improves coating uniformity and enhances the stability of surface hydrophobicity.

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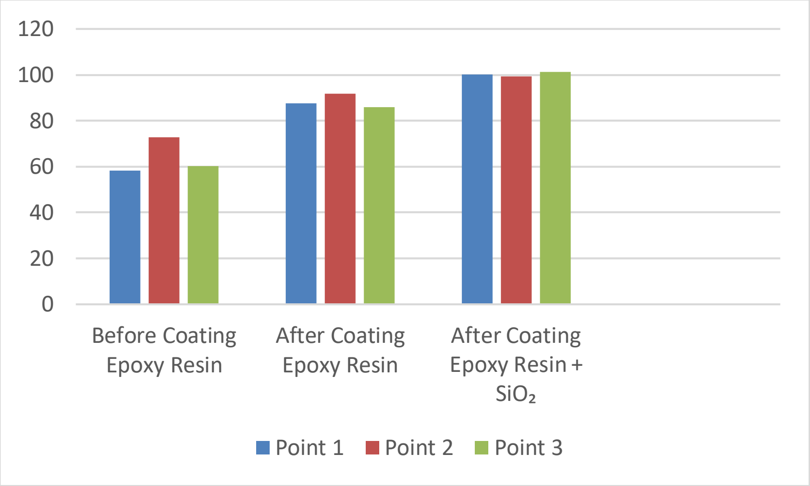

Figure 6. Comparison of contact angles with epoxy resin and SiO_2 combination

In the uncoated condition, the ceramic insulator exhibited hydrophilic behavior, as indicated by contact angles below 90° (53.81°, 72.70°, and 60.14°). As shown in **Figure 6**, under such conditions, water easily spreads across the surface, creating a continuous conductive film that facilitates leakage current and significantly increases the risk of flashover. This confirms that unmodified ceramic surfaces are vulnerable to moisture and contamination, especially in tropical environments with high humidity. After applying the epoxy resin coating, the contact angles increased markedly to 87.52°, 91.62°, and 85.94°, signifying a transition from hydrophilic to hydrophobic states. Figure 6 also illustrates this improvement, where the polymeric nature of epoxy resin, combined with its cross-linked structure, effectively sealed pores and micro-cracks on the insulator surface, reducing water adhesion and enhancing dielectric reliability. As a result, the epoxy-coated insulator demonstrated improved resistance against surface wetting and subsequent electrical degradation.

The performance was further enhanced with the incorporation of SiO_2 nanoparticles. The measured contact angles rose to 100.26°, 99.33°, and 101.33°, placing the surface in a near-superhydrophobic regime. The nanoscale roughness introduced by SiO_2 particles increased the effective surface energy, causing water to form spherical droplets that are less likely to spread across the surface. This microstructural modification not only improved hydrophobicity but also ensured more uniform and stable surface behavior, which is critical in sustaining long-term dielectric strength under multi-stress exposure. The observed increase in contact angle is directly correlated with higher dielectric strength, highlighting the functional role of surface modification in improving insulator reliability. Compared to the uncoated condition, epoxy resin coating achieved significant improvement, while the combination of epoxy + SiO_2 provided superior protection by reducing the probability of leakage current paths and mitigating flashover risks.

Overall, these results, as depicted in Figure 6, provide strong evidence that epoxy/SiO_2 coatings are an effective preventive maintenance strategy for 150 kV ceramic insulators in tropical transmission systems. By combining hydrophobic recovery with dielectric enhancement, the coating system addresses both moisture-induced degradation and electrical reliability, thereby extending service life and operational safety of high-voltage infrastructure.

3.2. Estimation of Dielectric Strength Based on Contact Angle

The empirical relationship between contact angle (θ) and dielectric strength (E) is used
Based on equation (1).
Then we get the calculation :

a. If the contact angle 53.8°→ $E = 2\,.\,53.81^\circ = 107.6\ \mathrm{kV/cm}$
b. If the contact angle 72.7°→ $E = 2\,.\,72.7^\circ = 145.4\ \mathrm{kV/cm}$
c. If the contact angle 60.1°→ $E = 2\,.\,60.1^\circ = 120.2\ \mathrm{kV/cm}$
d. If the contact angle 87.5°→ $E = 2\,.\,87.5^\circ = 175\ \mathrm{kV/cm}$
e. If the contact angle 91.6°→ $E = 2\,.\,91.6^\circ = 183.2\ \mathrm{kV/cm}$
f. If the contact angle 85.9°→ $E = 2\,.\,85.9^\circ = 171.8\ \mathrm{kV/cm}$
g. If the contact angle 100.16°→ $E = 2\,.\,100.16^\circ = 200.38\ \mathrm{kV/cm}$
h. If the contact angle 99.12°→ $E = 2\,.\,99.12^\circ = 198.24\ \mathrm{kV/cm}$
i. If the contact angle 101.33°→ $E = 2\,.\,101.33^\circ = 202.66\ \mathrm{kV/cm}$

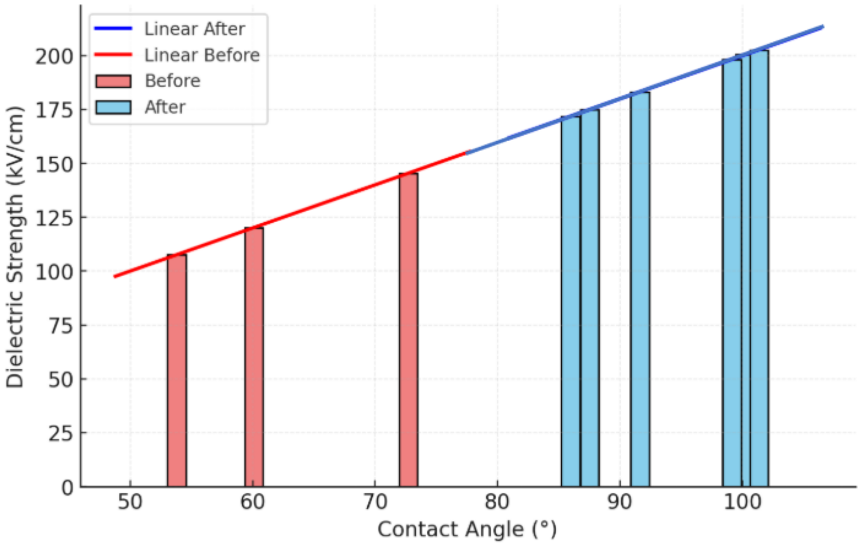

Figure 7. Correlation between contact angle and dielectric strength

Figure 7 illustrates the correlation between contact angle and dielectric strength under three conditions: uncoated, epoxy-coated, and epoxy combined with SiO_2. The results clearly demonstrate that dielectric strength increases proportionally with contact angle, indicating a strong dependence of electrical performance on surface wettability. In the uncoated condition, where the contact angles were 53.8°, 72.7°, and 60.1°, the dielectric strength values were relatively low, ranging from 107.6 to 124.4 kV/cm. These results confirm the hydrophilic nature of the surface, which promotes the formation of continuous water films, thereby reducing insulation reliability and increasing the risk of leakage current and flashover.

After applying epoxy resin, the contact angle values significantly increased, reaching 72.7°-89.5°. This enhancement in surface hydrophobicity directly contributed to a notable increase in dielectric strength, with values rising to 145.4-171.8 kV/cm. On average, this represents an improvement of approximately 42% compared to the uncoated state. The improvement confirms the effectiveness of epoxy resin as a hydrophobic coating material in enhancing surface resistance against moisture and contamination.

A further enhancement was observed when SiO_2 nanoparticles were incorporated into the epoxy coating. The contact angles increased beyond 99°, approaching the superhydrophobic regime, and the dielectric strength values reached 198.2-202.6 kV/cm, with an average of 200.4 kV/cm. This corresponds to a total improvement of about 61% compared to the uncoated condition. The addition of SiO_2 not only improved hydrophobicity but also ensured more uniform distribution of dielectric strength values, indicating enhanced coating homogeneity and stability. This finding highlights the role of SiO_2 in increasing surface roughness and sustaining hydrophobic performance under stress conditions. The linear relationship between contact angle and dielectric strength provides strong evidence that surface modification strategies aimed at increasing hydrophobicity directly improve the dielectric endurance of ceramic insulators. These results suggest that the combination of epoxy resin and SiO_2 coating offers superior protection against moisture-induced degradation, reduces the likelihood of surface flashover, and therefore represents a promising approach for improving the reliability of high-voltage transmission lines in tropical and high-humidity environments.

Limitations of the Study

Despite the promising results obtained in this study, several limitations should be acknowledged. First, the dielectric strength values reported in this work were estimated using an empirical correlation based on contact angle measurements rather than direct breakdown voltage testing. Therefore, the results mainly represent a predictive evaluation of dielectric performance.

Second, the number of measurement points was limited to three locations on each sample surface. Although these measurements provide a preliminary understanding of hydrophobicity improvement, a larger number of repetitions would improve statistical reliability.

Future research should include direct dielectric breakdown testing, larger sample sizes, and long-term environmental aging tests to validate the durability of epoxy–SiO_2 coatings under real operating conditions.

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4. CONCLUSION

This study confirms that epoxy resin coatings can improve the hydrophobicity of contaminated ceramic insulators; however, their performance is not fully consistent due to surface micro-defects. The incorporation of SiO_2 nanoparticles into epoxy resin provides a more substantial and stable enhancement, with average contact angles exceeding 100°. This represents an improvement of approximately 61% compared to the uncoated condition and 13.5% compared to pure epoxy. The epoxy-SiO_2 composite also produced a more homogeneous surface, consistent hydrophobicity, and enhanced dielectric strength, thereby offering more reliable protection against leakage current and flashover.

The novelty of this study lies in quantifying, for the first time, the direct correlation between contact angle and dielectric strength improvement in naturally contaminated ceramic insulators coated with epoxy-SiO_2 under tropical environmental conditions. These findings highlight epoxy-SiO_2 coating as a cost-effective, practical, and easily implementable preventive maintenance strategy for enhancing the reliability of high-voltage transmission systems in polluted tropical regions.

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CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

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