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EXPERIMENTAL STUDY OF THE CHARACTERISTICS OF TRANSFORMER OIL AND SOME SELECTED VEGETABLE OILS

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Abstract. The world's energy requirement has been dominated by petroleum oil resources for years in many applications, especially in the area of electricity generation and utilization. Mineral oil application in power system equipment can be potentially hazardous to the environment, especially when there are incidents of transformer explosion, which caused spillages of oil to the soils or water streams and thereby pollute the surrounding environments. This paper is aimed at finding a substitute for the use of mineral oil as transformer oil. Experiments on breakdown voltages, flash points, pour points, viscosities, densities and insulation resistances on conventional mineral oil and some selected vegetable oils were conducted, analyzed and compared to the internationally accepted standards, ASTM (America Standard Test of Material). Rubber seed oil, Palm oil, Melon oil, Ground oil and Palm kernel oil were found to have good electrical, chemical and thermal properties which the transformer *oil has.*

1.0 INTRODUCTION

Transformers are essential parts in the power system for voltage level conversion and maintaining the power flow. They are applied at four major regions (Endah, 2010):
a) At power plants, where power is generated and raised to transmission;
b) At sub-transmission stations, where the high transmission voltage is reduced to a medium high voltage;
c) At injection (medium high voltage) substations, where the incoming medium high voltage is reduced to distribution high voltage;
d) At service sub-station transformers, where the voltage is reduced to low voltage for utilization levels for routing into consumers' homes and businesses.
One of the most important factors which determine the life and satisfactory operation of a transformer is the oil in which it is immersed.

Over the years, petroleum-based mineral oils have been used for liquid insulation in high voltage equipment. At the present time the oils are still widely used as insulation for transmission and distribution power transformers, capacitors and other high voltage equipment. Petroleum-based insulating oil, in general, has excellent dielectric properties such as high electric field strength, low dielectric losses and long term performance. However, due to environmental consideration, there is a need to search for the alternative liquid insulating materials that will be friendly to the environment. There are some reasons why it is important to search for the environmental-friendly insulating oil. Firstly, conventional transformer oil is usually non-biodegradable. It can contaminate soil and water when serious spillage takes place (Oommen, 2002). This may disturb the plantation and other lives. Secondly, the mineral oil is being extracted from petroleum, which may run out in the future, since petroleum is nonrenewable (Claiborne *et al*, 1999). An alternative to biodegradable high voltage insulating material is a natural ester made from palm oil (Suwarno *et al*, 2003; Hikosaka *et al,* 2007).

Vegetable oil has a capability as the alternative source for transformer insulation. The biggest advantage of vegetable oil is the non-toxic material characteristic which will not produce any toxic product during combustion. Carbon dioxide and water are the only products that are formed during the biodegradation process. They are also less flammable liquids with a minimum flash point above 140^0c. They resist oxidation and absorb more moisture than mineral oil. On the other hand, their high viscosity might cause a problem with the heat transfer system in the transformer (Fofana *et al*, 2001).

However, it was reported that natural ester has the superior characteristics of breakdown strength and water solubility, but inferior in loss factor and viscosity (Wasserberg *et al*, 2005), (Suwarno and Aditama, 2005). Mineral oil has good thermal properties to evacuate heat from transformer, but inferior in ageing and biodegradability. In a composite state with paper, natural ester also indicates much better compatibility than mineral oils.

The insulating oil in a power transformer performs two major functions. Firstly, it serves as electrical insulation to withstand the high voltages present inside the transformer. Secondly, it functions as a heat transfer medium to dissipate heat generated within the transformer windings.

To meet the insulation function, the oil must have high dielectric strength and low dielectric dissipation factor to withstand the electrical stresses imposed in service (Kori et al, 2012). Paraffinic oil is derived from crude oil containing substantial quantities of naturally occurring n-paraffin's (wax) (Olutoye, 2005).

Paraffinic oil has a relatively high pour point and may require the inclusion of additives to reduce the pour point.

Naphthenic oil is derived from crude oil containing a very low level or none of naturally occurring n-paraffin's (wax). Naphthenic oil has a low pour point and requires no additives to reduce the pour point. Naphthenic oil provides better viscosity characteristics and longer life expectancy, and sludge is soluble and thus does not deposit out on windings, blocking cooling ducts and reducing cooling efficiency.

To measure the quality of insulating oil, several tests are used. The following list describes some of the most common laboratory tests, and references to the appropriate ASTM (American Standard Test of Material) method.

2.0 MATERIALS AND METHODS

Sample source: In order to investigate the performance of different vegetable oil as a new insulating liquid for transformer, several sample of the refined oil was collected from various farms in Nigeria. Rubber seed oil were obtained from Rubber Research Institute of Nigeria, Benin. Ground nut oil and melon seed oil were collected from various farm in Minna, Niger state of Nigeria. Palm oil and Palm kernel oil were also collected from Ondo in western region of Nigeria. A mineral oil sample collected from Power Holding Company of Nigeria (PHCN) was also included for comparison. The physical characterization of the oil was not determined, since the sample were obtained from processed farm.

The comparison of the sample were carried out base of the following properties of insulating liquid: Breakdown voltage, flash point, pour point, acidity, water content, resistivity and density.

2.1 Breakdown voltage measurement in oil

Determination of the breakdown voltage of insulating oil is included in international and national standards on liquid dielectrics. Among the most well-known are IEC60156 and ASTM D-1816. For manufacturers and users of liquid-insulated power equipment, these standards are used for checking the oil quality when filling new equipment and diagnosing in-service of insulation contamination or aging.

This test reveals the conductive contaminants & moisture present in the transformer oil. The dielectric strength is that minimum voltage at which arc discharge occurs between two electrodes set 2.5 mm apart. High BDV is desirable. Oil with low electric strength indicates presence of contaminants. The breakdown test set up for oils is illustrated in Plate 1 and the description of the setup is explained in sub-section 2.2.

Plate 1: Breakdown test setup

2.2 Measurement procedures

The procedures adopted in the measurement for determination of breakdown voltage of insulating oil are as outline:

• By first initiating the voltage application approximately 5 minutes after completion of the filling, and making sure that air bubbles which are visible in the electrode gap is avoided.

The applied voltages is increased uniformly from zero at the rate of 2 KV/s ± 0.2 KV/s until breakdown occurs.

• The measurements are then carried out until 6 breakdowns on the same cell filling occurred, allowing a pause of at least 2 minutes after each breakdown before reapplication of voltage or until there is no gas bubbles present within the electrode gap.

• The final result is calculated from the mean value of the 6 breakdowns in kV.

2.3 Insulation resistance test

The insulation resistance test is based on the absorption effect using the time - resistance method. It is measured by simply taking successive readings at a specific time and taken notes on the difference in readings. Tests of this method are sometimes referred to as Dielectric absorption ratio test.

$$\text{DAR} = \frac{R_{60s}}{R_{15s}} \tag{1}$$

A DC voltage of 1,000 volts is applied to the insulation and readings are taken to the insulation resistance versus time. Data were recorded at the 15 seconds and 60 seconds intervals.

Plate 2: Insulation resistance test setup

2.4 Determination of acid value

25 ml of diethyl ether and 25 ml of ethanol was mixed in a 250 ml beaker. The resulting mixture was added to 20 g of oil in a 25 ml conical flask and a few drops of phenolphthalein were added to the mixture. The mixture was titrated with 0.1 m KOH to the end point with consistent shaking for which a dark pink colour was observed and the volume of 0.1 m KOH (*Vo*) was noted.

The calculations were carried out in accordance with the equation below:

Calculations:

$$\text{Acid Value} = \frac{\text{mL KOH*N*56.1}}{\text{wt of Sample in gms}} \tag{2}$$

where mL KOH is the standardization of 0.1mKOH against 0.1mHCL =0.1064KOH

Average Volume of acid obtained during titration= N

The weight of the sample = 0.2kg

2.5 Determination of Viscosity of the oil

The experimental procedures were performed with Cannon-Fenske, constant-temperature bath was used in the procedures for viscosity determinations. This assembly maintains temperature uniformity. Cannon-Fenske Viscometers were used for the measurements of the kinematic Viscosities

Plate 3: Experimental setup (Water bath and Viscometer)

2.6 Determination of moisture content using Dean and Stack method

Water in oil appears is an unwanted substance, it is generally accepted that water in microscopic amounts - not gallons- is the cause of more electrical breakdowns than any other impurity. Moisture constitutes a hazard not only to the insulating qualities of the oil, but also to the windings and cores that are immersed in the oil.

2.7 Determination of Pour Point

The pour point of oil is the temperature below which the oil ceases to flow when it is cooled. As per ASTM D97 method, pour point of mineral oils is defined as the lowest temperature at which movement of the test specimen is observed under the prescribed conditions of the test. The apparatus used were; beakers, cellophane of nylon material, refrigerator, container, retort stand, and thermometer. For this experiment, six beakers were filled completely with a sample of the vegetable oils. The beakers were sealed with a cellophane material to protect the oil from being contaminated by moisture. The oils were then placed inside a refrigerator and allowed to freeze. After it has frozen, one beaker after the other was brought out and mounted on retort stand and tilted at an angle 45^0 to the horizontal in order for the oil to pour when it started melting. The thermometer was placed on the surface of the solid oil where it can pour when the temperature was reached. The nylon was removed from the surface before the beaker was placed on the retort stand. The temperature at which each of the oils started to pour was noted and recorded. The vegetable oils tested as described above were groundnut oil, melon seed oil, palm kernel oil, palm oil, and rubber seed oil.

2.8 Determination of Flash point by Pensky-Martens closed cup method

The flash point of a liquid is the lowest temperature at which it can form an ignitable mixture in air. At this temperature the vapor may cease to burn when the source of ignition is removed. A slightly higher temperature, the fire point, is defined as the temperature at which the vapor continues to burn after being ignited. Neither of these parameters is related to the temperatures of the ignition source or of the burning liquid, which are much higher. The flash point is often used as one descriptive characteristic of liquid fuel, but it is also used to describe liquids that are not used intentionally as fuels.

3.0 RESULTS

The results of breakdown voltages (BDV), pour points, flash points, water contents, densities, resistances and viscosities for standard transformer oil and vegetable oils are listed in Table 1.

Table 1: Results of tests on vegetable oils and transformer oil

Property	Standard Transformer Oil	Palm oil	Ground-nut oil	Palm kernel oil	Melon seed oil	Rubber seed oil	International Standard value(AST)
Breakdown Voltage (kV)	56.8	39	42	40	44.6	48.3	≥30
Pour Point (°C)	-40	25	8	20	23	-11	≤-10
Flash Point (°C)	146	263	268	244	282	175	≥145
Water Content (mg/kg)	Nil	0.02	0.01	Nil	Nil	Nil	≤35
Viscosity (cSt) at 40°C	7.9	49.58	37.90	28.10	33.15	45.90	≤50
Viscosity (cSt) at 100^0C	2.3	8.2	8.41	6.57	8.0	6.4	
Density (kg/dm^3) at 20°C	0.81	0,924	0.907	0.912	0.912	0.915	≤0.91
Acid Number (mg KOH/g)	0.597	58.198	4.477	67.152	5.969	0.5	
Insulation resistance at 60s (MΩ)	86000	7240	1110	7400	1430	560	≥200
Insulation resistance at 15s(MΩ)	51200	6920	1050	4200	1020	520	≥200
DAR	1.68	1.05	1.06	1.76	1.37	1.08	>1

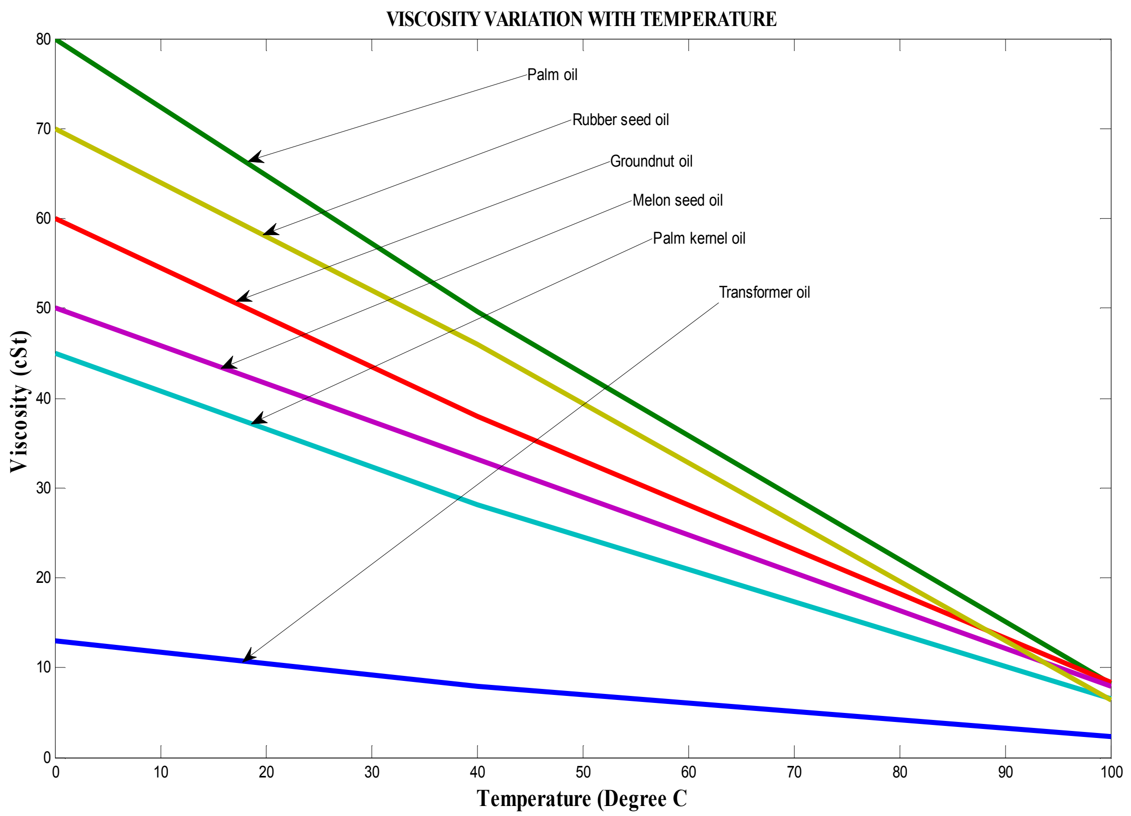

Figure 1: Viscosity variation of different oils versus temperature

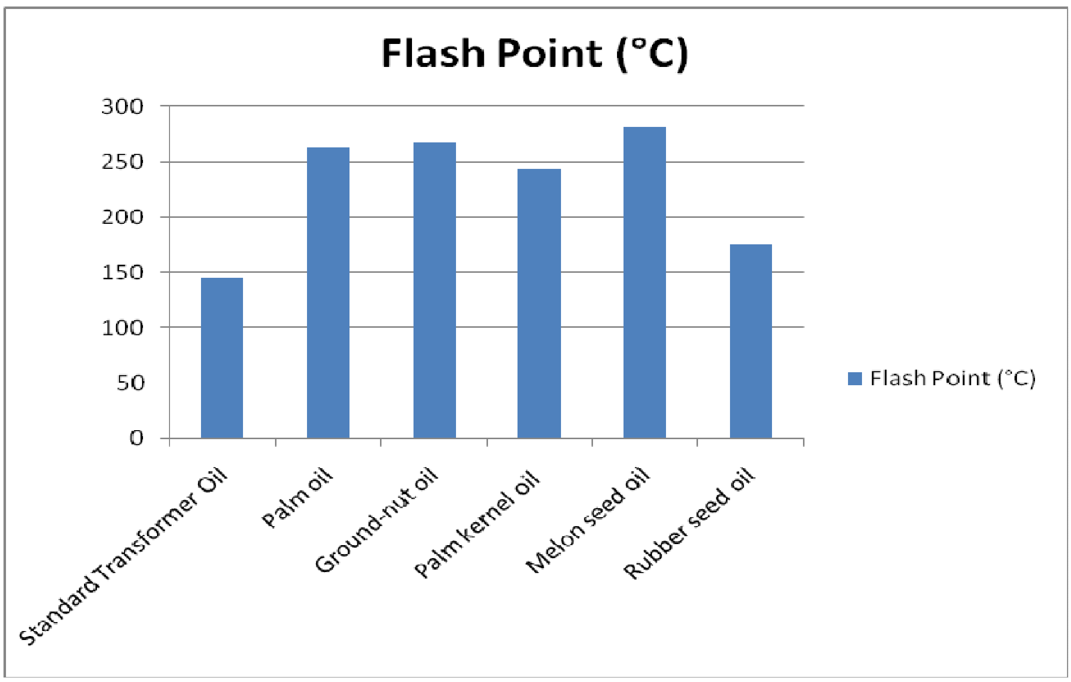

Figure 2: Comparison between standard transformer oil and vegetable oil flash point

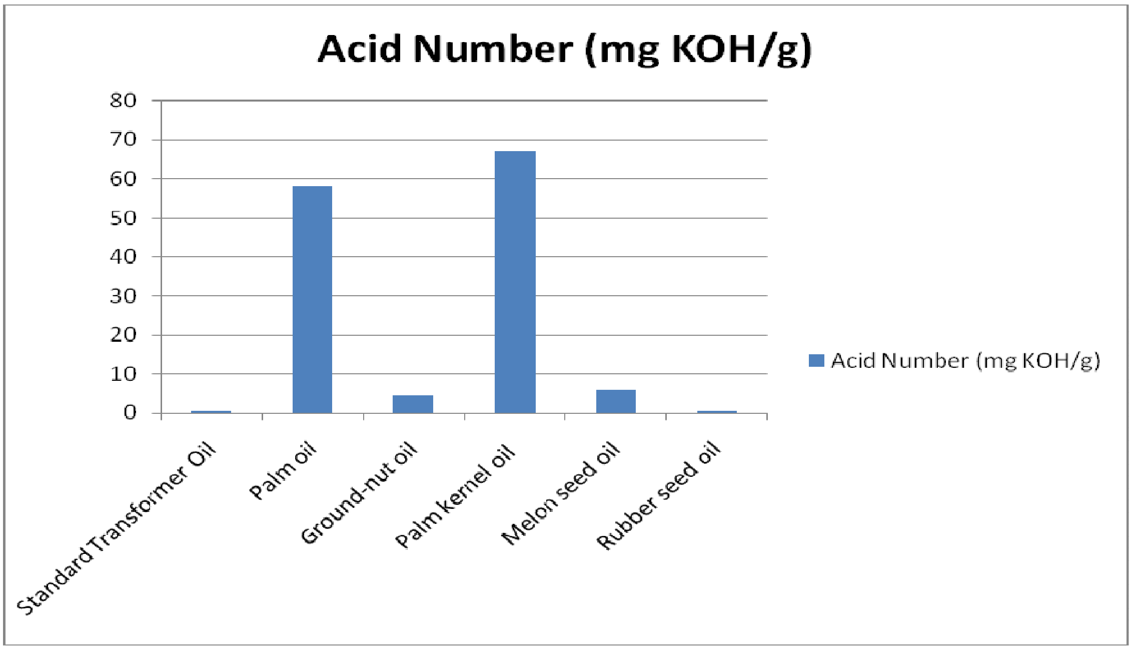

Figure 3: Comparison between standard transformer oil and vegetable oil acid number

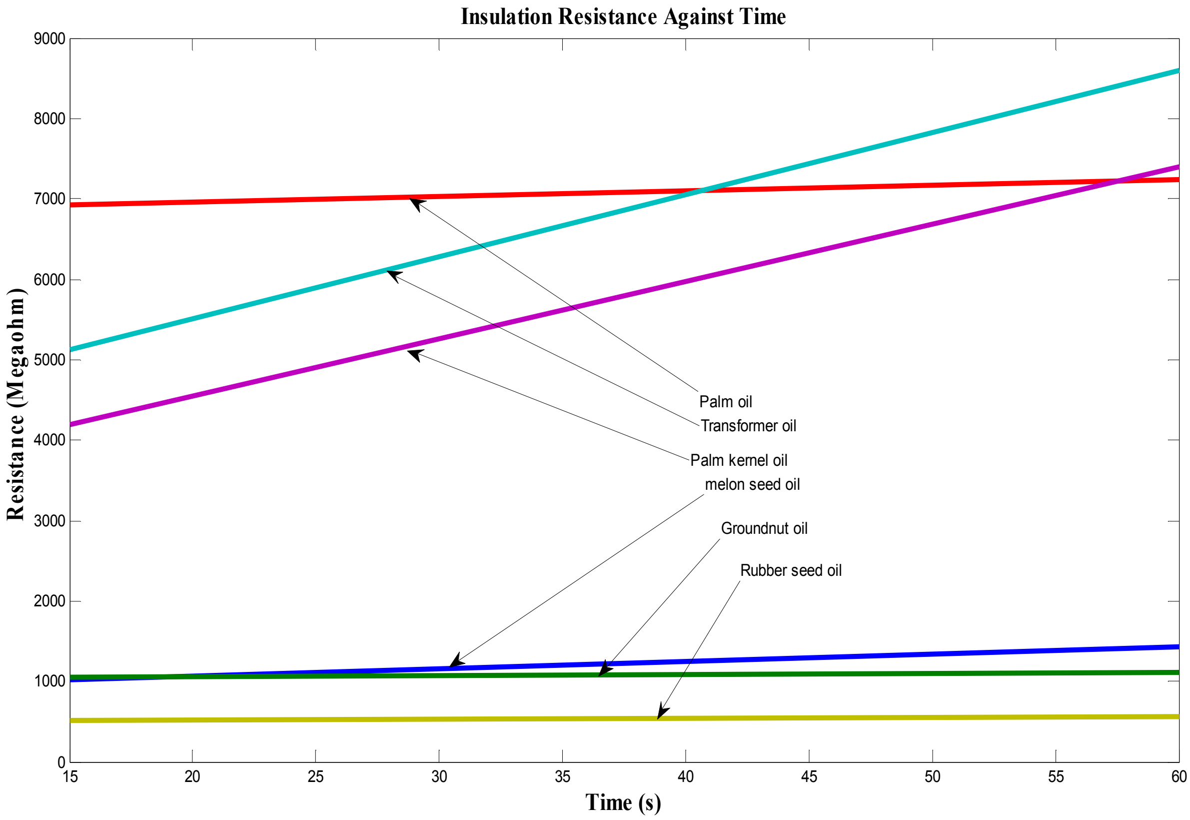

Figure 4: Comparison between standard transformer oil and vegetable oil insulation resistance against time(s)

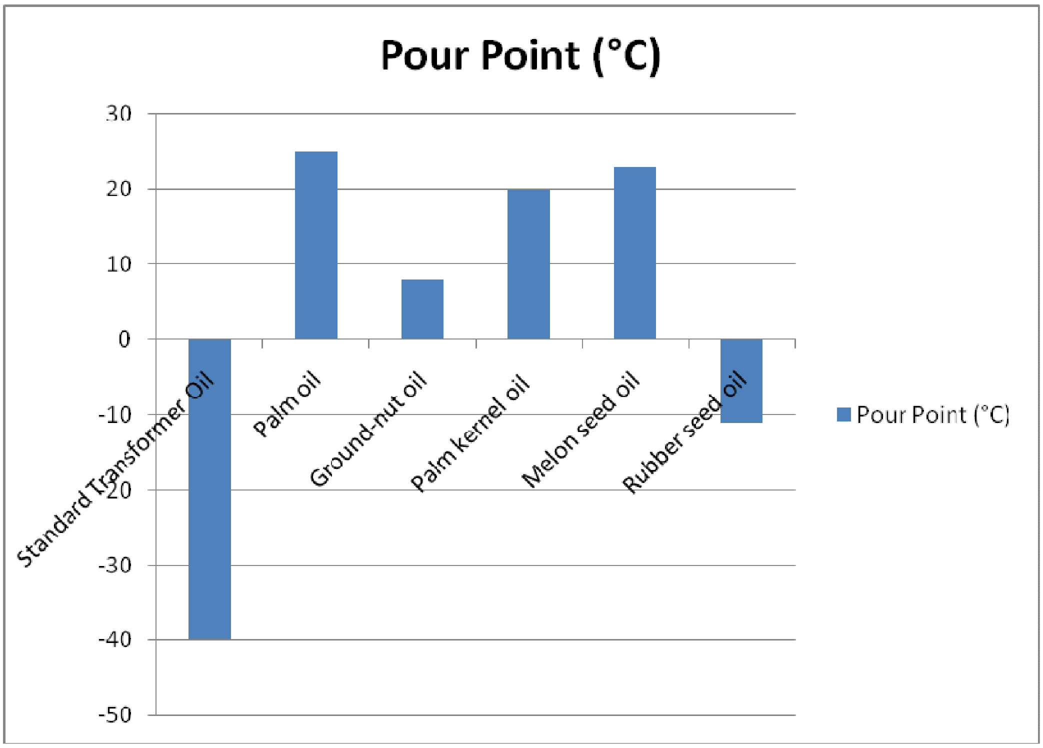

Figure 5: Comparison between standard transformer oil and vegetable oil pour point

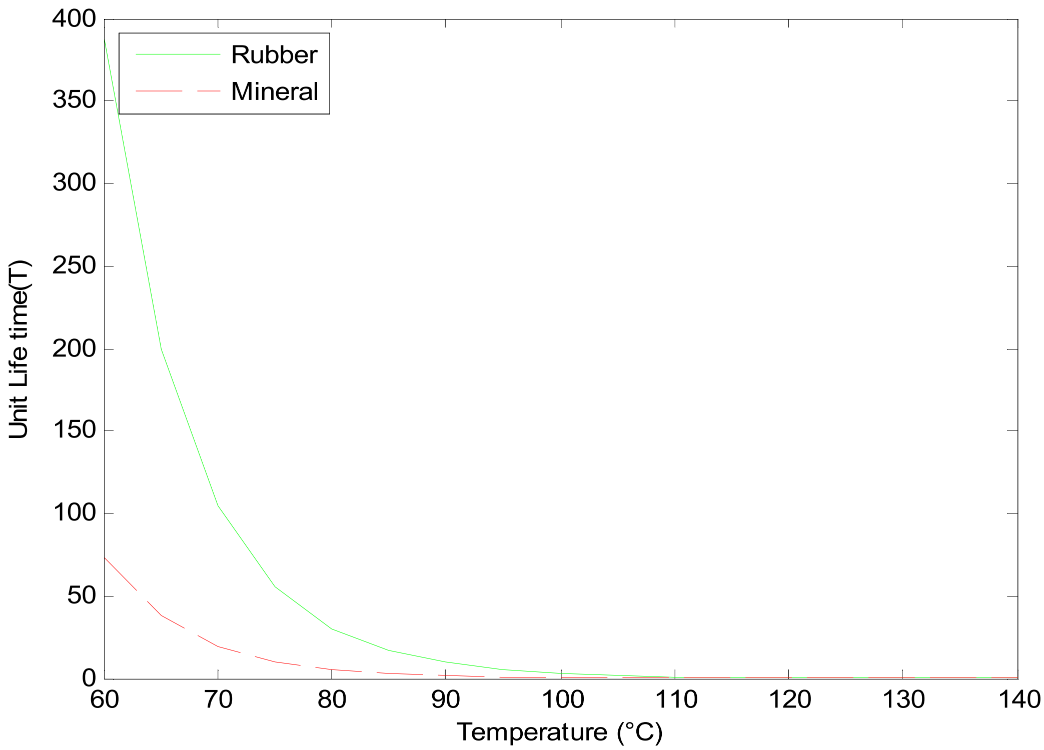

Figure 6: Comparison of Lifetime Expectancy between ruber seed oil and mineral oil

3.1 Discussion of Results

With reference to the results in Table 1 and Figure 1 through Figure 6, Since the breakdown voltage gives the overall indication of the dielectric strength, Rubber seed oil and Melon seed oil show the best values in this regards. It can be observed from Table I and Figure 4, that Rubber seed oil has the best insulating performance when comparing with other sample of vegetable oil. Also the comparison of insulation resistance by using the dielectric absorption ratio, tend to show favourable to all samples.

Higher viscosity has a high heat dissipation rate and reduces operating temperature. From Figure 1, the viscosity at 40^0C shows that all the natural oil samples are slightly higher and falls within the limiting value.
It is also noteworthy from Figure 2 that the flash points of all the samples are at a comfortable level to be utilized as insulating liquid, since a high flash point is required to reduce the risk of failure due to fire.
The buoyancy of the oil is determined by the density properties. The lower the density, better the flow of oil and it facilitates convection. Density of insulating liquid should be less than or equal to 0.91 according to ASTM. From the results shown in table I, all sample shows a good result to be new insulating liquid.
The acidity is very crucial in the analysis of insulating liquids, since higher acidity causes more losses. As shown in Figure 3, the acid value of rubber seed oil and transformer oil are slightly low as compared to other sample. This placed the other sample on the platform of harmful to the transformer.
The pour point of the oils is shown in Figure 5. The results showed that both mineral oil and Rubber seed oil had much lower pour points that the other samples. So the Rubber seed oil have the potential of using as the transformer liquid insulation even in much cooler environments in some countries.
It can be observed from Figure 6 which show the true picture of the life test on actual transformer under full load and voltage under different temperature. Therefore, was performed on the Rubber seed oil as it emerged as the best of the all the sample compared with a better life expectancy than the mineral oil.

4.0 CONCLUSIONS

In this paper, an experimental research is described in the investigation of different insulating oils for transformers. In order to rate the properties of alternative insulating oil, (vegetable oils) and widely used transformer oil (Honeywell) were investigated. In conclusion, Vegetable oil has been acknowledged as good alternative material for transformer oil due to its good biodegradability characteristic, low pour point, high flash point, and high solubility. The results of the investigations have confirmed that Rubber seed oil is the most suitable because for its high BDV, low pour point and low acid value as observed in other liquids.

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