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Potential of Oil Mixture of Palm Oil and Mineral as Future Transformer Oil

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Abstract

This study investigates the electrical performance of oil mixtures that composed of palm oil and mineral oil for potential use as an alternative transformer insulating fluid. The breakdown voltage of eleven oil samples, prepared with varying ratios of palm oil and mineral oil, is measured at temperatures of 50°C, 60°C, and 70°C. The results show that the breakdown voltage generally decreases as the percentage of palm oil decreases and the percentage of mineral oil increases. However, beyond certain points, the breakdown voltage starts to increase again. For example, at 50°C, the mixture with 60% palm oil and 40% mineral oil exhibited the lowest breakdown voltage, while the mixture with 100% mineral oil had the highest breakdown voltage. At 60°C, the sample with 40% palm oil and 60% mineral oil had the highest breakdown voltage, and at 70°C, the sample with 40% palm oil and 60% mineral oil again exhibited the highest breakdown voltage. The study also utilized Arrhenius plots to investigate the thermal activation energy of the oil mixtures, which provides insights into their thermal stability. The results demonstrate the potential of palm oil as a cost-effective and environmentally friendly option for transformer insulation, offering valuable implications for sustainable transformer technology development. Further investigation into moisture content in the oil mixtures and its correlation with thermal activation energy is recommended for future work.

1. Introduction

This study focuses on the vital role of transformers in the transmission and distribution of electrical energy, where they utilize oil as an insulation and cooling medium. Over time, the insulating oil can deteriorate due to aging, high temperatures, and oxidation, making it crucial for this study to monitor its condition and perform maintenance if necessary. This is essential to prevent sudden failure and ensure the dependable operation of the transformer [1]. The breakdown voltage measurement stands as a standard test for analyzing insulating oils, while the dissipation factor (tan delta) plays a key role in determining the quality of insulation. The dielectric properties of oil are influenced by various factors such as temperature, polarity, frequency, voltage level, electrode shape, presence of particles, and moisture [2-5]. Traditionally, mineral oil has been employed as a liquid insulator in high-voltage transformers due to its favourable breakdown voltage, viscosity, and oxidation stability [6-8]. However, in this study, we aim to investigate the potential of palm oil as an alternative to mineral oil, addressing concerns surrounding its environmental impact and toxicity [9]. As a biodegradable, non-toxic, and renewable resource, palm oil holds promise as a cost-effective replacement for mineral oil [2]. Its abundance in nature and status as a natural product makes it a favourable option worthy of consideration.

One of the critical aspects of this study involves investigating the thermal stability of the mineral oil-palm oil mixture. To accomplish this, an Arrhenius plot will be utilized to study the relationship between temperature and the rate of oil degradation. The Arrhenius plot allows us to determine the thermal activation energy, which is a crucial parameter in assessing the stability and breakdown characteristics of the insulating oil. By analyzing the activation energy, this study can gain valuable insights into the long-term performance and reliability of the oil in transformer applications. Previous research has shown that palm oil exhibits potential as a high-voltage insulating fluid and is the most widely used vegetable oil globally, offering various beneficial properties such as long-term stability and a semi-solid consistency. Moreover, its productivity surpasses that of other vegetable oils, yielding higher quantities at a lower cost, and it has been rapidly gaining both production and demand on a global scale [8]. This study contributes to the ongoing efforts to identify suitable alternative fluids for transformer oil, focusing on the three different Palm-based oils: Palm Fatty Acid Ester Oil (PFAE), Refined, Bleached & Deodorized Palm Oil (RBDPO), and FR3 [10]. Through a comparative analysis of their kinetic viscosity and flash points, this study seeks to evaluate the viability of reducing the total cost of insulator oil by introducing a blend of mineral oil with the more cost-effective palm oil.

By conducting this research, including the investigation of thermal stability and thermal activation energy using the Arrhenius plot, this target is to advance the development of sustainable and efficient transformer technology. The findings of this study can provide valuable insights into the performance of the mineral oil-palm oil mixture as a transformer oil, with a focus on both cost-effectiveness and environmental considerations. Ultimately, the aim is to contribute to the industry's efforts to ensure reliable, eco-friendly, and economically viable solutions for insulation and cooling in high-voltage transformers

2. Methodology

Table 1 shows eleven types of samples that have been tested in this project. The eleven samples contained a mixture of both palm and mineral oil. The mixture ratio started from 0% palm oil, i.e. 100% mineral oil and then increased by 10% on every sample by volume ratio. The BDV test stands for breakdown voltage test. It can be accomplished in two ways: DC breakdown voltage or AC breakdown voltage. It is a traditional test method for analyzing insulating oils. The breakdown voltage is the lowest applied voltage that will cause an insulator or electrode to break down. In this project, the Megger OTS100AF portable oil test set (Figure 1 and Figure 2) will be used to measure the breakdown voltage. The mushroom electrode pairs recommended by the IEC 60156 Standard will be used on the portable oil test. By measuring the oil's ability to withstand electric stress, the kit set will perform a breakdown voltage test on the mixture of Palm Oil and Mineral Oil. The mixture samples will be tested at three different temperatures, 50°C, 60°C, and 70°C. The BDV testing flow in detail as illustrated in Figure 3 below.

Table 1 *Percentage and ratio of oil mixture prepared*

Sample no	% Palm Oil	% Mineral Oil	Oil Ratio Palm:Mineral
1	0	100	0:100
2	10	90	1:9
3	20	80	1:4
4	30	70	3:7
5	40	60	2:3
6	50	50	1:1
7	60	40	3:2
8	70	30	7:3
9	80	20	4:1
10	90	10	9:1
11	100	0	100:0

Fig. 1 *Megger OTS100AF oil breakdown tester*

Fig. 2 *400 ml oil test cup*

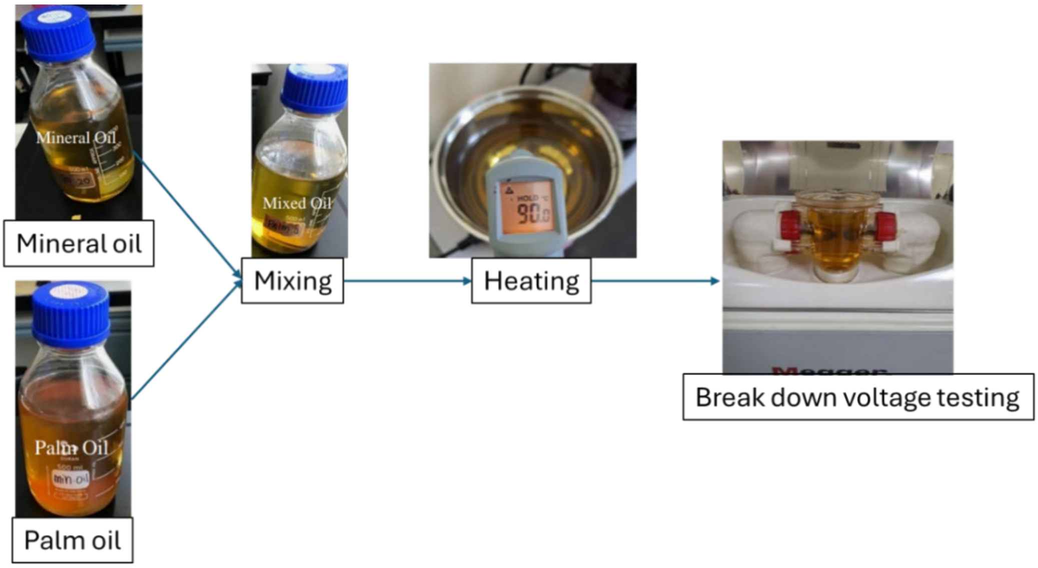

Fig. 3 *BDV testing process flow*

3. Results

3.1 AC Breakdown Voltage for Palm Oil and Mineral Oil Mixture at 50°C

Table 2 provides a detailed breakdown of the breakdown voltage at 50°C for different oil mixtures. Sample numbers 1 and 11 represent pure palm oil and pure mineral oil, respectively. Sample numbers 2 to 10 represent varying ratios of palm oil to mineral oil. As the percentage of palm oil decreases and the percentage of mineral oil increases, the breakdown voltage generally decreases. This trend is evident from sample numbers 2 to 7. The mixture with 60% palm oil and 40% mineral oil (sample number 7) has the lowest breakdown voltage of 15.03 kV. The mixture with 100% mineral oil (zero percentage of palm oil, sample number 11) has the highest breakdown voltage of 29.78 kV. The mixture with 60% palm oil and 60% mineral oil (sample number 7) exhibits the lowest standard deviation of 1.49, indicating more consistent results compared to other mixtures. The mixture with 90% mineral oil (sample number 2) has the highest standard deviation of 7.39, suggesting more variability in the breakdown voltage measurements.

At 50°C, as shown in Figure 4, the graph of breakdown voltage demonstrates a decreasing trend as the palm oil percentage drops from 100% to 60% (29.78 kV-15.03 kV). The value of breakdown voltage increased steadily after that up to 28.9 kV at 100% palm oil. The given results described an experiment that investigates the breakdown voltage of oil mixtures at a temperature of 50°C. The breakdown voltage is a measure of the ability of an insulating material to withstand electrical stress before it breaks down and allows current to flow. From Figure 3, it can be observed that as the percentage of palm oil decreases from 100% to 60%, the breakdown voltage decreases from 29.78 kV to 15.03 kV. This indicates that a higher concentration of palm oil leads to a higher breakdown voltage. The molecular structure of the oils can affect their electrical properties [11]. Palm oil contains triglycerides, which are relatively large molecules [12]. These larger molecules may create more effective barriers for electron movement, enhancing the insulating properties of the oil mixture and increasing the breakdown voltage. However, beyond 60% palm oil, the breakdown voltage starts to increase again, reaching 28.9 kV at 100% palm oil. This may be due to the presence of impurities or additives in the oil mixtures after heating that can influence their electrical characteristics. Impurities or contaminants in the oils can introduce conductive particles or ions that can reduce the breakdown voltage [13]. The results indicate that the sample with 100% mineral oil (zero percentage of palm oil) has the highest breakdown voltage (29.78 kV) and the mixture with 60% palm oil and 40% mineral oil has the lowest breakdown voltage (15.03 kV) at 50°C. As per Table 2, the mixture with 60% palm oil and 60% mineral oil exhibits the lowest standard deviation (1.49), while the mixture with 90% mineral oil has the highest standard deviation (7.39).

Table 2 *Breakdown voltage at 50°C*

Sample no	% Palm Oil	% Mineral Oil	Ratio Palm:Mineral	Breakdown Voltage	Standard Deviation
1 (Mineral oil)	0	100	0:100	29.78	1.51
2	10	90	1:9	27.37	7.39
3	20	80	1:4	32.05	4.1
4	30	70	3:7	27.18	3.97
5	40	60	2:3	25.17	4.99
6	50	50	1:1	19.37	2.15
7	60	40	3:2	15.03	1.49
8	70	30	7:3	16.33	1.58
9	80	20	4:1	17.78	1.62
10	90	10	9:1	16.72	2.67
11 (Palm oil)	100	0	100:0	28.9	3.77

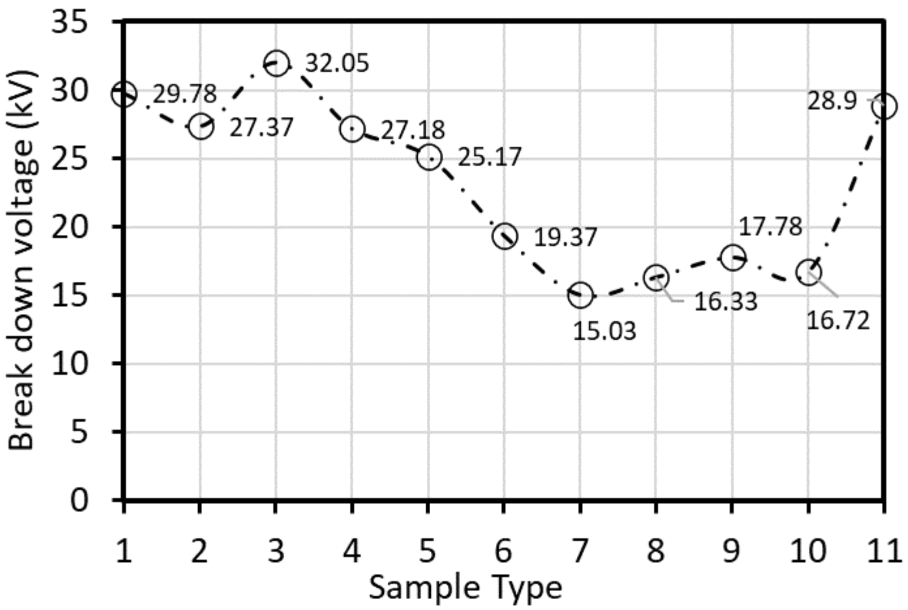

Fig. 4 *Oil mixture breakdown voltage at 50°C*

3.2 AC Breakdown Voltage for Palm Oil and Mineral Oil Mixture at 60°C

Table 3 shows that the sample with 40% palm oil and 60% mineral oil has the highest breakdown voltage (46.45 kV) at 60°C, while the mixture with 80% palm oil and 20% mineral oil gives another spike at 37.9 kV. The mixture of 20% palm oil gives the lowest breakdown voltage at 22.67 kV. Table 3 shows that the lowest standard deviation is found in the mixture with 90% palm oil and 10% mineral oil (2.65), while the sample with 80% palm oil has the highest standard deviation (6.66).

Figure 5 displays the graph of the breakdown voltage of samples at 60°C, the graph shows the decreasing pattern when the percentage of palm oil increased from 0–20% but increased back from 20% – 40% with 46.45 kV as the peak value. The breakdown voltage decreased again after that and showed another spike at 80% palm oil at 37.9 kV. The voltage at 100% palm oil is 26 kV).

3.3 AC Breakdown Voltage for Palm Oil and Mineral Oil Mixture at 70°C

The highest breakdown voltage at 70°C is 47.87 kV in the sample with 40% palm oil and 60% mineral oil. The lowest breakdown voltage is 28.75 kV in the sample with 50% palm oil and 50% mineral oil. Table 4 shows the lowest standard deviation of 2.4 in the sample with 50% palm oil and 50% mineral oil. The highest standard deviation of 6.77 found are in the sample with 80% palm oil and 20% mineral oil. As seen from Figure 6, the breakdown voltage of the samples decreases as the percentage of palm oil decreases from 100% to 90% (38.15 kV and 37.57 kV respectively) at 70°C. However, a sudden increase to 47.87 kV is observed when the mixture contains 20% palm oil. The breakdown voltage suddenly dropped to 32.37 kV at 30% palm oil portion and suddenly spike to 49.37 kV at the mixture of 40:60 ratio. The breakdown voltage dropped to 28.75 kV at 50% palm oil then increased steadily to 44.42 kV at 80% palm oil dan decreased to 41.65 kV for 100% palm oil.

Table 3 *Breakdown voltage at 60°C*

Sample no	% Palm Oil	% Mineral Oil	Ratio Palm:Mineral	Breakdown Voltage	Standard Deviation
1 (Mineral oil)	0	100	0:100	35.33	2.99
2	10	90	1:9	30.92	3.00
3	20	80	1:4	22.67	3.86
4	30	70	3:7	25.82	3.47
5	40	60	2:3	46.45	3.75
6	50	50	1:1	25.82	3.66
7	60	40	3:2	28.97	3.79
8	70	30	7:3	27.32	4.19
9	80	20	4:1	37.9	6.66
10	90	10	9:1	26.97	2.65
11 (Palm oil)	100	0	100:0	26.00	3.07

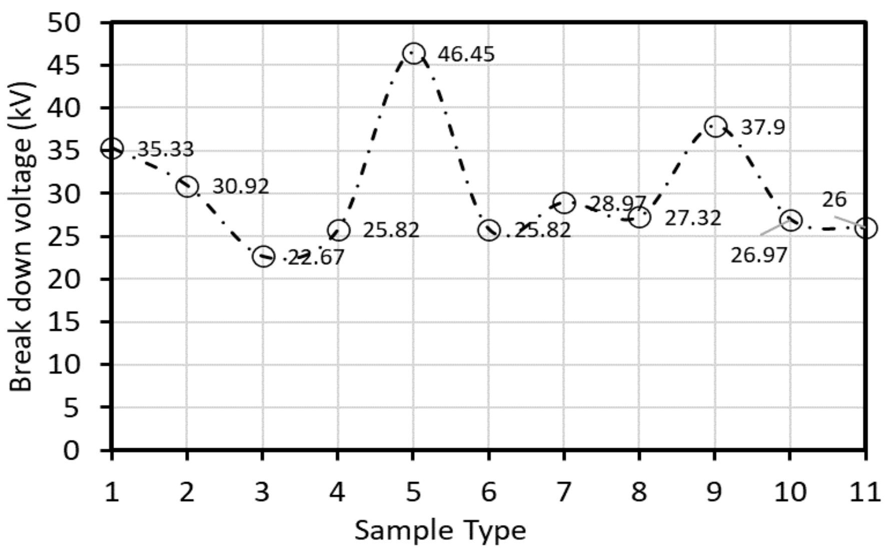

Fig. 5 *Oil mixture breakdown voltage at 60°C*

Table 4 *Breakdown voltage at 70°C*

Sample no	% Palm Oil	% Mineral Oil	Ratio Palm:Mineral	Breakdown Voltage	Standard Deviation
1 (Mineral oil)	0	100	0:100	38.15	6.19
2	10	90	1:9	37.57	4.94
3	20	80	1:4	47.87	5.67
4	30	70	3:7	32.37	5.34
5	40	60	2:3	49.37	5.02
6	50	50	1:1	28.75	2.4
7	60	40	3:2	33.08	6.71
8	70	30	7:3	40.78	5.35
9	80	20	4:1	44.42	6.77
10	90	10	9:1	41.8	5.42
11 (Palm oil)	100	0	100:0	41.65	5.86

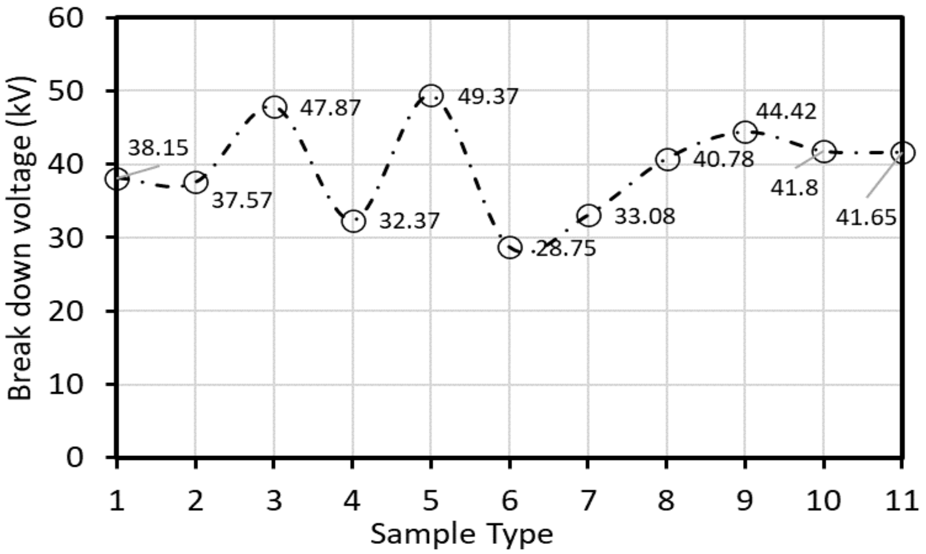

Fig. 6 *Oil mixture breakdown voltage at 70°C*

The results in Figure 7 indicate a dependence of the breakdown voltage on the mixture of palm oil and mineral oil for temperatures of 50, 60, and 70 °C. Temperature plays a crucial role in the breakdown voltage of insulating materials. As the temperature increases, the breakdown voltage may decrease due to increased molecular mobility and thermal effects [14-16]. Higher temperatures can cause thermal effects within the insulating material, such as thermal expansion and chemical reactions [16]. Thermal expansion can create microscopic voids or gaps in the material, reducing its overall dielectric strength and increasing the likelihood of breakdown [15-16]. Additionally, elevated temperatures can induce chemical reactions or degradation processes in the insulating material, which can alter its electrical properties and contribute to a decrease in breakdown voltage. However, the highest breakdown voltages were observed for the temperature of 70 °C, with most values higher than those for temperatures of 50 °C and 60 °C. The distribution of data for temperatures 60 °C and 70 °C was almost similar, while the data for 50 °C had a different distribution. From all the data shown, the highest breakdown voltage in the experiment was found to be in the sample containing 20% palm oil which was tested at 50 °C. As the percentage of palm oil decreases to 90%, the breakdown voltage also decreases, with the highest breakdown voltage found at 70 °C, followed by 60 °C and 50 °C. At the temperature of 60°C and 70 °C are mixture with 40% palm oil and 60% mineral oil gives the highest breakdown voltages. At this temperature, the breakdown voltages are on the higher side 37.9 kV and 44.42 kV respectively.

It's important to note that the relationship between temperature and breakdown voltage may not be linear for 3, 4 and 11 as observed in Figure 8. Different insulating materials exhibit varying responses to temperature changes. Those samples experience a more significant decrease in breakdown voltage after 50 °C and a significant increase from 60-70 °C, while others may be less affected. The relationship between temperature and breakdown voltage can be attributed to two main factors: increased molecular mobility and thermal effects. As the temperature rises, the kinetic energy of molecules within the insulating material increases. This increased energy

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leads to greater molecular mobility, which can facilitate the movement of charge carriers within the material. When charge carriers gain greater mobility, they can more easily initiate and sustain electric currents, leading to a reduction in breakdown voltage [17-18]. Essentially, the increased molecular mobility enhances the oil mixture's conductivity, making it easier for electrical breakdown to occur.

3.4 Arrhenius Study of AC Breakdown Voltage for Palm Oil and Mineral Oil Mixture

This study initiates the break down analysis of oil mixture using an Arrhenius plot as shown in figure 9 that replot from data breakdown voltage versus temperature in Figure 6, to provide several insights and discussions regarding the behaviour of the composite mixture of dielectric material in term of thermal activation energy. The Arrhenius equation is given by:

$$\ln\left(V_{BD}\right) = \ln\left(V_{BD\_O}\right) - \left(\frac{E_a}{k}\right)\left(\frac{1}{T}\right) \tag{1}$$

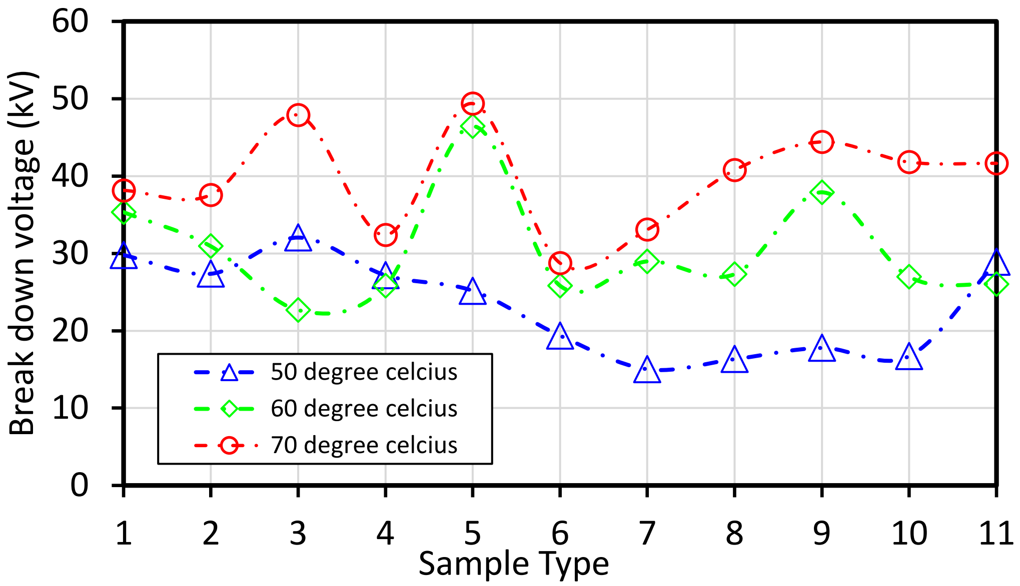

Fig. 7 *Comparison of oil mixture breakdown voltage at different temperatures of 50°C, 60 °C, and 70°C*

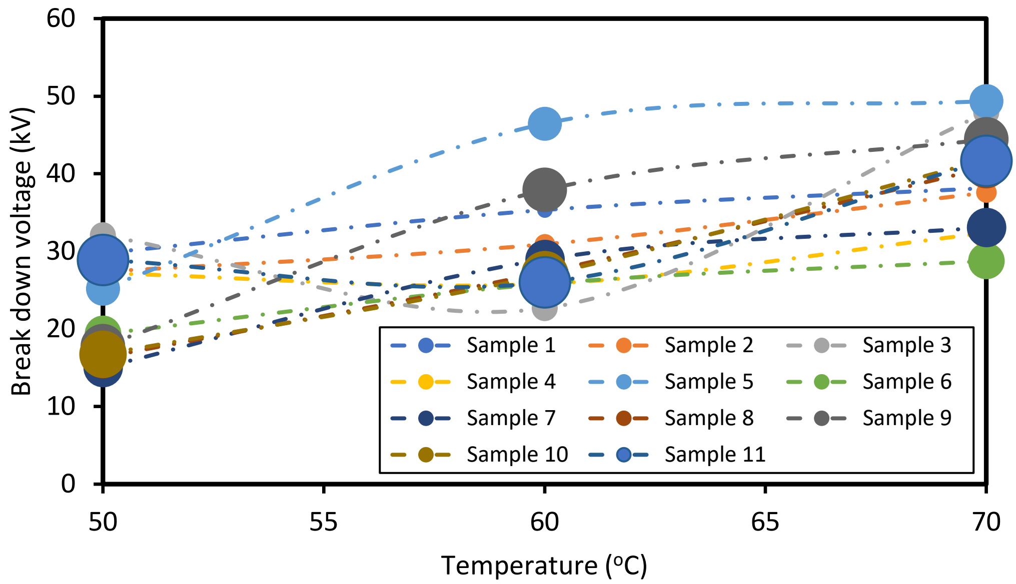

Fig. 8 *Comparison of oil mixture breakdown voltage at different temperatures of 50°C, 60°C, and 70°C*

Where V_{BD} is the breakdown voltage, V_{BD_0} is a reference voltage, E_a is the thermal activation energy, k is the Boltzmann constant, and T is the temperature in Kelvin. The slope of the linear portion of the plot is determined by fitting a linear regression line to the data points within the linear range to calculate the activation energy. The slope of the linear portion of the Arrhenius plot represents the activation energy associated with the dielectric breakdown process activated by thermal. The higher the thermal activation energy, the stronger the thermal energy barrier for breakdown. The discussion focuses on the magnitude of the thermal activation energy and its behaviour relationship with the oil mixture's breakdown voltage in function of temperature.

Figure 9 shows there is a linear relationship at a temperature range of 50 -70 °C, and it suggests that the breakdown process follows an Arrhenius-type behaviour for a specific sample. Table 5 shows that all samples except sample 2, 3, 4 and 11 are following Arrhenius-type behaviour with goodness fit near to 1. Those samples that do not follow Arrhenius-type behaviour are inferred to have thermal instability and high chemical reactivity with moisture content. If comparing mixed oil mixtures, the Arrhenius plot shows differences in thermal activation energy among the samples. It can be highlighted that the mixture of palm and mineral oil has the potential to increase the oil breakdown voltage at high temperatures due to an increase of thermal activation energy [19-20]. This may be due to solvent reorganisation energy that increases the oil resistance at high temperatures.

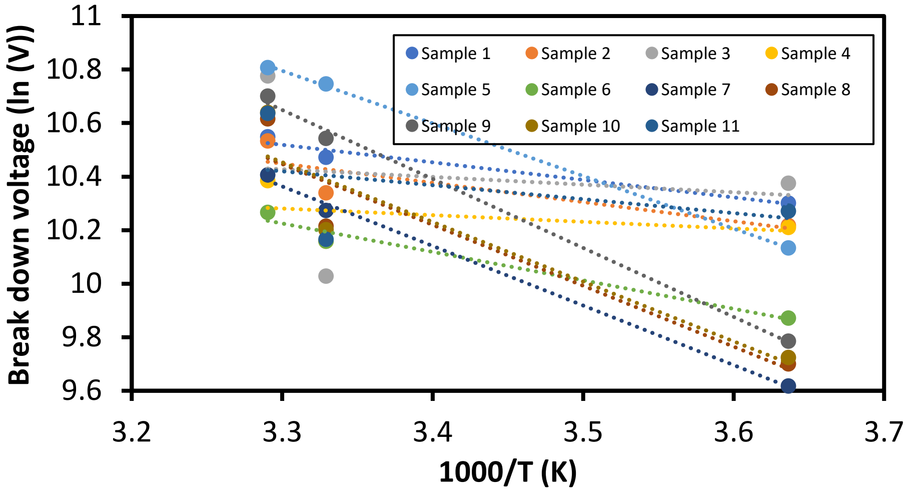

Fig. 8 *Arrhenius plot of oil mixtures breakdown voltage*

Figure 10 shows that, the thermal activation energy values range from 21.38 meV to 222.04 meV. Sample 9 has the highest activation energy of 222.04 meV, indicating a relatively high energy barrier for the breakdown process. This trend shows good agreement with the corresponding significant increase of breakdown voltage of sample 9 with an increase of temperature. Sample 4 has the lowest activation energy of 21.38 meV and the lowest breakdown voltage of 28.75 kV, suggesting a relatively lower energy barrier for breakdown compared to the other samples. This supported by the breakdown voltage trend when sample 4 is heated to high temperature where the breakdown voltage is not increase significantly.

Palm oil and mineral oil are both hydrophobic substances and are generally immiscible with water. However, they can be miscible with each other to some extent, depending on the composition and conditions of the mixture. The solubility behaviour of the oils can affect their overall stability and performance as a mixture. Thus, this study aware that factor such moisture absorption of the oil mixture also need to be considered to ensure the correlation between thermal activation energy with breakdown voltage trend become more promising. This is shown by the trend of Sample 5 which has the highest breakdown voltage of 49.37 kV even the thermal activation energy is not the optimum. Thus, moisture content in the new oil mixture relation with the thermal activation energy investigation will be highlighted as future work to shows strong correlation between the moisture content of oil mixture that can lowering the actual thermal activation energy towards designing the optimum oil mixture thermal activation energy condition.

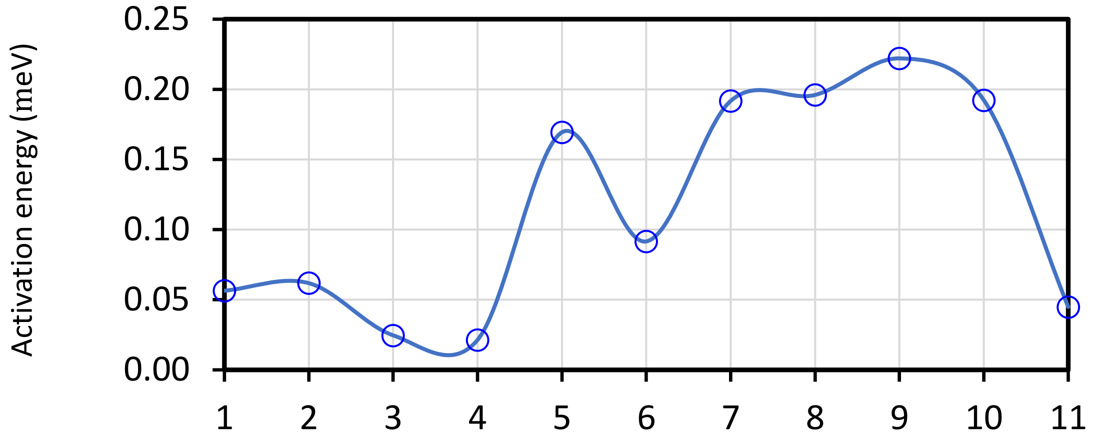

Fig. 10 *Activation energy for breakdown of oil mixtures breakdown voltage calculated from slope of Arrhenius plot in Fig. 8*

Table 5 *Arrhenius coefficient extracted from Arrhenius plot in figure 8*

Sample no	$-\left(\frac{E_a}{k}\right)$	$\ln\left(V_{BD\_O}\right)$	E_a (meV)	goodness of fit (R^2)
1 (Mineral oil)	-0.6549	12.68	0.06	0.9586
2	-0.7173	5.5658	0.06	0.7243
3	-0.2855	11.369	0.02	0.0209
4	-0.2481	11.1	0.02	0.1575
5	-1.9653	17.281	0.17	0.9996
6	-1.0628	13.732	0.09	0.9735
7	-2.2251	17.706	0.19	0.997
8	-2.2744	17.953	0.20	0.8831
9	-2.5766	19.152	0.22	0.9964
10	-2.231	17.816	0.19	0.8514
11 (Palm oil)	-0.5209	12.139	0.04	0.1595

4. Conclusions

The study aims to analyze the breakdown voltage of oil mixtures consisting of palm oil and mineral oil at different temperatures. Eleven oil samples are prepared with varying ratios of palm oil and mineral oil. The mixture ratios range from 0% palm oil (100% mineral oil) to 100% palm oil (0% mineral oil). The breakdown voltage of each sample is measured at three different temperatures: 50°C, 60°C, and 70°C. The results indicate that the breakdown voltage generally decreases as the percentage of palm oil decreases and the percentage of mineral oil increases. However, beyond a certain point, the breakdown voltage starts to increase again. For example, at 50°C, the mixture with 60% palm oil and 40% mineral oil exhibits the lowest breakdown voltage, while the mixture with 100% mineral oil has the highest breakdown voltage. At 60°C, the sample with 40% palm oil and 60% mineral oil has the highest breakdown voltage, while the mixture with 20% palm oil shows another spike in breakdown voltage. At 70°C, the sample with 40% palm oil and 60% mineral oil again has the highest breakdown voltage, while the mixture with 50% palm oil has the lowest breakdown voltage. The results also show that the breakdown voltage is influenced by temperature.

As the temperature increases, the breakdown voltage may decrease due to increased molecular mobility and thermal effects. Additionally, the molecular structure of the oils can affect their electrical properties. Palm oil, which contains triglycerides with relatively large molecules, may enhance the insulating properties of the oil mixture and increase the breakdown voltage. The study provides insights into the electrical performance of oil mixtures containing palm oil and mineral oil in transformer applications. By understanding the breakdown voltage characteristics, researchers and industry professionals can assess the suitability of palm oil as a potential alternative to mineral oil, considering both cost and environmental considerations.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***investigation and writing:*** *Naidhila Junaidi;* ***project administration, conceptualization, writing methodology:*** *Pungut Ibrahim;* ***formal analysis, visualization:*** *Megat Muhammad Ikhsan Megat Hasnan;* ***data curation, validation:*** *Ahmad Razani Haron;* ***funding acquisition, resources:*** *Nur Aqilah Mohamad;* ***proofreading:*** *Herwansyah Lago;* ***review & editing:*** *Chai Chang Yii. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] Ariffin, M. M., Ishak , M. T., Hamid, M.H.A., Katim, N.I.A.,Ishak, A.M., and Azis,N. "Ageing effect of vegetable oils impregnated paper in transformer application." *International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*, pp. 183-187. IEEE, 2017. 10.1109/ICHVEPS.2017.8225939

[2] Azhary, Zuan & Samion, Syahrullail & Zaminain, M.D.. (2017). “Tribological Properties of Mineral Oil Mix with RBD Palm Stearin Using Four-Ball Tribotester at Various Loads.” *Advanced Science Letters*. 23. 4725-4727. https://doi.org/10.1166/asl.2017.8865

[3] Bashi, S. M., Abdullahi, U.U., Robia Yunus, and Amir Nordin. "Use of natural vegetable oils as alternative dielectric transformer coolants." *The Institution of Engineers*, vol. 67, no. 2, pp. 4-9. 2006. http://dspace.unimap.edu.my/xmlui/handle/123456789/13739

[4] Beldjilali, A., Idir, O., Saidi-Amroun, N., Saidi, M., & Moulai, H. (2018). Electrical and physicochemical properties and transient charging currents in mineral and vegetable oils mixtures. *IEEE Transactions on Dielectrics and Electrical Insulation*, 25(5), 1739-1748. https://doi.org/10.1109/TDEI.2018.007150

[5] Kocatepe, C., E. Taslak, C. F. Kumru, and O. Arıkan. "An investigation on vegetable oils as potential insulating liquid." *International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering* 9, no. 8 (2015): 794-797. https://doi.org/10.5281/zenodo.1107702

[6] Narayani, A., Willjuice Iruthayarajan,M., and Bakrutheen, M. "A statistical study on the AC breakdown voltage of corn oil and mineral oil for liquid insulation." *Third International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB)*, pp. 320-323. IEEE, 2017. https://doi.org/10.1109/AEEICB.2017.7972324

[7] Fritz, Willy. "Numerical simulation of the peculiar subsonic flow-field about the VFE-2 delta wing with rounded leading edge." *Aerospace Science and Technology* 24, no. 1 (2013): 45-55. https://doi.org/10.1016/j.ast.2012.02.006

[8] Falcon, Walter P., Rosamond L. Naylor, and Nikhil D. Shankar. "Rethinking Global Food Demand for 2050." *Population and Development Review* (2022). https://doi.org/10.1111/padr.12508

[9] Azmi, Kiasatina , Ahmad, Azmier, and Kamarol, Mohamad.” Study of Dielectric Properties of a Potential RBD Palm Oil and RBD Soybean Oil Mixture as Insulating Liquid in Transformer.” *Journal of Electrical Engineering and Technology*, vol. 10, no. 5, pp. 2105-2119, 2015. https://doi.org/10.5370/JEET.2015.10.5.2105

[10] Hamid, M. H. A., Ishak, M. T., Suhaimi, N. S., Adnan, J., Hashim, N. I., Ariffin, M., Katim, N. I. A., and Rahisham Abd Rahman. "Electrical properties of palm oil and rice bran oil under AC stress for transformer application." *Alexandria Engineering Journal* 61, no. 11 (2022): 9095-9105. https://doi.org/10.1016/j.aej.2022.02.049

[11] Ghazali, Nazlee Faisal, Khairilanuar Md Hanim, Qadly Ameen Pahlawi, and Ki Min Lim. "Enrichment of carotene from palm oil by organic solvent nanofiltration." *Journal of the American Oil Chemists' Society* 99, no. 3 (2022): 189-202. https://doi.org/10.1002/aocs.12563

[12] Mohamad, S. A., Abd Aziz, A. S., Dabwan, A. H. A., Abdullah, A. H., and Mohamed, A. H.. "Physiochemical properties of palm olein." *Journal of Physics: Conference Series*, vol. 2266, no. 1, p. 012007. IOP Publishing, 2022. https://doi.org/10.1088/1742-6596/2266/1/012007

[13] Pagger, Ernst Peter, Norasage Pattanadech, Frank Uhlig, and Michael Muhr. "Properties of New Insulating Liquids and Main Differences." *Biological Insulating Liquids: New Insulating Liquids for High Voltage Engineering*, pp. 65-140. Cham: Springer International Publishing, 2023. https://doi.org/10.1007/978-3-031-22460-7

[14] Suhaimi, Nur S., Mohd T. Ishak, Abdul RA Rahman, F. Muhammad, Mohd ZZ Abidin, and Azhar K. Khairi. "A Review on Palm Oil-based Nanofluids as a Future Resource for Green Transformer Insulation System." *IEEE Access* (2022). https://doi.org/10.1109/ACCESS.2022.3209416

[15] Saidj, Idir Ben, Mohammed Nedjar, Smain Hocine, and Ferhat Belabbas. "Effects of Hydrothermal Aging on the Breakdown Voltage of Polyesterimide." *Annales de Chimie-Science des Matériaux*, vol. 46, no. 2, pp. 95-102. 2022. https://doi.org/10.18280/acsm.460205

[16] He, Junjie, Qiuwang Wang, Jian Wu, Yongmin Zhang, and Wenxiao Chu. "Hybrid thermal management strategy with PCM and insulation materials for pulsed-power source controller in extreme oil-well thermal environment." *Applied Thermal Engineering* 214 (2022): 118864. https://doi.org/10.1016/j.applthermaleng.2022.118864

[17] Zheng, Hanbo, Yongji Feng, Xufan Li, Hang Yang, Weijie Lv, and Songjiang Li. "Investigation on molecular dynamics simulation for predicting kinematic viscosity of natural ester insulating oil." *IEEE Transactions on Dielectrics and Electrical Insulation* 29, no. 5 (2022): 1882-1888. https://doi.org/10.1109/TDEI.2022.3198763

[18] Qian, Yihua, Qing Wang, and Yaohong Zhao. "Study on electric aging mechanism of transformer insulation oil based on molecular simulation." *7th Asia Conference on Power and Electrical Engineering (ACPEE), pp. 849-853. IEEE, 2022*. https://doi.org/10.1109/ACPEE53904.2022.9783628

[19] Emektar, Kubra, Meryem Nur Kantekin-Erdogan, and Aziz Tekin. "Furan formation in some vegetable oils during heat treatments." *Food Chemistry* 386 (2022): 132744. https://doi.org/10.1016/j.foodchem.2022.132744

[20] Khelkhal, Mohammed A., Semen E. Lapuk, Aleksey V. Buzyurov, Nikita E. Ignashev, Elvira I. Shmeleva, Irek I. Mukhamatdinov, and Alexey V. Vakhin. "Thermal behavior of heavy oil catalytic pyrolysis and aquathermolysis." *Catalysts* 12, no. 4 (2022): 449. https://doi.org/10.3390/catal12040449