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Fabrication and Testing of Epoxy Resin-Based Composites for Electrical Insulation Material Applications

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ABSTRACT

Electrical insulation materials are a critical component in the design and development of electrical systems, playing a crucial role in ensuring the safe and efficient transmission and distribution of electrical power. The aim of this study is to examine the effect of incorporating rice husk ash and silane on the hydrophobicity, leakage current, and tensile strength properties of composite specimens. This study focused on fabricating composites by varying filler concentrations, using epoxy resin as the matrix. The specimens RTV 10, RTV 20, RTV 30, RTV 40, and RTV 50 utilized a filler composed of rice husk ash and silane, with concentrations of 10%, 20%, 30%, 40%, and 50%, respectively. The obtained samples were subjected to testing for leakage current, tensile strength, and water contact angle (hydrophobicity). The study results indicate that increasing the filler content to 40 wt.% in RTV 40 specimens improves the composite's tracking time, and hydrophobic properties. RTV 40 specimens demonstrated the longest tracking time and the most favourable hydrophobic characteristics compared to the other specimens. However, when the filler content exceeds 40 wt.%, the water contact angle decreases, leading to higher leakage currents and diminished insulating effectiveness. For the RTV 40 specimen, the measured values were a water contact angle of 92°, a tracking time of 1956 seconds, and a tensile strength of 39.59 N/mm². This study addresses several points of the Sustainable Development Goals (SDGs) by improving material properties (SDG 9), promoting sustainable materials (SDG 12) and improving energy-efficient infrastructure (SDG 7).

1. Introduction

Composite materials have emerged as a remarkable field of study, attracting the attention of engineers across various industries [1-4]. These materials offer a unique mix of properties that make them particularly appealing for a number of applications, thus they have also been the focus of much research and development [5-7]. The constituent elements typically combine to form these materials, with one serving as the reinforcement (in fiber form) and the other acting as the matrix [8-

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10]. The advantages of composite materials are their high specific strength and stiffness, which allow for substantial weight savings in applications such as the aviation and automotive sectors [11-13].

Innovation in composite material has attracted significant interest in numerous industries due to their adaptability and capacity to provide specific mechanical properties. One of the primary factors that influences composite performance is the type of reinforcement, which can vary from traditional materials like glass, carbon, and aramid fibers to more advanced options like ceramic, metal, and natural fibers [14-17]. Each type of reinforcement has its own unique properties, such as strength, stiffness, thermal and electrical conductivity, and resistance to environmental factors, which directly impact the overall behavior and performance of the composite. Furthermore, the interfacial bonding between the reinforcement and the matrix, as well as the effectiveness of load transfer, can be strongly impacted by the particular features of the reinforcement, such as its size, shape, aspect ratio, and surface qualities [18,19].

Composite-based insulating materials have been extensively developed to address the limitations of polymer materials such as epoxy resins, phenolic resins (PF), polyether ether ketone (PEEK), polyphenylene sulphide (PPS), and polyetherimide (PEI). These limitations primarily concern inadequate resistance to high temperatures, thermal conductivity, and mechanical strength, which are crucial for applications in high-temperature environments [17]. The composite field has also gained significant attention in the electrical insulation industry due to their exceptional mechanical, thermal, and electrical properties. These materials have a wide range of uses in the electrical sector, particularly as low-dielectric materials, due to their outstanding electrical insulating capabilities, low dielectric loss, and appropriate mechanical properties. Electrical insulation materials are a critical component in the design and development of electrical systems, playing a crucial role in ensuring the safe and efficient transmission and distribution of electrical power. The performance of these materials is critical, since they must withstand high voltages, reduce the risk of electrical failures, and provide dependable service over long periods [20-23].

In the development of composite materials for electrical insulation applications, it is essential to carefully consider the fabrication method and the resulting fiber-matrix interaction, as these factors can have a significant impact on the dielectric characteristics of the material. The fabrication method employed in the production of composite materials can have a significant impact on their electrical insulation properties [24,25]. The arrangement and distribution of the fillers within the composite matrix can influence the dielectric characteristics of the material. The dielectric characteristics are influenced by the process of diffusion and trapping of electric charges, which is largely dependent on the fiber-matrix interface and fiber orientation. The fiber's orientation and volume percentage are two important factors that affect the composite's strength and flexibility [26,27].

Natural fibers have long been used in a variety of applications, these renewable and biodegradable materials have gained increasing attention as potential reinforcements for polymer composites, offering advantages over synthetic fibers such as glass or carbon in terms of cost, weight, and environmental impact [28]. One class of applications where natural fiber composites have shown promise is electrical insulation [23,29]. Natural fibers like jute, hemp, and ramie possess inherent dielectric properties that make them suitable for use as insulators or fillers in composite materials [30,31]. These materials can be used to fabricate electrical components, cable casings, or structural elements with enhanced electrical resistance and thermal stability.

Epoxy resins are commonly employed in high-voltage electrical devices because of their exceptional electrical insulating capabilities, excellent heat resistance, and favorable mechanical characteristics. Epoxy loaded with nanoparticles has superior qualities compared to epoxy filled with fillers of micrometer size. Epoxy compositions containing SiO_2 exhibit superior dielectric characteristics in comparison to other fillers [32]. Rajamanikandan *et al.,* [22] asserted that using rice husk and epoxy resin as electrical insulation materials is ecologically sustainable and exceptionally long-lasting. Rice husk is a readily available and plentiful natural material. Rice husk serves as a naturally occurring reservoir of silica [33]. The amount of silica in rice husk can reach 87% - 98% by appropriate processing [34,35]. As a result, rice husk ash is conducive to insulation of heat, electrical equipment, and photonic purposes [36].

A range of additives has been explored for the development of epoxy composites intended for use as electrical insulators. However, there is a notable gap in comprehensive research regarding the effects of silane concentration and rice husk ash as filler materials in composites with epoxy matrices. Therefore, this study focused on producing and evaluating epoxy resin-based composites filled using rice husk ash and silane for electrical insulation. The objective of the study is to examine the impact of incorporating rice husk and silane on the hydrophobicity, leakage current, and tensile strength properties of the composite specimens. Using epoxy resin-based composite materials in electrical insulation applications can enhance energy efficiency, foster technical advancement, and encourage responsible consumption and production, thus contributing to a more sustainable future. This research aligns with various influential objectives outlined in the Sustainable Development Goals (SDGs) agenda, specifically in relation to points SDG 9 (industry, innovation and infrastructure) and 12 (responsible consumption and production).

This study contributes to the circular economy principles by using rice chaff, an agricultural by-product, as a filling material. The study demonstrates upcycling of waste products into functional and valuable products for reducing environmental waste. Moreover, improving the electrical insulation of composite materials could lead to a more energy-efficient and durable infrastructure. Enhancing the reliability and security of electricity systems, therefore, also contributes to achieving SDG 7 (affordable and sustainable energy). Silane also greatly enhances the durability and performance of composites, needing less frequent replacements and encouraging more sustainable products. Notably, this approach aligns with SDG point 12 because it promotes energy-efficient industrial practices by the smart use of resources with a reduction in waste generation.

2. Methodology

The epoxy resins DGEBA (diglycidyl ether of bisphenol A), and MPDA (Meta Phenylene Diamine) utilized in this study were acquired from PT Justus Kimia Raya, located in Semarang, Indonesia. Typically, the DGEBA-type epoxy resin has a molecular weight of approximately 390 g/mol, an epoxy resin equivalent of approximately 189 ± 5, and a viscosity of 15,000 mPa.s [37,38]. Meta Phenylene Diamine (MPDA) is a hardener commonly used with epoxy resins. It possesses a molecular weight of 108.14 g/mol. Integrating MPDA into insulating materials enhances the materials' stability and performance [39,40]. The study employed silane, often known as glass glue, as a coupling agent. Silane is an intermediary between the epoxy polymer matrix and the filler material in the composite. Silane enhances both the mechanical and chemical characteristics of epoxy composites [41-43].

This study employed rice husks collected from cultivated land in Semarang, Central Java, Indonesia. The rice husk was immersed in a 0.5 M sodium lauryl sulfate solution and stirred for 30 minutes. It was then rinsed with distilled water until the pH reached a neutral level. Subsequently, the cleaned rice husk was leached using a 0.5 M H_2SO_4 solution at 60°C for 30 minutes. The object was flushed with distilled water until the pH reached a neutral level, and then it was left to dry at room temperature. The drying process was conducted in an oven at a temperature of 110°C for 24 hours. The rice husk was fired at 950°C for 3 hours. The result of this process was the production of rice husk ash containing 86.67% silica. Subsequently, the rice husk ash underwent filtration using a 300-mesh screen.

Table 1
Code and composition of composite specimens

Specimen codes	DGEBA (wt.%)	MPDA (wt.%)	Silane (wt.%)	RHA (wt.%)
RTV 10	45	45	5	5
RTV 20	40	40	10	10
RTV 30	35	35	15	15
RTV 40	30	30	20	20
RTV 50	25	25	25	25

The composition and specimen codes are listed in Table 1. The initial stage of the composite preparation involves gradually adding silane and RHA into DGEBA under slow stirring to obtain a completely homogeneous mixture. Then, MPDA is added and stirred until the texture is homogeneous. The mixture is then placed in a vacuum process to evacuate air contained in the mixture. The mixture is poured into a mold and cured at room temperature for three hours until solidified. The samples are then trimmed to specific dimensions following the curing process to conduct more testing.

Three repetitions of leakage current, tensile, and water contact angle (hydrophobic) tests were conducted in this study. The collected results were further computed to derive an average value. The tensile testing performed in this study adhered to the ASTM D 638-02 standard, with specimen dimensions illustrated in Figure 1. The HT-2402 Computer Servo Control Material Testing Machines (Hung Ta Instrument Co, Ltd, Samutprakarn, Thailand) were employed to perform the tensile testing procedure.

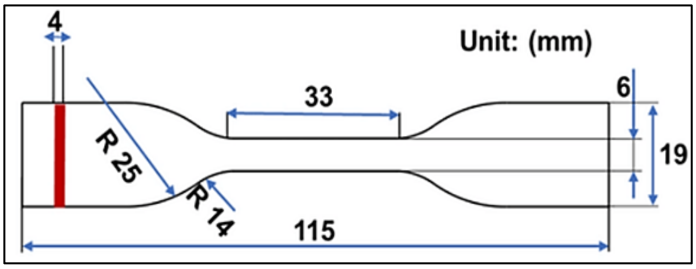

Fig. 1. Specifications for the size and shape of tensile test specimens

The electrical resistance qualities of composite polymer insulator materials were evaluated by leakage current testing, which involved tracking and erosion operations in line with the IEC 587:1984 standard. The test, also known as Inclined Plane Tracking (IPT), is used to evaluate the resistance of polymeric materials to tracking and erosion under external insulating circumstances. The test specimen is oriented at a 45° inclination during this test. NH4Cl was employed as a pollutant with a 0.3 ml/min discharge rate, which exposed the specimen's bottom surface. This was conducted to replicate the conditions experienced by external insulators in Indonesia, where heavy rainfall is prevalent. Leakage current testing employs transformers with an input voltage of 220 Volts and an output voltage of 50 kilovolts, with a capacity of 5 kilovolt-amperes. The existence of voltage waves on the oscilloscope shows the occurrence of leakage current in this test. The voltage divider circuit's voltage wave represents the oscilloscope's input voltage, which is required to surpass the high voltage input to the oscilloscope.

The water contact angle test was conducted by placing the specimen horizontally onto the testing apparatus and exposing it to a 1000W light bulb. A calibrated pipette was employed to dispense a 50 µL droplet of water directly on the specimen's top surface. A lateral view of the droplet was taken using the testing apparatus camera, and necessary adjustments were made to the output to be intrinsic and smooth. Next, the images obtained were analyzed by Famas software, specifically authored for KYOWA goniometers and calculated the contact angle by measuring the angle formed between the edge of the droplet and the surface of the specimen.

3. Results

The angle of water contact test results from the present study are shown in Figure 2. The water contact angle of the RTV 10, RTV 20, RTV 30, RTV 40, and RTV 50 specimens were found at 82°, 88°, 91°, 92°, and 90°, respectively. Measuring the water contact angle is crucial in evaluating the hydrophobicity of insulating materials, which refers to their capacity for attracting water. Excellent hydrophobic characteristics in insulators are essential for preventing leakage currents by forming a water film on the surface of the insulator. According to the findings of this investigation, the RTV 10 and RTV 20 specimens have a propensity towards being more hydrophilic, as seen by the water contact angle formed in these two samples being less than 90° [44]. Conversely, the RTV 30 and RTV 40 specimens exhibited water contact angles above 90°, indicating significant hydrophobic characteristics [44]. The RTV 50 specimen has moderate (neutral) hydrophobic characteristics, as evidenced by a water contact angle of 90°.

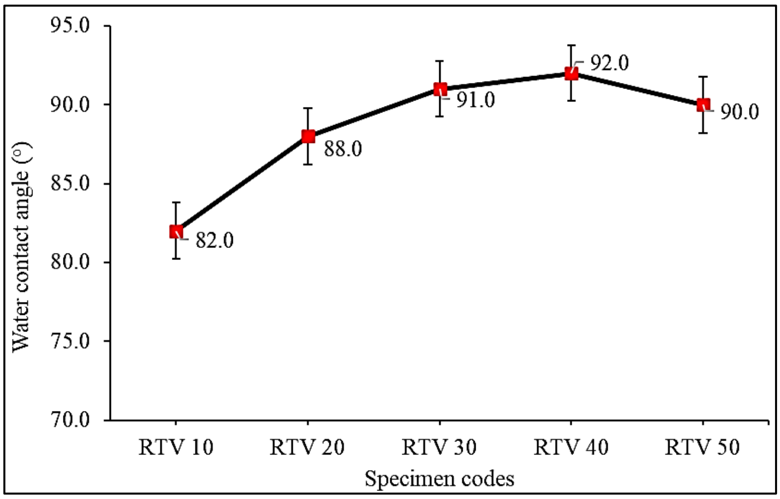

Fig. 2. The effects of filer additions on the composite specimen's water contact angle

The study's findings indicate that higher concentrations of fillers (silane and rice husk ash) enhance the surface hydrophobicity of the composite specimens, as observed in the RTV 10 to RTV 40 specimens. Nevertheless, the hydrophobicity of the composite specimens decreases when the filler content surpasses 40%. This is evident in the RTV 50 specimen, which has a lower water contact angle than the RTV 40 specimen. The study findings indicate that the RTV 40 specimen, which contained a filler concentration of 40% (comprising 20% silane and 20% rice husk ash), exhibited the most significant water contact angle. This characteristic establishes it as the specimen with the most superior hydrophobic qualities among all the specimens examined. Rice husk-based products have increased hydrophobic qualities compared to wood-based products due to their higher lignin concentration [45].

Furthermore, rice husk has a silicon-cellulose layer that provides hydrophobic characteristics and reduces water absorption capacity [46]. Muthuraj *et al.,*'s [47] research indicates that rice husk ash contains a high SiO_2 content, which gives it hydrophobic properties. This property can be utilized to enhance the water resistance of textiles. The findings of this study align with those of Jaya *et al.,* [47].

Their findings indicate that including polydimethylsiloxane (PDMS) in the epoxy polymer, along with RHA as a filler, can enhance the hydrophobic properties of the material's surface. The surface hydrophobicity of external insulating materials is crucial. During humid and rainy weather, the surface of the insulator needs to be resistant to moisture absorption. This is necessary to maintain a low level of conductivity on the insulator surface, which reduces the amount of surface leakage current and helps minimize it. Syakur *et al.,*'s [40] research reveals that the composite specimens' hydrophobic characteristics become stronger as the concentration of SiO_2 filler increases. SiO_2 was employed to fabricate composites derived from silica grains and silica rubber.

Subsequently, the specimens containing a mixture of 25% silica sand and 25% silica rubber exhibited the highest water contact angle. Nevertheless, 20% silica sand and 20% silica rubber composite specimens had the lowest water contact angle. Silvia *et al.,* [48] asserted that silica exhibits non-polar characteristics when used as a filler material, resulting in reduced surface energy and a significant contact angle between a water droplet's edge and bottom surface. Furthermore, a polyethene/SiO_2 layer on the glass generates a textured surface that diminishes the contact between water and glass, leading to a hydrophobic surface. This is corroborated by Rahmadhani *et al.,*'s [49] research, which asserts that the hydrophobicity of a material's surface is enhanced when the surface roughness is decreased or when it has minimal contact with water.

The research conducted by Roseli *et al.,* [5] investigates the water contact angle on both untreated and silane-treated bamboo fibers. The findings reveal that higher water contact angles, ranging from 120° to 150°, suggest an improvement in hydrophobicity. Specifically, untreated bamboo fibers exhibited a water contact angle of 160.2°, whereas treated bamboo fibers demonstrated a significant increase, with an average contact angle of 192.5°. This increase highlights the enhanced water-repellent properties of the treated fibers. The current leakege test results from the present study are shown in Figure 3. The time to tracking of the RTV 10, RTV 20, RTV 30, RTV 40, and RTV 50 specimens were found at 1500 s, 1685 s, 1904 s, 1956 s, and 1589 s, respectively. The results of this investigation indicate that raising the filler concentration from 10% to 40% leads to a longer tracking time. Nevertheless, as the filler concentration is beyond 40%, the tracking time decreases. This is evident in the RTV 50 specimen since it exhibits a shorter tracking time than the RTV 40 specimen. The specimen with the longest tracking time was discovered in the sample with a filler content of 40% (RTV 40), composed of 20% rice husk ash and 20% silane.

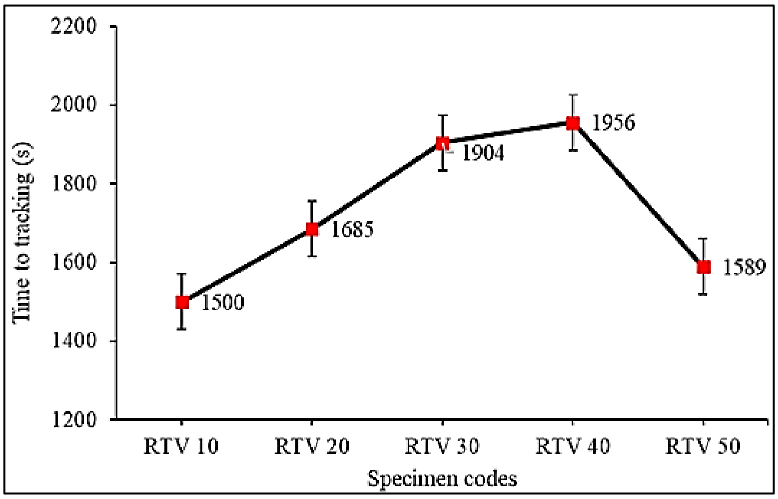

Fig. 3. The effects of filer additions on the composite specimen's time to tracking

Conversely, the specimen with a filler content of 10% (RTV 10), comprising 5% rice husk ash and 5% silane, demonstrated the shortest tracking time. The extended duration of tracking time signifies an enhanced ability to sustain the creation of conductive pathways inside the insulating material. Dielectric failure and electrical problems can occur due to conductive pathways present in insulating materials. The leakage current test results align with the findings of the water contact angle tests that have been carried out. Specimen RTV 40 exhibited the greatest water contact angle compared to all other specimens. Thus, this particular specimen demonstrated superior hydrophobicity in comparison to the other specimens. Enhanced hydrophobicity leads to higher track resistance of the insulator material. Conversely, the leakage current may increase when the hydrophobicity of the composite specimen is weakened.

According to Ullah *et al.,* [50], different chemical reactions in composite materials can lead to a decrease in hydrophobicity and an increase in leakage current. Increased leakage currents can cause various electrical phenomena, including rising surface temperature, corona discharge, and dry band arcing. These effects can accelerate chemical reactions and ultimately degrade the desired properties of the insulating material. In another study, Ullah *et al.,* [51] stated that the initial loss of hydrophobicity can be partially attributed to the increase in leakage current in composite specimens with the use of a higher silica content. The composite specimens experience leakage current increases of greater magnitude as a result of the gradual loss of hydrophobicity of the specimens over time.

According to Manjang *et al.,*'s [52] research, FAT0-T specimens without fillers exhibit high conductivity and have a strong tendency to absorb water. This results in a higher surface leakage current in the FAT0-T specimen than in the FAT30-T specimen, which was constructed with a fly ash filler concentration of 30 wt.%. Kurimoto *et al.,* [53] assert that the occurrence of electrical pulse discharge is strongly linked to the level of hydrophobicity exhibited by the specimen. When the hydrophobicity conditions are favorable, water droplets can effortlessly slide off without leaving noticeable marks. As the hydrophobicity declines, water droplets are more likely to be retained and have longer interactions with the surface, leading to increased frequent pulse discharges. This phenomenon becomes more pronounced as a thin layer of water vapor develops on the surface, leading to a continuous flow of leakage current.

The tensile test results from the present study are shown in Figure 4. The tensile strength of the RTV 10, RTV 20, RTV 30, RTV 40, and RTV 50 specimens were found at 225.69 N/mm^2, 74.02 N/mm^2, 42.28 N/mm^2, 39.59 N/mm^2, and 14.73 N/mm^2, respectively. The RTV 10 specimen exhibited the highest tensile strength when rice husk ash and silane were used at 5% each. Rice husk ash and silane were used at 25% each in the RTV 50 specimen, which exhibited the lowest tensile strength. The findings of this investigation indicate that the tensile strength of composite specimens decreases as the concentration of fillers increases. The findings of this study align with the research conducted by Mourad *et al.,* [54]. Their research indicates that as the filler concentration increases, the tensile strength of the composite decreases. On the other hand, composites with smaller particle size fillers exhibit higher tensile strength when a specific concentration of filler is employed. This occurs due to the improved dispersion of the filler and enhanced interaction between the matrix and the filler.

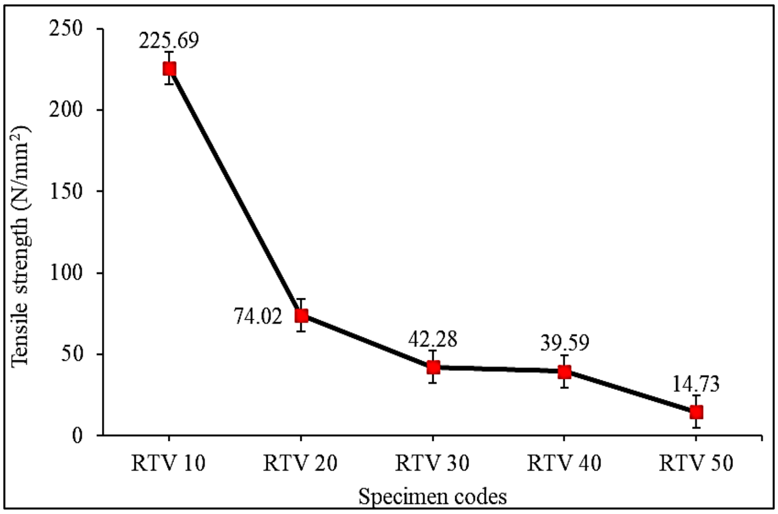

Fig. 4. The effects of filer additions on the composite specimen's tensile strength

Baranovsky *et al.,* [55] discovered that when the filler content exceeds 25%, the hardness of the composite decreases to 382 HB. The rise in porosity inside the composite material is responsible for the decline in hardness. Higher filler concentration leads to greater porosity in the composite material. This leads to a decrease in the mechanical characteristics of the composite. Ramesh *et al.,* [56] have found that the tensile strength of composite specimens decreases due to defects generated by the clustering and empty spaces between the fibers and matrix. Furthermore, the tensile strength diminishes as the particle loading increases due to inadequate blending of the fibers and resin. The research conducted by Dailami *et al.,* [57] indicates that increasing the concentration of filler particles reduces tensile strength. This phenomenon arises due to rigid glass particles that serve as potential sites for initiating cracks when subjected to a tensile force. The composite specimen with a particle concentration of 10% had the maximum tensile strength, measuring 39.15 MPa.

The tensile strength reported in this study was also higher than that of neat diglycidyl ether of bisphenol A (DGEBA) epoxy resin, measuring at 71 MPa. Cai *et al.*, [58] have reported that neat DGEBA epoxy resin has a tensile strength of around 71 MPa. When the DHC-N content reached 20 wt%, the DHC-N polymerization within the DGEBA epoxy matrix completed the polymeric network. This alignment allowed for the transfer of external forces between the superstructure and the chain networks and effective energy dissipation. On the other hand, below this DHC-N concentration of 20% wt%, the DHC-N network wasn't fully developed, so the mechanical properties got better as the DHC-N content went up.

4. Conclusions

The present study aimed to assess the influence of different concentrations of rice husk ash and silane fillers on the characteristics of epoxy resin-based composites designed for electrical insulator applications. The measurements of water contact angles for specimens RTV 10, RTV 20, RTV 30, RTV 40, and RTV 50 were 82°, 88°, 91°, 92°, and 90°, respectively. Additionally, the tracking times for the RTV 10, RTV 20, RTV 30, RTV 40, and RTV 50 specimens were 1500 seconds, 1685 seconds, 1904 seconds, 1956 seconds, and 1589 seconds, respectively. The findings indicated that enhancing the filler content to 40 wt.% in RTV 40 specimens enhanced the tracking time and hydrophobic characteristics of the composites. The RTV 40 specimen exhibited the longest tracking time and the most advantageous hydrophobic properties, rendering it appropriate for electrical insulator applications. When the filler content surpasses 40 wt.%, a reduction in the water contact angle occurs, resulting in an increase in leakage current and a decrease in the insulating performance of the composite material.

Moreover, the study findings indicate that the tensile strength of composite specimens decreases with increased filler concentrations. The tensile strengths of the RTV 10, RTV 20, RTV 30, RTV 40, and RTV 50 specimens were measured at 225.69 N/mm^2, 74.02 N/mm^2, 42.28 N/mm^2, 39.59 N/mm^2, and 14.73 N/mm^2, respectively. This problem occurs because to an elevated concentration of filler, resulting in insufficient homogeneous mixing of the filler and matrix specimens. This results in the creation of clusters and voids, which directly undermines the mechanical properties of the composite specimens.

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