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Investigation of the Dielectric Properties of Mineral Oil Blended with Soyabean Oil for Power Transformers

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Abstract

The power transformer is a critical equipment in the transmission and distribution network that must be managed to ensure uninterrupted power service. The liquid insulation is essential for the proper functioning of the transformer, as it serves as both coolant and insulating medium, which influences the transformer's durability. Further, the insulating state of a power transformer has a significant impact on its reliability. Mineral oil derived from petroleum crude oil has been employed as liquid dielectrics for decades due to its superior operating characteristics, however as a resource for the same are getting depleted over the years. Research is undertaken across the globe to identify a viable substitute for mineral oil. Further, alternate insulating oils are being investigated for better environmental impact, biodegradability and economics. Several combinations of vegetable oil ba sed natural esters are being investigated by researchers across the globe in these domains. In this work, mineral oil is blended with soyabean oil with various proportions and dielectric properties like dielectric breakdown voltage, viscosity, flash and fire point have been investigated according to international standards. A quantitative comparison is made among various samples and is observed that the blended oil sample of equal proportion of mineral oil and soyabean oil exhibits superior dielectric properties compared to the base mineral oil and other samples of different proportions.

1. INTRODUCTION

The power transformers (PT) are the foremost crucial and vital components of a power system, any failure in the transformer exacerbates an entire drop in the power system configuration (Kumar and Mariappan). The liquid insulation medium employed in power transformers has been shown to have a substantial effect on enhancing the productivity and longevity of power transformers (Young). They play the role of electrical insulation as well as cooling medium in transformers (Bakrutheen et al. Cao Heathcote and Book). Mineral oil has monopolized the liquid insulation industry for almost a century owing to its high insulation, heat dissipation attributes, and being relatively inexpensive . Furthermore, as a petroleum product, mineral oilis extremely toxic, poorly biodegradable, and nonrenewable and has the potential to disrupt the environment and cause concealed fire safety issues if it spills (Bertrand and Hoang).

The inadequacies of mineral oil have been dramatically affected as people's awareness of environmental issues has gained more importance (Z Erhan and Asadauskas). These changes can be attributed to the evolution of environmentally sustainable, biodegradable liquid insulation as a viable replacement for conventional mineral oil (M. Karthik, Willjuiceiruthayarajan, and Bakrutheen). Then, investigators all around the globe look at vegetable oil, a non-toxic biodegradable and renewable resource, as a green replacement for mineral oil and a viable alternative (Boyde Azis et al.). Vegetable oils extracted from seeds and plants are used to produce natural esters. They are treated and refined by several physical and chemical techniques to transform crude oil into refined oil (Sindhuja and Srinivasan). Besides investigating the individual vegetable oil, vegetable oils with the incorporation of boosting additives (nanoparticles, antioxidants, etc.), reconfiguration of its ester composition by trans-esterification, ageing analysis with and without the solid insulations to promote the sustainability of potential replacement of mineral oil for advanced employment in power transformers is being researched (Bakrutheen, R. Karthik, and Madavan).Blending different oils in varied proportions to build new liquid insulation is one approach for changing the characteristics of liquid insulation. Blended oil has low dielectric loss and low degradation ratio. The characteristics of those blended oils fluctuate due to their miscibility.

In the present work, the natural ester, soyabean oil blended with mineral oil, is investigated to determine the new beneficial properties of liquid insulation. Blended oil sample properties like dielectric breakdown voltage, dissipation factor, relative permittivity, viscosity, flash and fire point are all examined in accordance with the guidelines prescribed by IEC and ASTM standards and also Weibull Probability Distribution analysis on breakdown voltage of liquid insulation has been carried out.

2. STANDARDS AND PARAMETERS EMPLOYED

Dielectric properties of an insulating liquid include dielectric breakdown voltage, dissipation factor, relative permittivity, viscosity, flash/fire point which are the key properties tested in the investigation. Parameters investigated and equipment used for measurement are as shown in Table 1.

The soyabean oil is blended with conventional mineral oil inproportions of 50, 60, and 80%. Table 2 gives the details ofdifferent samples used in the investigation. Figure 1 shows the photographs of different oil samples used for investigation.

TABLE 1. Properties and associated standards.

Parameters	Measuring equipment/ Standard	Quantity of oil used
Breakdown voltage	100kV test kit/ IEC60156[19]	500 ml
Viscosity	Redwood viscome-terASTMD445[22]	50 ml
Flash and fire point	Pensky martins closed cupapparatus / ASTMD93[	70 ml

TABLE 2. Details of different samples used in the investigation.

Samples	Mineral oil (%)	Soyabean oil
Sample A	100	0
Sample B	0	100
Sample C	50	50
Sample D	60	40
Sample E	80	20

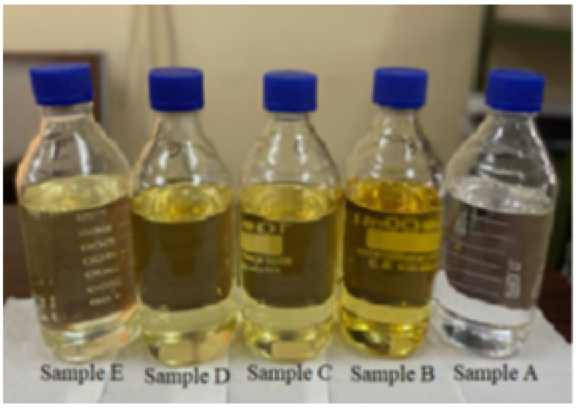

FIGURE 1. Blended oil samples.

3. EXPERIMENTAL DETAILS

For investigating the impact and effect of blending, the properties such as breakdown voltage (BDV), viscosity, flash and fire point are assessed or different blended combinations of oil samples in accordance with IEC and ASTM international standards. All the investigations were carried out at normal room temperature and pressure.

3.1. Measurement of Dielectric Breakdown voltage of oil insulation

The breakdown voltage is used to determine the liquid insulation's electrical endurance capability for significant electrical stress and may be used to determine the quality of insulating liquid. The breakdown voltage of insulating oil is affected by the presence of moisture, solid particles and air bubbles (R. Karthik et al.).To measure the breakdown voltage, a test cell of 2.5mm spacing of spherical electrodes is used and experimental set up is as shown in Figure 2. The BDV of liquid insulation sample is determined by gradually increasing the high voltage AC at rate of 2kV/s till a flash-over takes place. A total of 10 readings has been consider for every sample to arrive at the average BDV.

FIGURE 2. BDV test experimental setup.

3.2. Measurement of Flash/Fire point of oil insulation

The flash point is a critical feature of insulating oils, particularlyin high-risk areas such as those vulnerable to fire (Deepa et al.).Flash point temperature is the maximum allowable temperatureof the oil within transformers (R. Karthik and Raja). The Flash point is measuredusing a Pensky Martin flash point apparatus Figure 3 with a 60ml capacity test cell and heating setup. When a test flame is introduced in the test orifice by increasing the oil temperature with heater setup, a transient flame appears on the surface of the oil sample which indicates the flash point, and further heating flame catches the fire which indicates the fire point, and this procedure is carried out for every oil samples.

FIGURE 3. Pensky Martin flash point equipment

3.3. Measurement of oil Viscosity

The oil's viscosity is a measure of its resistance to flow,which indirectly indicates the oil's capacity to cool inside thetransformer (R. Karthik and Raja). In a Redwood viscometer Figure 4, the timetaken for 50ml of oil to flow through the test orifice is measured,and the oil's time viscosity is calculated.

FIGURE 4. Test setup to measure viscosity.

4. RESULTS AND DISCUSSION

The objective of present work is to make a quantitative studyof insulating properties of various oil samples. Table 3 providesthe experimental data of electrical properties like dielectric breakdown voltage.While Table 4 provides the allied properties like viscosity, flashand fire point of mineral oil and soyabean oil of prepared samplesand investigated according to international standards.

TABLE 3. Propriety values of oil samples.

Oil Samples	BDV (kV)
Sample A	59.02
Sample B	53.19
Sample C	65.00
Sample D	62.15
Sample E	55.25

TABLE 4. Propriety values of oil sampl

Oil Samples	Viscosity (cSt)	Flash Point (°C)	Fire Point (°C)
Sample A	10.179	144	156
Sample B	28.978	270	284
Sample C	17.067	168	180
Sample D	11.636	150	170

4.1. Breakdown Voltage (BDV

Figure 5 shows the dependence of breakdown voltage onthe soyabean oil content at varied proportions with mineral oil at room temperature. It is observed that the measurement ofbreakdown voltage of various oil samples in the course of investigationare:

• Breakdown voltage of blending mineral oil with soyabeanoil is considerably high and found to be 65kV at 50:50proportion (Sample C).

• Breakdown voltage of pure soyabean oil (i.e.,100% soyabeanoil – Sample B) is significantly lower i.e., 53.19kVcompared to pure mineral oil of 59.02kV.

• For increasing percentage concentrations of soyabean oil,the blended oil samples had a lower breakdown voltage.

• Therefore, in terms of breakdown voltage, the equal proportionof soyabean oil content improved the dielectricstrength of the blended oil.

As compared to mineral oil and soyabean oil, the breakdown voltage of the oil combination is significantly greater. This is largely attributable to the oil mixture's high-water solubility in which the property of natural ester promotes to adsorb and absorb water from its surrounding called as hygroscopicity.The higher capacity of the polar carboxyl group(-COOR) in the molecular chain structure of esters to engage in hydrogen bonding accounts for their hygroscopicity (Suwarno and Darma Martins). Hence, with a low relative water content, the natural ester could dissolve significantly more water content, improving the breakdown voltage of oil combination.

Values of Breakdown voltage measured for each investigated samples are tabulated in Table 5 and the distribution plot has been depicted in Figure 6.

TABLE 5. Breakdown voltage of all prepared samples.

Sl No.	Sample A	Sample B	Sample C	Sample D	Sample E
1.	62.3	51.3	60.4	63.7	54.2
2.	63.3	50.3	65.7	61.6	55.7
3.	60.3	62.2	63.9	61.5	59.4
4.	58.3	61.2	62.8	61.4	55.4
5.	60.1	50.2	65	61.5	53.5
6.	61.7	51.2	65	61.5	54.9
7.	61.8	52.2	66.6	61.4	53.3
8.	64.4	52.3	67	63.1	53.3
9.	65.2	50.8	67.1	63.1	56.4
10.	62.8	50.2	66.5	62.7	56.4

hows the median, standard deviation, kurtosis, and skewness for the distributed trials of each of the sample. A normallydistributed data set has a skewness value of zero and akurtosis value of three, with any change in these values indicatinga divergence from the normal (Rao, Fofana, and N'cho). The skewness andkurtosis measure the symmetry of data and the number of extremevalues. It is evident from Table 6 that skewness valuesfor Sample A and Sample C are negative, indicating the data isskewed left and the Sample B, Sample D, Sample E are positive,indicating the data to be skewed right.

The standard deviation was nearly consistent in all testedliquids, except Sample B when 100% soyabean oil was used.The breakdown voltage values vary from 58.3kV to 65.2kV inSample A, 50.2kV to 62.2kV in Sample B, 60.4kV to 67.1kVin Sample C, 61.4kV to 63.7kV in Sample D and 53.3kV to59.4kV in Sample E.

5. Histogram of breakdown voltage of investigated samples

Figure 7 shows the histograms indicating the frequency distributions of breakdown voltages for all investigated oil samples. The data looks to have a symmetrical distribution around themean

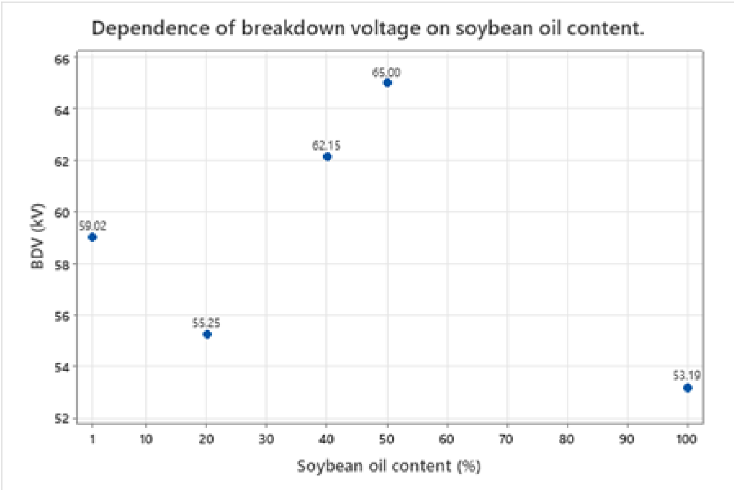

FIGURE 5. reakdown voltage v/s % of soyabean oil content.

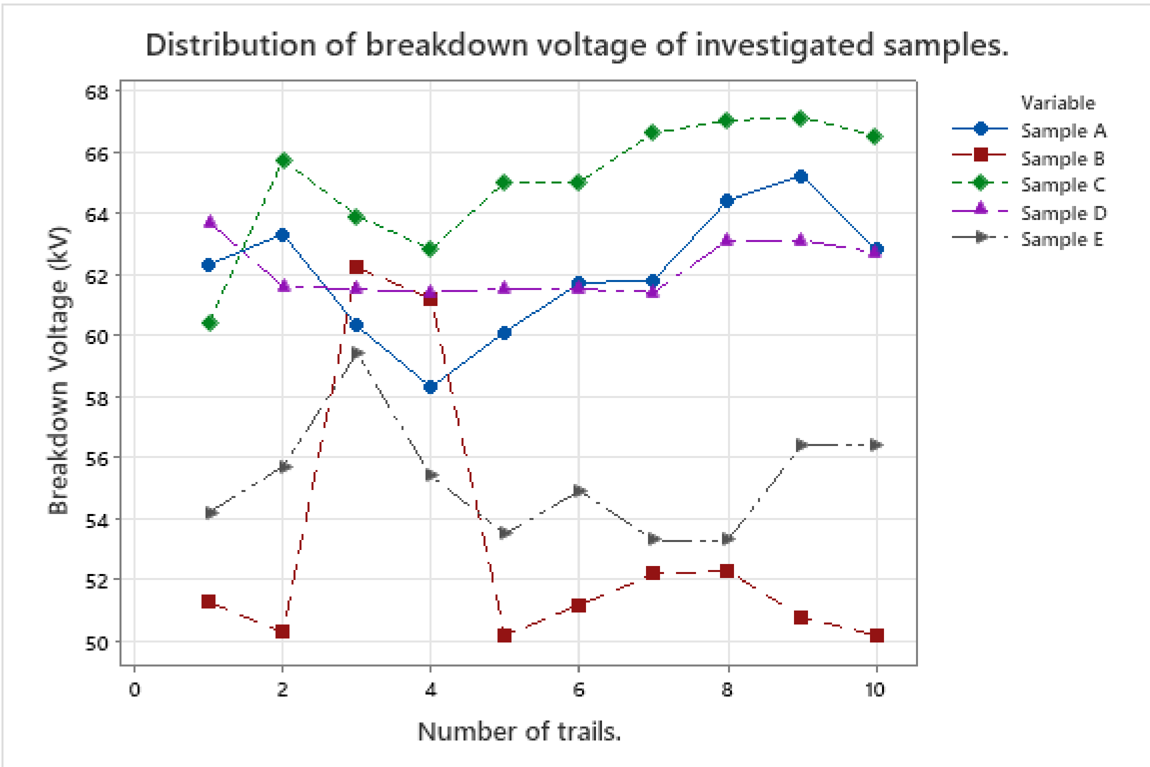

FIGURE 6. Distribution of breakdown voltage of samples.

TABLE 6. The mean, median, standard deviation, skewness and kurtosis of the breakdown voltage of all samples.

Variable	Mean	St. Dev	Mini	Median	Maximum	Skewness	Kurtosis
Sample A	62.02	2.075	58.3	62.05	65.2	-0.24	-0.2
Sample B	53.19	4.55	50.2	51.25	62.2	1.67	1.25
Sample C	65.00	2.132	60.4	65.35	67.1	-1.21	1.15
Sample D	62.15	0.895	61.4	61.55	63.7	0.73	-1.36
Sample E	55.25	1.885	53.3	55.15	59.4	1.1	1.53

value, indicating that the distribution is normal. TheAnderson-Darling normality test was performed to establishthat the breakdown voltages of the investigated oil samples arenormally distributed.

6. Normal Probability Distribution

Figure 8 depicts the normal probability plots of all investigated oil samples. The solid reference lines represent breakdown voltage data anticipated by the normal distribution, which is then used to estimate the likelihood of liquid breakdown. Table7 depicts the values of hypothesis test of conformity to normal distribution of investigated samples.

It can be observed that, this test accepts the hypothesis that breakdown voltages are regularly distributed for all liquid samples. Sample A and Sample D had relatively similar breakdown voltage characteristics in the 54.8% probability region. The breakdown voltage of Samples B and E had similar breakdown voltage characteristics in the 75.15% probability region. Sample C exhibited best breakdown voltage in the 16.34% probability region. For some samples with low and high probability, there is a clear deviation in the breakdown voltage values from a perfect normal distribution.

7. Weibull Probability Distribution

The Anderson–Darling test is used to investigate the Weibulldistribution of the measurements of breakdown voltage of mineraloil and its blending with soyabean oil samples shown inTable 5. It is evident that they are within the limits of acceptablerange. The acceptance of conformance hypothesis testsfor all samples as shown in Table 8 enables the investigation ofBDV characteristics with the Weibull distribution function.

Figure 9 depicts the probability curves emerging from the Weibull distribution. Sample A and Sample D had relatively similar breakdown voltage characteristics in the 45.19% probability region. The breakdown voltage of Samples B and E worsens in this region. Sample C exhibits best breakdown voltage in the 16.3% probability region.

7.1. Viscosity (cSt)

Figure 10 shows the dependence of viscosity (cSt) on the soyabean oil content for varied proportions with mineral oil at room temperature. Viscosity of a liquid insulation is the fluid's resistance to flow and thereby heat conduction which has to be ideally low for better performance and the following observations are made from the experimental results.

When the oils are blended with different proportions, blended oil Sample D shows the acceptable results.

At room temperature of 27°C, viscosity of Sample D is improved when compared to received oil samples and blended oil samples. But at higher temperature (90°C) the values of different samples are not so appreciably varied.

The viscosity of four samples are investigated for various temperatures and are tabulated in Table 10. The maximal viscosity for the various insulating liquid samples (Figure 11) can be seen at temperature of 27°C for sample B. The viscosity of these liquids significantly reduces as the temperature is increased. The viscosity of all blended samples (Samples B, C, and D) is somewhat higher than that of mineral oil (Sample A) at the same temperature, making flow of this liquid harder at low temperatures. The following order is a categorization of the examined liquid samples based on the lowest viscosity of each of them at a temperature of 90°C are, Sample A, Sample D, Sample C and Sample B.

The deviation in viscosity could be associated with differences in mono and polysaturated fatty acid concentration among the samples. It's also been revealed that when the temperature of the oil rises, the intermolecular interactions among the aclylglycerids improves, leading to a decline of viscosity. Lower viscosity in blended oil samples led to lower activation energies (Debnath, Vidyarthi, and Singh).

7.2. Flash and Fire Point

Figure 12 shows the dependence of flash point on the soyabean oil content at varied proportions with mineral oil at room temperature.

The following conclusions that are drawn by determining the flash and fire point of blended oil samples are;

- Soyabean oil has a substantially greater flash and fire point temperature than mineral oil.
- Mineral oil (Sample A) has a low flash and fire point temperature of 144°C, indicating its weak thermal properties.
- Forsoyabean oil blended with mineral oil, the flash and fire point temperatures increase as the mineral oil concentration falls. Sample B had the higher

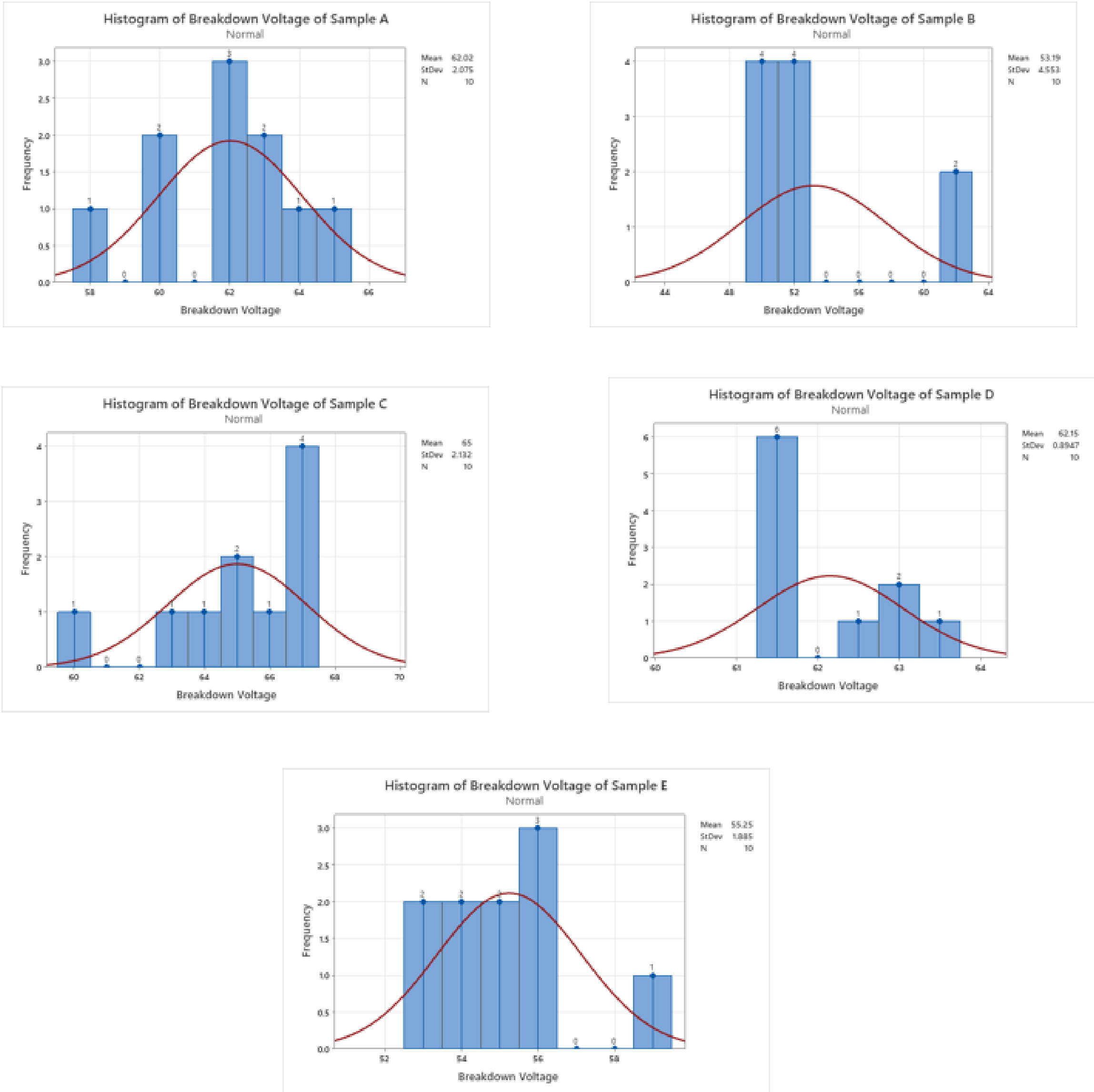

FIGURE 7. Histogram of average breakdown voltage of samples

TABLE 7. Hypothesis test of conformity to Normal distribution.

Oil Samples	AD	p-Value	Conformity of Normal Distribution
Sample A	0.142	0.955	Accepted
Sample B	1.586	< 0.005	Accepted
Sample C	0.455	0.209	Accepted
Sample D	1.038	0.006	Accepted
Sample E	0.390	0.312	Accepted

flash and fire point of 270°C and 284°C respectively.

- The mineral oil concentration in soyabean oil has a significant impact on the flash and fire point temperatures of blended samples.

8. Conclusion

In the present work, blended Soyabean oil and mineral oil for different proportions are investigated to develop and analyze their qualities for the suitable replacement of liquid insulation in power transformers. Results shows that the soyabean oil has excellent dielectric and thermal properties. Its viscos-

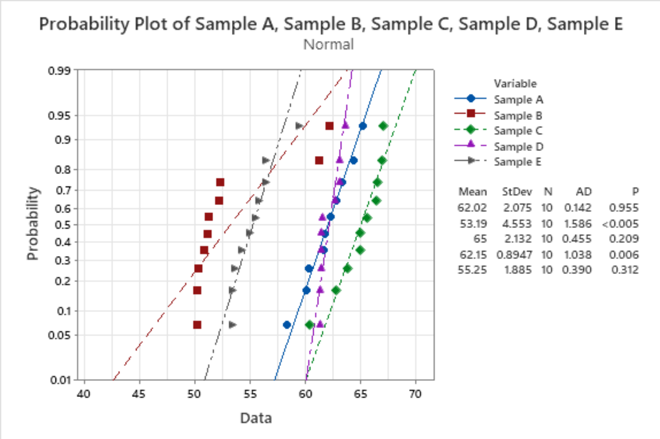

FIGURE 8. Normal probability plot of investigated samples for breakdown voltages.

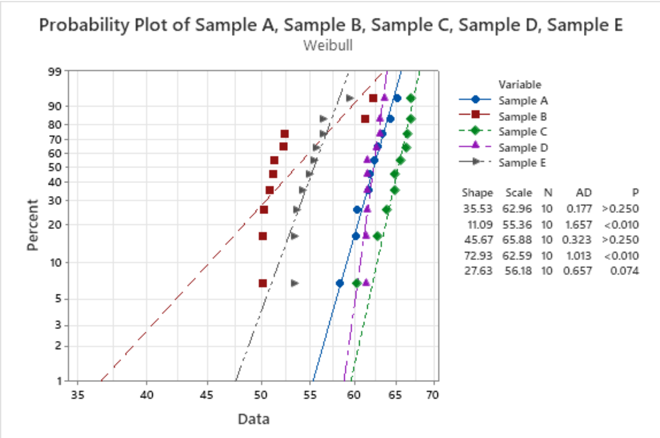

FIGURE 9. Weibull Probability plot of investigated samples.

TABLE 8. Hypothesis test of conformity to Weibull distribution.

Oil Samples	AD	p-Value	Conformity of Weibull Distribution
Sample A	0.177	> 0.250	Accepted
Sample B	1.657	< 0.010	Accepted
Sample C	0.323	> 0.250	Accepted
Sample D	1.013	< 0.010	Accepted
Sample E	0.657	0.074	Accepted

ity is substantially above the required low value for the power transformer application. Despite having a greater breakdown voltage and low viscosity, mineral oil has a low flash point. To overcome these limitations with respect to soyabean oil and mineral oil, blended oil samples were prepared and investigated. According to the experimental outcomes, the

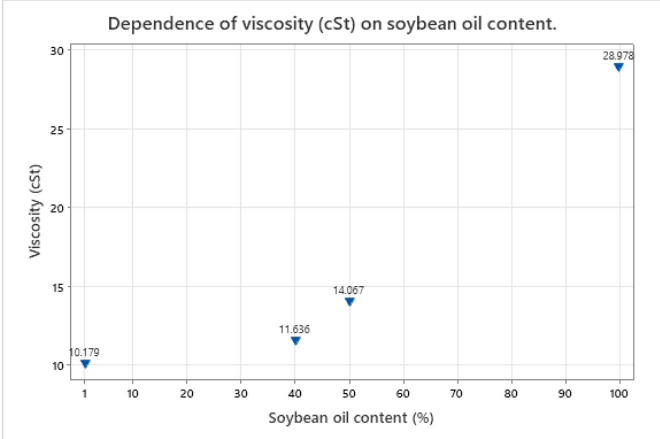

FIGURE 10. Dependence of viscosity (cSt) on soyabean oil content.

TABLE 9. Viscosity of investigated samples at different temperatures.

Temperat (°C)	Sample A	Sample B	Sample C	Sample D
27	10.18	28.98	17.07	11.64
40	7.93	24.71	14.73	11.05
45	6.45	21.93	12.88	9.94
50	5.84	18.87	12.77	9.07
55	5.21	18.35	9.90	7.64
60	4.57	14.20	8.15	7.05
65	4.57	13.15	7.93	6.15
70	3.90	11.54	7.35	5.84
75	3.90	10.45	6.75	5.53
80	3.90	9.63	6.15	4.89
85	3.55	8.50	5.53	4.23
90	3.55	7.64	4.89	3.90

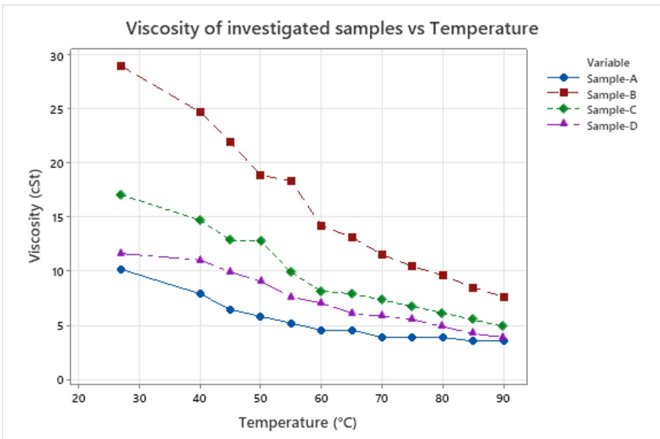

FIGURE 11. Viscosity of investigated samples at different temperatures.

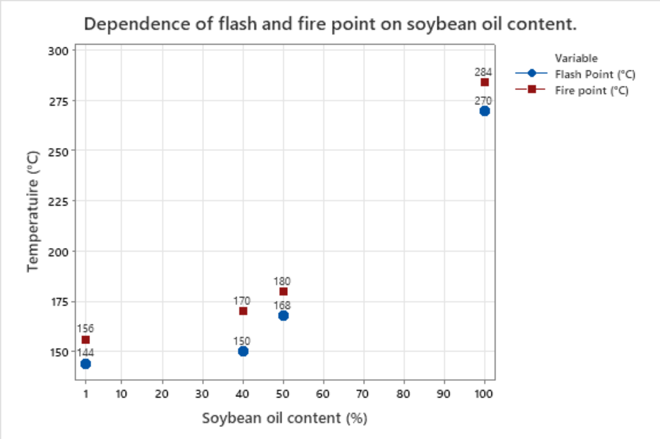

FIGURE 12. Dependence of flash and fire point on soyabean oil content.

blended oil samples have transformed their characteristics depending on the blended percentages and the original attributes of the mineral oil. After blending of oil, all the samples behave the same kind of changes. The samples prepared with 50% mineral oil and 50% soyabean oil of Sample C, had characteristics that are closer to the range of values recommended for power transformer applications. Interesting observation is that, the BDV values of all the investigated oil samples obeyed the Weibull and Normal probability distribution.

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