Optimizing palm oil insulation with rice husk powder: A mechanistic study of breakdown voltage enhancement

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ABSTRACT This study investigates the enhancement of breakdown voltage (BDV) in palm oil (PO) insulation by varying concentrations of rice husk (RH), aiming to address the mechanisms responsible for its performance optimization. Dielectric (real permittivity and loss tangent) and physicochemical tests were conducted. At low RH concentrations (up to 0.20 g/L), well-dispersed RH particles effectively reduce dielectric loss tangent to a minimum of 0.0083 and moderately decrease real permittivity due to optimal charge trapping and improvement of homogenized electric fields. Beyond 0.50 g/L, particle agglomeration becomes dominant, leading to a sharp increase in both real permittivity and loss tangent, degrading BDV performance due to interfacial polarization and increased conduction paths. The inverted U-shaped viscosity trend shows a transition from stable RH dispersion to agglomeration. While moisture content was also analyzed, moisture scavenging was not identified as a dominant mechanism. UV-Vis spectroscopy confirms the presence and varying concentrations of RH particles. This research provides mechanistic insights into the interplay between filler concentration, dispersion quality, and electrical properties, which highlights the importance of dispersion control for optimizing natural ester-based insulating fluids. This study is unique in demonstrating how the U-shaped trends of real permittivity and loss tangent mirror the inverted U-shaped BDV curve, suggesting a common mechanistic foundation for optimizing natural ester-based insulating fluids.

KEYWORDS: Breakdown voltage; Loss tangent; Natural esters; Palm oil (PO); Real permittivity.
Received 7 Jume 2026 **Revised** 2 July 2026 **Accepted** 10 July 2026 **Online** 13 July 2026

Original Article

TRANSACTIONS ON SCIENCE AND TECHNOLOGY

INTRODUCTION

Many palms oil (PO) research have been conducted to replace mineral oils (MO) as liquid insulating material because of its renewability, biodegradable and non-toxic. To improve its performance, several modifications have been done, including using natural fillers such as rice husk (RH) (Junian *et al.*, 2025). The breakdown voltage (BDV) of PO can be improved by adding RH up to 55.9 % as compared to PO without any fillers (Junian *et al.*, 2025). However, the mechanisms of BDV improvement have yet to be fully understood. Understanding these mechanisms will be beneficial in further optimization of such mixture.

One of the mechanisms affecting BDV is the dielectric behaviour of the oil, namely permittivity and dielectric losses, which have been studied to have a link in BDV variations. Materials with high dielectric constants, such as TiO2 and ZnO, are also electrical insulators (Sudhakar *et al.*, 2024). The higher the value, the higher the ability of the particles to polarize when the particles are under an electric field. In other words, an electric field concentration can be resisted when the particles have better polarization. This is because BDV usually occurs at electric field concentrations (Sudhakar *et al.*, 2024). Dielectric loss or loss tangent is the loss of energy as heat under a certain frequency, voltage and temperature (Adekunle & Oparanti, 2023). Two main causes that are usually affecting the dielectric loss are conduction and polarization. The effect of adding more TiO2 in the base fluid will further reduce the dielectric loss, but it was the opposite for Fe-Cu and Fe3O4 (Khan *et al.*, 2023). The reason being that Fe-Cu and Fe3O4 are magnetic fillers, hence a conductive chain may have been formed and lead to conduction in the base fluid.

Viscosity is a key property of dielectric insulation fluids, representing the fluid's resistance to flow. It is essential to maintain low viscosity at operating temperatures, as lower viscosity means the fluid is thinner and can flow more easily (Roslan *et al.*, 2021). Viscosity can also significantly influence the breakdown voltage (BDV) of dielectric nanofluids by affecting the mobility and dispersion stability of fillers within the fluid. High viscosity restricts filler particles movement, limiting their ability to interact with and capture high-speed electrons which, in turn, hampers a key mechanism for inhibiting streamer development and postponing electrical breakdown (Khan *et al.*, 2024). In contrast, when viscosity is moderate or slightly lowered, fillers exhibit enhanced mobility, improving their chances of intercepting electrons and consequently increasing the BDV (Hussin *et al.*, 2021). The effect of ZrO2, SiC and Bn fillers at different concentrations of 0.125 wt%, 0.250 wt% and 0.35 wt%, respectively, on the kinematic viscosity of a synthetic oil shows lower viscosity than base oil except SiC (Khan *et al.*, 2024). The researchers deduced that the fluidity of the oil-filler particle mixture is enhanced. The reason being that ZrO2 and BN have self-lubricating properties. The particles formed lubricating coating which reduced friction and in turn, reduced the viscosity of the mixture. The BDV also shows improvement for all fillers at all concentrations except for 0.375 %.

Water content is a critical factor in determining oil quality. Because water has high electrical conductivity and a high dielectric constant, it can easily create a conductive path when exposed to an electric field. This leads to a reduction in the oil's breakdown voltage, posing a significant risk to power generation safety (Zhao *et al.*, 2023). Adding fillers can reduce the effect of moisture. The fillers prevent the water from spreading in oil due to the hydrophilic characteristic of filler which adsorb and collect water on its surface (Abd-Elhady *et al.*, 2021).

This study investigates the mechanisms that may explain the maximum peak in the BDV across eight different RH concentrations. Four analyses are carried out in terms of dielectric and physicochemical properties. The first analysis is dielectric, which is divided into two, namely real permittivity and tangent delta. The second analysis is viscosity at 40 ˚C. These analyses conducted aimed to find the relationship between RH concentration

METHODOLOGY

Sample Preparation

Rice husk filler preparation

The rice husk (RH) filler was sourced from a local rice mill. It was subsequently washed with distilled water to remove impurities, dried, and then ground. The resulting powder was sieved to an average particle size of 63 μm. The preparation flowchart of RH can be referred to in (Junian *et al.*, 2023).

Palm oil with rice husk filler preparation

The palm oil (PO) with varying concentrations of RH (see Table 1) was prepared according to the method in (Junian *et al.*, 2025). An 800 ml of PO was first dried in 24 hours at 80 ◦C. The RH filler was then added, and the blend was stirred for 8 hours with a magnetic stirrer. A pure PO sample without any filler was also prepared as a control. All samples were then left for 5 hours before testing.

Dielectric properties

The impedance of the samples was measured using electrochemical impedance spectroscopy (EIS). Measurements were taken at a fixed frequency of 100 Hz, with a voltage of 0.4 Vrms, at room temperature. A 4 cm × 4 cm piece of Kraft paper, with a thickness of 1×10^{-4} m, was placed between two stainless steel electrodes (30 mm diameter, 10 mm thickness). The electrodes and paper were fully immersed in each sample. The real permittivity and loss tangent at 100 Hz were then recorded using EIS.

Table 1. Sample composition of palm oil (PO) and rice husk (RH)

Sample	Amount of rice husk (g/L)
PO	0.00
PO – 0.05	0.05
PO – 0.10	0.10
PO – 0.20	0.20
PO – 0.50	0.50
PO – 1.00	1.00
PO – 1.50	1.50
PO – 1.75	1.75
PO – 2.00	2.00

Physicochemical Analysis

Viscosity

The viscosity of a sample is the measure of a fluid’s resistance to flow. Viscosity determines the ability of the sample as a transformer coolant. It is determined by using Brookfield Viscometer Model DV-II+ Pro (Figure 1). The speed is set at 50 rpm. The viscosity is measured at room temperature.

Figure 1. Brookfield Viscometer Model DV-II+ Pro

Moisture content

Moisture analysis is adopted from (Abd Manaf & Halim, 2003). A weight of 3.5 g for each sample was tested on the instrument Mettler Toledo HG 63 Halogen Moisture Analyzer (Figure 2), and the moisture content is analyzed and tabulated in terms of percentage.

Figure 2. Mettler Toledo HG 63 Halogen Moisture Analyzer

UV-Vis spectroscopy

Ultraviolet-visible (UV-Vis) spectrometer (Agilent Cary 60) (Figure 3) was used to analyze the filler concentration of RH suspended in PO in terms of optical absorption properties. The results were then presented in a graph.

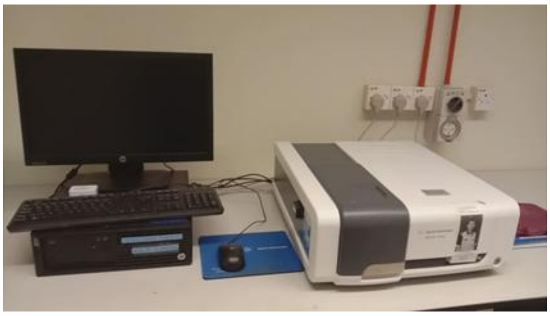

Figure 3. Agilent Cary 60 UV-Vis Spectrometer

RESULTS AND DISCUSSION

Dielectric Properties

Table 2 shows the real permittivity (ϵ′) and loss tangent (tan δ) of PO with varying concentrations of RH. The real permittivity and loss tangent are also graphed as shown in Figure 4. The real and loss tangent exhibits U-shaped trends with increasing RH concentrations. The trends mirror the breakdown voltage (BDV) peak (Figure 5) at 0.2 g/L. The real permittivity decreases from 2.83 (0.00 g/L) to a minimum of 1.93 at 0.5 g/L, then increases sharply to 5.17 at 2.00 g/L. The loss tangent drops from 0.064 (0.00 g/L) to 0.008 at 0.20 g/L, then rises to 0.124 at 2.00 g/L. This inverse correlation between real permittivity/loss tangent and BDV may be due to a common mechanism, namely interfacial polarization theory (Maxwell-Wagner-Sillars effect) (Perez-Rosa *et al.*, 2021) and percolation threshold behaviours (da Silva *et al.*, 2021; Shittu *et al.*, 2021).

Table 2. Real permittivity and loss tangent of palm oil with varying concentrations of rice husk at 100 Hz

Sample	Real permittivity	Real permittivity increment (%)	Loss tangent	Loss tangent increment (%)
PO	2.82601	-	0.0642437	-
PO – 0.05	2.68750	-4.9	0.0747545	16.4
PO – 0.10	2.03920	-27.8	0.05112873	-20.4
PO – 0.20	2.26916	-19.7	0.00834804	-87.0
PO – 0.50	1.93314	-31.6	0.0100289	-84.4
PO – 1.00	1.88683	-33.2	0.0182582	-71.6
PO – 1.50	3.31744	17.4	0.0842337	31.1
PO – 1.75	2.62545	-7.1	0.0862145	34.2
PO – 2.00	5.17257	83.0	0.124128	93.2

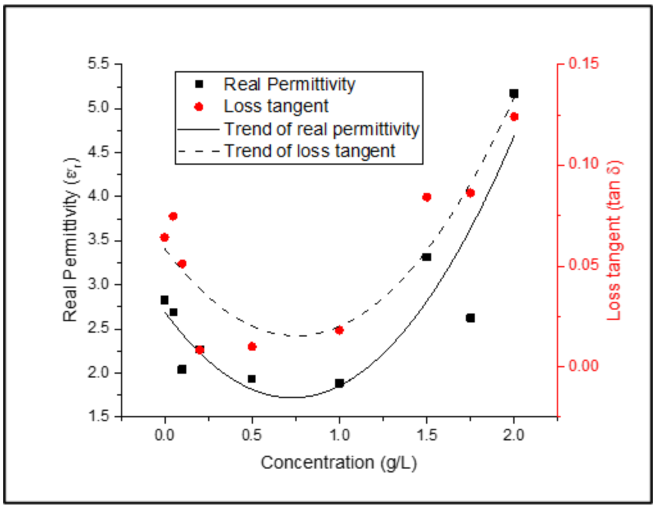

Figure 4. Graph of real permittivity and loss tangent at different concentrations of rice husk from 0.00 g/L to 2.00 g/L.

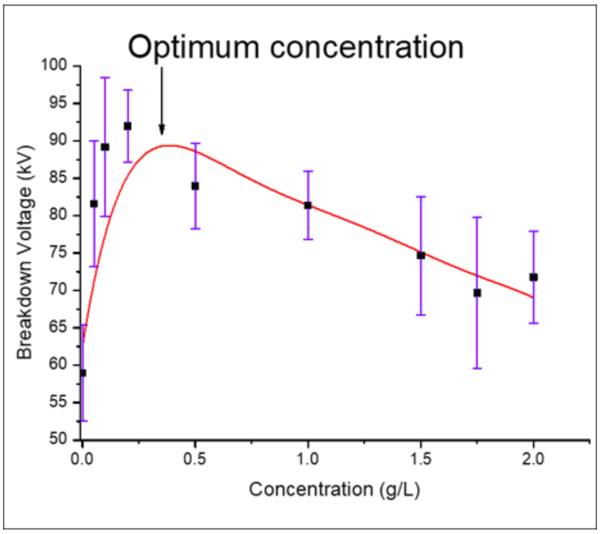

Figure 5. Graph of mean breakdown voltage (kV) with standard deviation (kV) at different concentrations of rice husk powder from 0.00 g/L to 2.00 g/L (Junian *et al.,* 2025). The arrow indicates the optimum concentration regime.

Low RH concentration (≤ 0.1 g/L)

At low filler concentrations (0.05 – 0.10 g/L), RH particles are well-dispersed in the PO matrix. The large interfacial area between the polar-hydrophilic RH surface and the non-polar PO particle promotes charge trapping at the RH-PO interface, effectively suppressing free charge mobility. This results in lower effective real permittivity and loss tangent. The homogenized electric field distribution delays the onset of streamer propagation and thus improving BDV. Figure 6 shows a diagram of the above phenomenon.

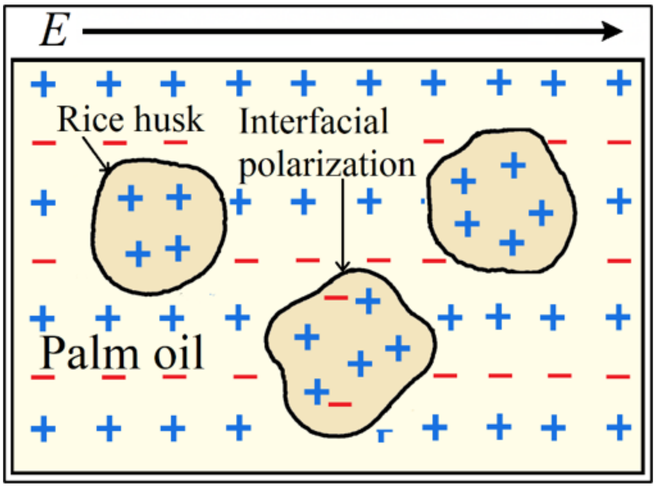

Figure 6. A sketch of interfacial polarization at low rice husk concentration in an electric field, *E*.

Optimum concentration (0.2 g/L)

RH particles are effectively dispersed, where the interface area and MWS effect are maximum. BDV also reaches its peak at an optimum concentration of 0.2 g/L, with a maximum value of 92.0 kV as shown in Figure 5.

High RH concentration (≥ 0.5 g/L)

As filler concentration increases to and beyond 0.5 g/L, particle-particle interactions become significant. The sharp rise in ε' (5.173 at 2.0 g/L) and loss tangent (0.124 at 2.0 g/L) indicates the onset of percolation-like behaviour. According to percolation theory, when the volume fraction of dispersed particles in a matrix reaches a critical threshold, they begin to form connected pathways or networks, leading to a sudden change in the material's physical properties (da Silva *et al.*, 2021; Shittu *et al.*, 2021). In conductive composites, this results in a sharp increase in electrical conductivity once the percolation threshold is crossed. Although RH is not a fully conductive filler like carbon or metal nanoparticles, its polar components, such as silica and cellulose (Alam *et al.*, 2020), are significantly more polarizable than the surrounding PO matrix. As RH concentration increases, particle-particle interactions intensify, promoting the formation of agglomerates and quasi-continuous networks. Moreover, RH has higher dielectric permittivity of about 10 (Junian *et al.*, 2021) than PO. When dispersed individually, their effect is minimal. But when clustered, they create regions with significantly different dielectric properties (permittivity) from the surrounding PO. Electric field concentration regions are formed in the clusters and facilitate conductive path formation under high voltage. This explains why the dielectric performance deteriorates at high concentrations. This phenomenon is drawn in as shown on Figure 7.

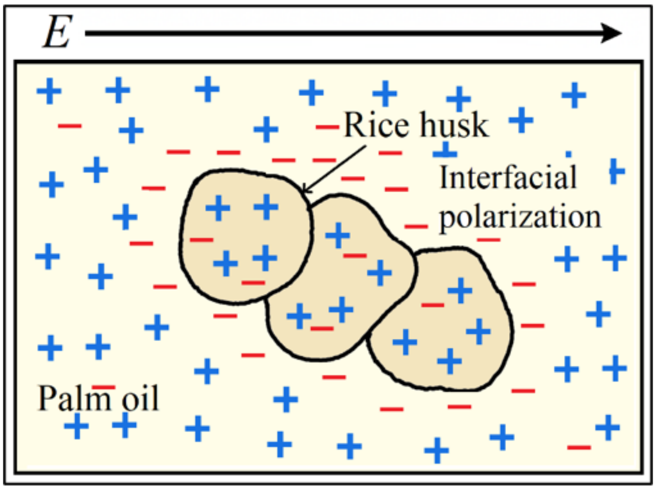

Figure 7. A sketch of percolation at high rice husk concentration in an electric field, *E*.

Viscosity

The viscosity of rice husk (RH)-filled palm oil (PO) was measured at 40 °C across nine different filler concentrations ranging from 0 to 2.0 g/L as shown in Table 3. The data is graphed as shown in Figure 8. A distinct maximum trend is observed on Figure 8 in which viscosity initially increases with filler concentration, reaching a maximum of 34.0 cP at 1.0 g/L, followed by a decrease in higher concentrations of RH. This peaked behaviour correlates with the previously reported BDV maximum curve, which exhibits its highest value at 0.2 g/L before decreasing.

Table 3. Viscosity of palm oil with varying concentrations of rice husk at 40 ˚C

Sample	Viscosity (cP)
PO	28.5
PO – 0.05	32.4
PO – 0.10	31.2
PO – 0.20	32.1
PO – 0.50	31.2
PO – 1.00	34.0
PO – 1.50	29.1
PO – 1.75	28.8
PO – 2.00	29.1

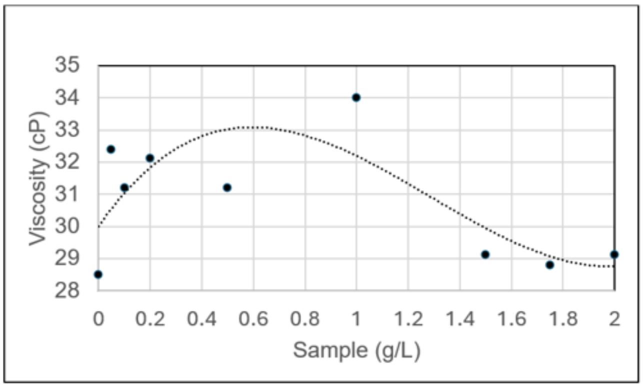

Figure 8. Graph of viscosity at different concentrations of rice husk from 0.00 g/L to 2.00 g/L.

Beyond 1.0 g/L, the viscosity decreases significantly, dropping to 29.1 cP at both 1.5 and 2.0 g/L. This reduction indicates a breakdown in colloidal stability, where RH particle-particle interactions begin to dominate over RH particle-PO fluid interactions. At high concentrations, van der Waals forces (Jacob *et al.*, 2020) effects, which make the RH particles attracting each other, promoting agglomeration and leads to the formation of larger clusters that reduce the effective surface area and interfacial friction within the fluid. These agglomerates behave more like suspended aggregates than well-dispersed particles, resulting in reduced resistance to flow, hence the decreased in viscosity. The viscosity drop serves as an indirect but reliable indicator of poor dispersion, which correlates directly with the deterioration in BDV performance.

It is also noteworthy that the peak in viscosity occurs at 1.0 g/L, which is higher than the concentration at which BDV reaches its maximum (0.2 g/L). This may suggest that viscosity is not the primary factor affecting BDV performance. Instead, the optimal dielectric behaviour at 0.2 g/L is more strongly influenced by interfacial polarization and charge trapping mechanisms, as reflected in the real permittivity and loss tangent data. Viscosity, therefore, acts as a secondary but supportive parameter that reflects the physical stability of the nanofluid.

Overall, the variation in viscosity across filler concentrations provides valuable insight into the dispersion quality of RH in PO. The initial increase in viscosity indicates favourable particle-fluid interactions and stable suspension behaviour, contributing to enhanced insulation performance. The subsequent decline at high concentrations signals the onset of agglomeration, which undermines both the rheological and dielectric integrity of the composite. Thus, viscosity serves as a macroscopic indicator of microstructural changes that ultimately influence the breakdown strength of the oil.

Moisture Content

Table 4 shows the moisture content of PO with varying concentrations of RH. The data shows only minor variation, with moisture content fluctuating between 0.05% and 0.09%. The lowest moisture level (0.05%) occurs at 0.05 g/L, while a slight increase to 0.09% is observed at 1.75 g/L. To note, the concentration corresponding to the maximum BDV (0.2 g/L) does not exhibit the lowest moisture content, nor is there a consistent trend of decreasing moisture with increasing RH concentration. This suggests that moisture reduction is not the primary mechanism responsible for the observed BDV peak. However, the slight decrease in moisture at low concentrations (0.05–0.5 g/L) may still play a secondary role. RH contains hydrophilic components such as silica, cellulose, and lignin, which have the capacity to adsorb and immobilize water molecules at the RH-PO interface (Chirsty & Sivarukshy, 2021). This moisture scavenging effect could contribute to improved dielectric strength at low loadings by reducing the number of free ions available for conduction (Adekunle & Oparanti, 2023). The minimal moisture content at 0.05 g/L supports this possibility, although the lack of further reduction at higher concentrations indicates that the adsorption capacity is quickly saturated.

Table 4. Moisture content of palm oil with varying concentrations of rice husk

Sample	Moisture Content (%)
PO	0.08
PO – 0.05	0.05
PO – 0.10	0.08
PO – 0.20	0.08
PO – 0.50	0.07
PO – 1.00	0.07
PO – 1.50	0.07
PO – 1.75	0.09
PO – 2.00	0.07

Beyond 1.0 g/L, the moisture content remains relatively stable (0.07–0.09%), despite the sharp decrease in BDV. This stability suggests that moisture is not the main factor behind the decrease in BDV. Instead, other mechanisms, such as filler agglomeration, increased interfacial polarisation, and field distortion, may be the factors at high concentrations. The slight increase in moisture percentage

at 1.75 g/L may even suggest that poorly dispersed agglomerates trap moisture within micro voids or interstitial spaces, potentially creating localised regions of high electric stress.

UV-Vis Analysis

The UV-Vis absorbance spectra (Figure 9) are recorded from approximately 400 to 700 nm across RH concentrations from 0 to 2.0 g/L. The absorbance intensity in the 400–700 nm range increases systematically with rising RH concentration.

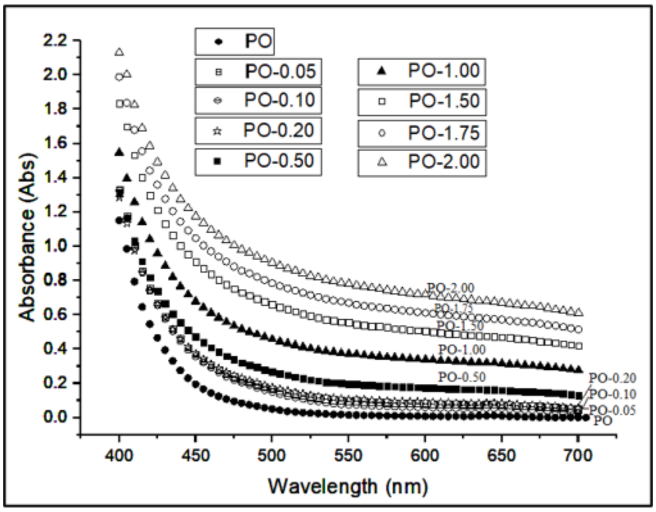

Figure 9. The absorbance spectrum of palm oil from 400 to 700 nm across RH concentrations from 0.0 to 2.0 g/L.

At 0 g/L, the spectrum shows minimal absorbance, consistent with the transparent nature of pure PO. With increasing filler content, a steady rise in absorbance is observed across the entire visible range, confirming that RH particles are present and suspended in the oil matrix. This increasing trend in absorbance is directly related to the concentration of suspended particles (Rabbi *et al.*, 2021). The higher the concentration of RH, the greater the number of particles interacting with incident light, resulting in increased absorbance values.

UV-Vis spectroscopy successfully confirms the presence and relative concentration of RH filler in palm oil. The uniform increase in absorbance with filler content validates the experimental design and ensures that observed changes in dielectric and rheological properties can be meaningfully correlated with RH concentration.

CONCLUSION

The behaviour of breakdown voltage (BDV), which peaks at 0.2 g/L of RH filler in PO, is a balance between interfacial effects at low concentrations and detrimental microstructural changes at higher RH concentrations. This study integrates dielectric and rheological analysis to uncover the underlying physical mechanisms responsible for this optimization in insulation performance.

At low filler concentrations (less than 0.2 g/L), RH particles are well-dispersed, leading to a significant reduction in loss tangent (tan δ), reaching a minimum of 0.0083, and a moderate decrease in real permittivity (ε'). These changes indicate decreased dielectric losses and improved electric field homogenization, delaying streamer initiation and maximizing BDV at 92.0 kV. At high concentrations (more than 0.2 g/L), particle agglomeration may begin to dominate. This is shown in the permittivity data, in which there is a sharp increase in both dielectric real permittivity and loss tangent in the specified concentration range, signifying severe electric field distortions and increasing conduction losses, respectively.

The viscosity trend, peaking at 34.0 cP at 1.0 g/L before declining, further supports the transition from stable suspension to agglomeration-driven instability. The decrease in viscosity at higher RH concentrations indicates that RH particles are clumping together instead of in individually dispersed units. While viscosity contributes to particle mobility and dispersion quality, its peak occurs after the BDV maximum, indicating it plays a secondary role compared to dielectric parameters. However, moisture content shows only small variation (0.05–0.09%) across concentrations, with no consistent trend correlating to BDV. Although RH has hydrophilic components that may adsorb water, this effect is insufficient to explain the observed insulation enhancement, confirming that moisture scavenging is not the dominant mechanism.

The maximum in BDV at 0.2 g/L is primarily attributed to optimal dispersion of RH particles, which suppresses dielectric losses and enhances charge trapping. At higher concentrations, agglomeration leads to percolation, increased dielectric loss which degrades BDV performance. The combined analysis of real permittivity, loss tangent, UV-Vis absorbance, and viscosity provides an understanding of the physical mechanisms in PO-based insulating oil, highlighting the importance of dispersion control over filler concentration.

ACKNOWLEDGEMENTS

This research is funded under Universiti Malaysia Sabah Geran Bantuan Penyelidikan Pascasiswazah (UMSGreat) number GUG2019-1/2018, and is greatly acknowledged.

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