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ANALYSIS OF BREAKDOWN STRENGTH AND PHYSICAL CHARACTERISTICS OF VEGETABLE OILS FOR HIGH VOLTAGE INSULATION APPLICATIONS

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ABSTRACT

The success of any electrical system lies in its insulating system performance. Petroleum based mineral oils are the generally used fluids for electrical insulation and heat transfer. But they are non-biodegradable. Vegetable oils obtained from seeds, flowers and vegetables are biodegradable, non-toxic, environmental friendly and benign to aquatic or terrestrial. The objective of this paper is to analyse the breakdown strength and physical characteristics of extra virgin olive oil and castor oil under unaged and thermally aged conditions. In order to compare the results obtained for vegetable oils with mineral oil, the same aging process and tests have been carried out on mineral oil.

Indexing terms/Keywords

Vegetable oils, Breakdown Voltage (BDV), Physical Characteristics, Viscosity, Flash point, Fire point

1.INTRODUCTION

Insulating liquids are extensively used in electrical apparatuses which are operating in distribution and transmission systems. The function of electrical equipment strongly depends on the conditions of liquid dielectric. Liquid dielectrics are used in the most expensive components in power systems like transformers and circuit breakers. A failure of these equipment would cause a heavy loss to the electrical industry. Insulation failures are the leading cause of transformer failures and thus the liquid dielectrics plays a major role in the safe operation of transformers. Conventionally petroleum based mineral oils are used in high power apparatuses.Even though the mineral oils have excellent dielectric properties such as high electric field strength, low dielectric losses, good long-term performance and are obtained at reasonably low price, mineral oils or synthetic insulating liquids are usually non-biodegradable. In case of equipment failure or spillage, their decomposition is very slow and could cause serious contamination of soil and waterways [1-6]. In addition, petroleum products are eventually going to run out. So it is essential to find out the solution to the problems identified in the field of liquid dielectrics.

Based on the above, the alternative of mineral oil, which is reliable, cost-effective and environmentally friendly, was a target for several researchers in the last two decades. Vegetable oils obtained from seeds, flowers and vegetables are biodegradable, non-toxic, environmental friendly and benign to aquatic or terrestrial [7]. Suwarno & Ilyas [8] have already reported that the water absorption of paper under vegetable oils was considerably lower than mineral oil. Also the lifetime of paper which are normally used in a transformer, is considerably longer when aged under vegetable oil compared to mineral oil [9].

Before considering vegetable oils for liquid insulation applications, it is essential to investigate the electrical, physical and chemical characteristics of vegetable oils. After reviewing the previous research works on vegetable oils, in this research work the characteristics of extra virgin olive oil and castor oil have been analyzed and the results are compared with the mineral oil.

The objective of this paper is to analyse the electrical breakdown voltage strength, physical characteristics such as viscosity, flash point and fire point of extra virgin olive oil and castor oil under unaged and thermally aged conditions. All oil samples undergo thermal aging which influences their chemical reaction rate at high temperature. In order to compare the results obtained for vegetable oils with mineral oil, the same aging process and tests have been carried out on mineral oil. In general, the different test carried out in this thesis project follow the international standards (IEC).

In order to analyze the change in dielectric characteristics at high temperatures, accelerated thermal aging was carried out in the laboratory. The way, aging takes place in vegetable oil can be defined by the oxidation and sticking of the carbon double bonds (unsaturated bonds) under thermal stress. During aging the following chemical reactions takes place in vegetable oil i) Hydrolysis - This hydrolysis process increases the total acid number and viscosity of the oils. ii) Oxidation - Oxidation process also encourages the sludge formation and acidity level in insulating oil. iii) Oxidative polymerization [10]. These in turn affects the dielectric properties of the oil. During thermal aging the oils were exposed to extreme temperature conditions for a definite period of time.

2.INSULATING LIQUIDS USED IN THESIS

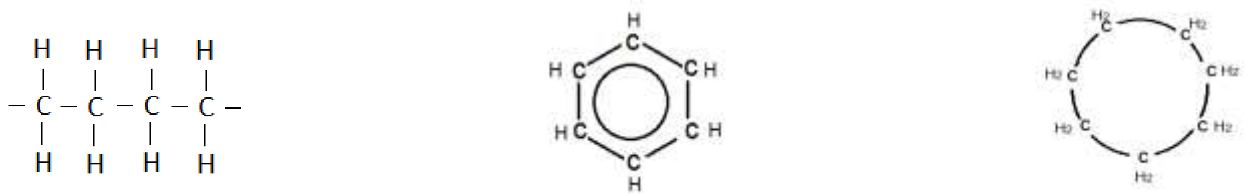
This work reports an investigation of the suitability of extra virgin olive oil and castor oil to replace conventional petroleum based mineral oil in large power transformers.

2.1 Mineral Oil

Mineral oil consists of 14% hydrogen, 84% carbon in different structures and 1-3% sulphur oxygen-nitrogen call heteatoms [11]. Mineral oil is a complex mixture of hydrocarbon molecules. These hydrocarbon molecules can be divided into three groups, which are paraffins, naphthenes and aromatics. Each has a unique characteristic molecular structure, and no two crude oils are exactly same in the relative proportions of the hydrocarbon types or in the properties and proportions of the products to which they give rise. In every oil the hydrocarbon molecules are in different ratios [12].

- Paraffins - The simplest paraffin, Methane (CH_4) is a gas, normal butane (C_4H_{10}), and isobutene;
- Naphthenes - It has ring structures with six carbon atoms (within six-membered rings) or fourteen carbon atoms (within three-membered rings);
- Aromatics- It has ring structures with six carbon atoms (monoaromatics - single rings) or fourteen carbon atoms (polyaromatics - two or more rings).

Figure 1 shows the typical molecular structure of the three types of hydrocarbon, and includes some of the simplest members of the groups.



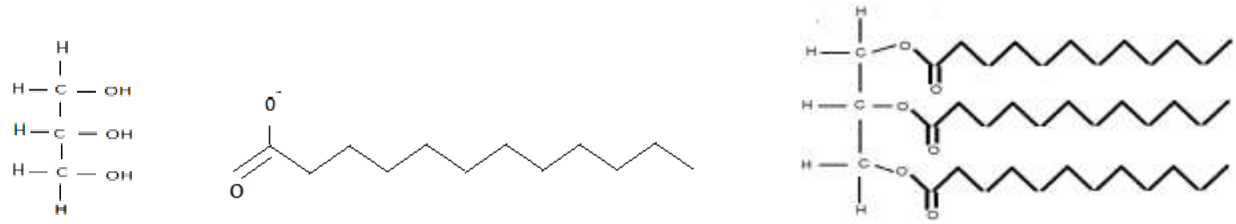
(a) Paraffin **(b) Aromatic** **(c) Naphthenic**

Fig 1: Basic Hydrocarbon structure of Mineral oi

2.2 Extra Virgin Olive Oil

Olive oil is an oil acquired from the olive (Olea europaea; family Oleaceae), a traditional tree crop of the Mediterranean Basin. Extra-virgin olive oil comes from virgin oil production only, contains no more than 0.8% acidity. Olive oil contains more oleic acid and less linoleic and linolenic acids than other vegetable oils, that is, more monounsaturated than polyunsaturated fatty acids. Olive oil consists of 13.2% of saturated fatty acids, 73.3% of single, 7.9% of double and 0.6% of triple unsaturated fatty acids [13&14].

This renders olive oil more resistant to oxidation because generally, the greater the number of double bonds in the fatty acid, the more unstable and easily broken down by heat, light, and other factors the oil is. The chemical structure of olive oil is shown in Figure 2 [15].



(a) **Glycerol** **(b) A free fatty acid** **(c) Triglyceride**

Fig 2: Components of Olive oil

Fatty acid is a part of the triacylglycerol molecule. The composition of fatty acid in olive oil varies generally depending on the cultivar, maturity of the fruit, height above sea level, weather, and other factors.

A fatty acid has the general formula: *$CH_3(CH_2)_nCOOH$* where n is typically an even number between 12 and 22. If no double bonds are present the molecule is called a saturated fatty acid. If a chain contains double bonds, it is called an unsaturated fatty acid. A single double bond makes a monounsaturated fatty acid. More than one double bond makes a polyunsaturated fatty acid.

The major fatty acids in olive oil triacylglycerols are:

- Oleic Acid (C18:1), a monounsaturated omega-9 fatty acid. It makes up 55 to 83% of olive oil.
- Linoleic Acid (C18:2), a polyunsaturated omega-6 fatty acid that makes up about 3.5 to 21% of olive oil.

- Palmitic Acid (C16:0), a saturated fatty acid that makes up 7.5 to 20% of olive oil.
- Stearic Acid (C18:0), a saturated fatty acid that makes up 0.5 to 5% of olive oil.
- Linolenic Acid (C18:3)(specifically alpha-Linolenic Acid), a polyunsaturated omega-3 fatty acid that makes up 0 to 1.5% of olive oil.
- Triacylglycerols are usually composed of a mixture of three fatty acids. Most common in olive oil is the oleic-oleic-oleic (OOO) triacylglycerol, followed, in order of incidence, by palmitic-oleic-oleic (POO), then oleic-oleic-linoleic (OOL), then palmitic-oleic-linoleic (POL), then stearic-oleic-oleic (SOO), and so on.

Saturated fatty acids are chemically stable, but of high viscosity. Triple unsaturated fatty acids have a low viscosity but they are very unstable in oxidation. Fluids with a high percentage of single unsaturated fatty acids are useful in HV applications [13]. (Eberhardt et al 2010).

2.3 Castor Oil

The castor oil plant, Ricinus communis, is a species of flowering plant in the spurge family. Castor seed is the source of castor oil, which has a wide variety of uses. The seeds contain 40% to 60% of oil. Castor oil is famous as a source of ricinoleic acid, a monounsaturated, 18-carbon fatty acid. Among the fatty acids, ricinoleic acid is unusual in that it has a hydroxyl functional group on the 12th carbon. This functional group causes ricinoleic acid (castor oil) to be more polar than most fats.

Castor oil is one of the few naturally occurring glycerides with high purity, since the fatty acid portion is nearly 90% of ricinoleic [16].

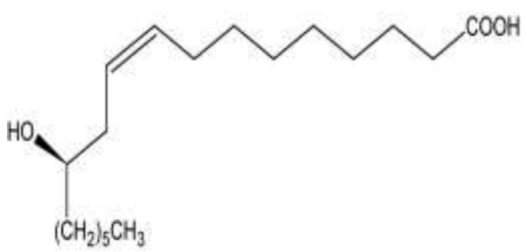


Fig 3: Chemical Structure for Ricinoleic Acid

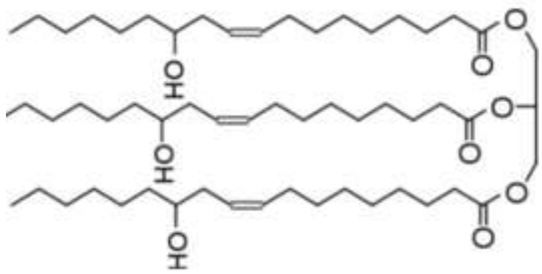


Fig 4: Structure of the major component of castor oil

Salimon, J et al [17] have illustrated the chemical structure of Ricinoleic acid (Figure 3). The structure of major component of castor oil is shown in Figure 4 [18].

The major fatty acids in castor oils are

- Oleic Acid (C18:1), a monounsaturated fatty acid. It makes up 2 to 6% of castor oil.
- Linoleic Acid (C18:2), a polyunsaturated fatty acid that makes up about 1 to 5 % of castor oil.
- Palmitic Acid (C16:0), a saturated fatty acid that makes up 0.5 to 1 %of castor oil.
- Stearic Acid (C18:0), a saturated fatty acid that makes up 0.5 to 1 % of castor oil.
- Linolenic Acid (C18:3), a polyunsaturated fatty acid that makes up 0.5 to 1% of castor oil.
- Ricinoleic; C18:1ω OH, mono- hydroxylated oleic acid. It makes up 85 to 95 % of castor oil

Castor oil has remarkable dielectric properties and complaint almost IEC standards [9].(Suwarno et al 2008).

3. EXPERIMENTAL STUDIES

3.1. Specimen Preparation

In this work commercially available extra virgin olive oil, castor oil and mineral oil were used. The moisture content in oils were eradicated before the test by keeping them in a sealed steel container and thermally treated at 70°C for 48 hours in a regulated temperature oven and then the samples were permitted to cool to room temperature for 24 hours.

In this work, to analyze the aging behavior, the oils were kept inside the oven for the period of initially 7 days and after the BDV test the same oils were kept in the oven for one month (Figure 5). Since the transformer would not normally see temperatures in excess of 90^{o}C an ageing temperature of 150^{o}C was used to accelerate ageing. Mineral oil undergoes chemical reactions with copper [19] during operation at high temperatures, overloading etc. leading to corrosion. So in addition to fresh oil one set of oils (mineral oil, olive oil and castor oil) in a separate vessel were kept inside the oven with copper material (2 mm diameter and 5 cm long). Copper was added to the samples to assess its effect on oil aging.

Fig 5: Picture of oven used for thermal aging of oils

The viscosity, flash point and fire point were carried out with virgin oils and thermally aged for 30 days oils (with and without copper).

3.2. Breakdown Voltage Test

This test was conducted as per IEC 60156 standard. The schematic diagram of the experimental setup which was used to assess the breakdown voltage of oil is shown in Figure 6. The test kit consists of one rectangular test cup made up of glass. The test cup consists of two sphere shaped electrodes of 12.5 mm diameter and there are two screws by which the gap between the spheres can be adjusted. The same test was repeated with mushroom shaped electrodes also.

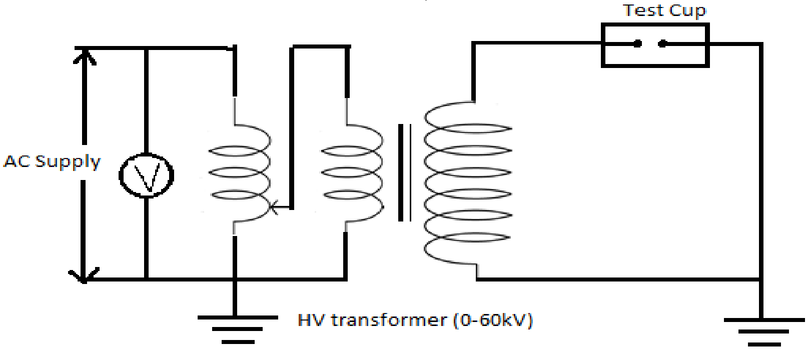


Fig 6: Schematic diagram of BDV tester

Initially the distance between the electrodes was maintained as 2.5 mm and the test cup was filled with the mineral oil. High voltage AC supply was gradually raised at a rate of 2kV/s till the breakdown takes place. A time interval of 1 minute is used between consecutive breakdowns. This test was repeated for virgin, thermally aged and thermally aged with copper oil samples, Due to the rise in viscosity for aged and aged with copper vegetable oils, the interval time between the breakdowns was increased. The bubbles formed in vegetable oils took longer time to settle.

3.3. Viscosity

Viscosity is an important property of all liquids. The internal resistance offered by a liquid to the flow of one layer of fluid over a next layer is called viscosity. This is due to the interrelation between the molecules of the fluid. Viscosity of liquids affect by the temperature and pressure [20].

In this work kinematic viscosity of oils are obtained with the help of redwood viscometer. The redwood viscometer shown in Figure 7, consists of a vertical cylindrical oil cup made up of copper or brass and plated with silver inside.

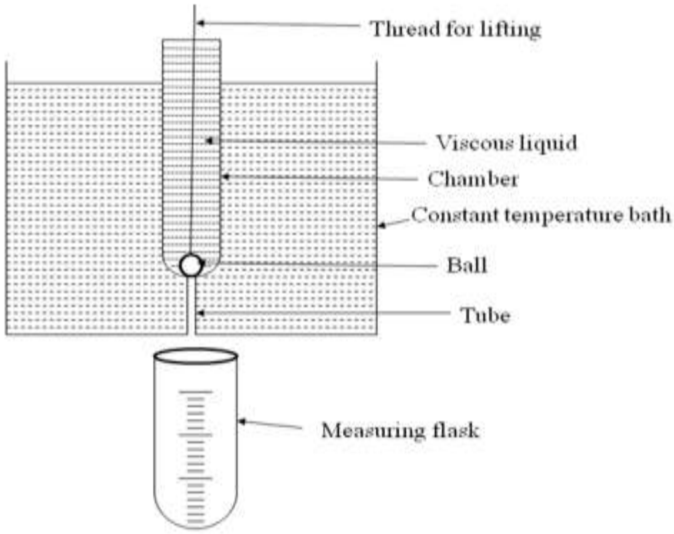


Fig 7: Redwood Viscometer

Initially the orifice is closed with ball valve and the mineral oil is filled in the cleaned cylindrical oil cup up to the mark. The water bath is filled with water. The thermometer is inserted in the appropriate place to measure the temperature of water and oil. The water bath is heated with the help of electric heater and it was stirred to maintain the uniform temperature.

At the required temperature the ball valve is lifted and the oil is collected in the Kohlrausch flask. The time taken by the oil to reach the mark in the flask (50 cc) is noted down by using stop watch. This time is called Redwood seconds and kinematic viscosity is calculated and the test was repeated for different temperatures. The same procedure is followed to find out the viscosity of the other insulating liquid samples also.

3.4. Flash Point and Fire Point

The flash point and fire point of all the oil samples were determined using Cleaveland open cup test method. As a first step the mineral oil is poured into a cleaned test cup up to the standard level indicated by the filling mark. On the top edge of the cup, there is a provision to hold the thermometer in right position so that it does not have physical contact with any metallic parts. The oil gives out vapour when it was stirred and heated. A test flame was applied over the surface of the oil and flash point was noted from the thermometer when there is a distinct flash and flickering sound. Heating process is continued further to find out the fire point. A test flame is applied over the oil surface, but this time the vapour has to burn continuously. The minimum temperature at which the ignited vapours over the surface of the oil burns continuously is called fire point and it is also noted with the help of thermometer. The same procedure was repeated for other samples also.

4.RESULT AND DISCUSSIONS

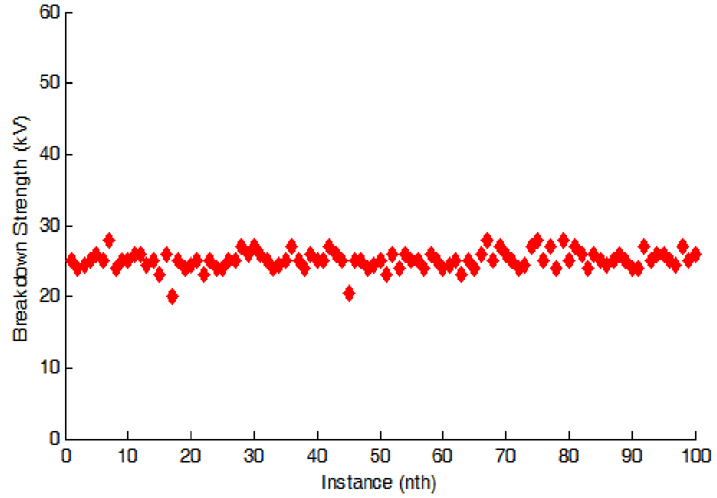
4.1 BDV Analysis of Oils

The dielectric or breakdown strength of insulating oil is a measure of its capability to withstand electrical stress without any failure. The understanding of AC breakdown voltage for a given insulating medium is one of vital parameters for the design of power transformers. BDV of any oil depends on the physicochemical properties of oil, impurities that can be present and as the electrode arrangement. In this work the BDV test was conducted with two types of electrode set one is spherical electrodes and the other one is mushroom electrodes.

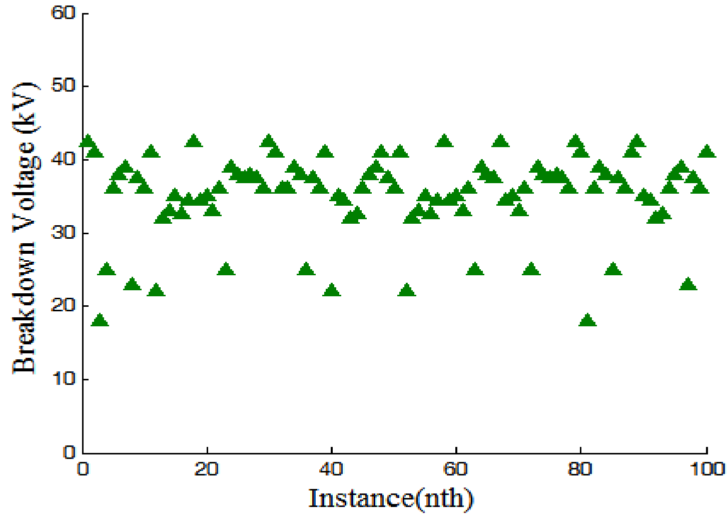
4.1.1. BDV of Unaged Oil with Mushroom Electrodes

The BDV test conducted with mushroom electrode is considered for statistical analysis and hundred breakdowns were acquired to get a large number of data. The breakdown data obtained for 2.5 mm gap between the mushroom electrodes was considered here for analysis. The statistical analysis was performed with the unaged mineral oil, olive oil and castor oil.

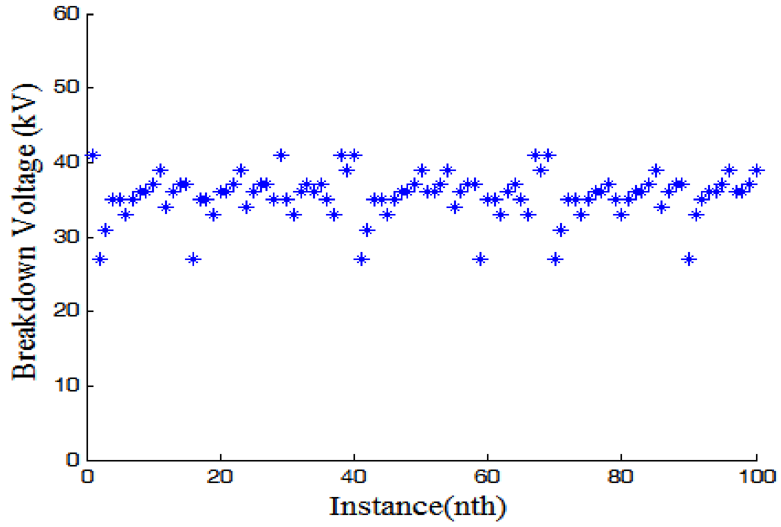
Figure 8 shows the distribution of breakdown strength of virgin mineral oil, extra virgin olive oil and castor oil. From the plots it is very clear that the breakdown strength of vegetable oils is greater than mineral oil. The breakdown voltage range of castor oil mostly lies from 30kV to 40 kV. For olive oil it lies between 26kV and 41kV and for mineral oil it ranges from 20kV to 28kV.



(a)



(b)



(c)

Fig 8: BDV Distribution of (a) Mineral oil (b) Olive Oil (c) Castor Oil

4.1.2. BDV of Aged oils with Spherical electrodes

The results obtained for spherically shaped electrodes separated by 2.5mm distance are considered here for discussion. For spherically shaped electrode the test was repeated for eight times for each oil and the average value was taken as the dielectric strength of the particular oil. The oils undergone for this test are virgin oil, oils aged for 7 days with and without copper and oils thermally aged for 30 days with and without copper.

The breakdown voltage test results obtained for oil samples are plotted against the aging time (Figure 9). It clearly indicates that the dielectric strength of mineral oil is reduced gradually day by day, whereas the dielectric strength of vegetable oils shows higher value after 7 days of aging. The increase in BDV value is due to chemical change takes place in the vegetable oils and the increase in BDV value after aging in vegetable oils are already reported by [10,21&22]. After 30 days of aging there is reduction in dielectric strength of olive oil, since the oil was under thermal stress for a long period, the fat in the oil may release aldehyde, volatile acid, water and may be also hydrogen gas due to oxidation. The oxidation due to aging of vegetable oils also increase their acidity level considerably [23].

On the other hand, there is a slight increase in BDV value of castor oil and decrease in breakdown strength of olive oil is also somewhat lower when compared with mineral oil. When react with oxygen, the sludge formation in vegetable oil is less and this may be the reason for higher BDV value of vegetable oil than mineral oil even after 30 days of aging [24]. Generally, significant increase in breakdown strength is observed for all the oil samples pertaining to increase in distance between the electrodes.

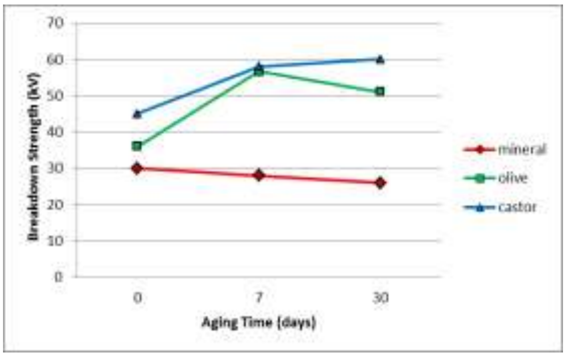


Fig 9: Breakdown Voltage Values of Oil Samples with Respect to Thermal Aging Time

4.2 Viscosity

Viscosity is an important property and deciding parameter in the cooling capacity of a liquid insulator. The simple way of cooling system in transformer depends on the viscosity of the fluid, so the oil with low viscosity is desirable and it is important to analyze the viscosity of oil. As the long term thermal aging affects the viscosity of the oil samples, in this work the kinematic viscosity of 30 days thermally aged oils were determined by Redwood viscometer. For comparison purpose, the viscosities of virgin vegetable oils (olive oil and castor oil) are presented along with virgin mineral oil.

The kinematic viscosity of oils with respect to temperature is shown in Figure 10. Viscosity of insulating oil decreases with increase in temperature, that is viscosity is inversely proportional to the temperature. This is because of reduction in intermolecular attraction. The change in viscosity with refer to temperature is less in mineral oil when compared to vegetable oils [25]. Especially the viscosity of castor oil at 30^{o}C is very high value and it is not desirable. In case of cold countries, where the atmospheric temperature falls even below this, a doubt arises about function of castor oil as a cooling agent.

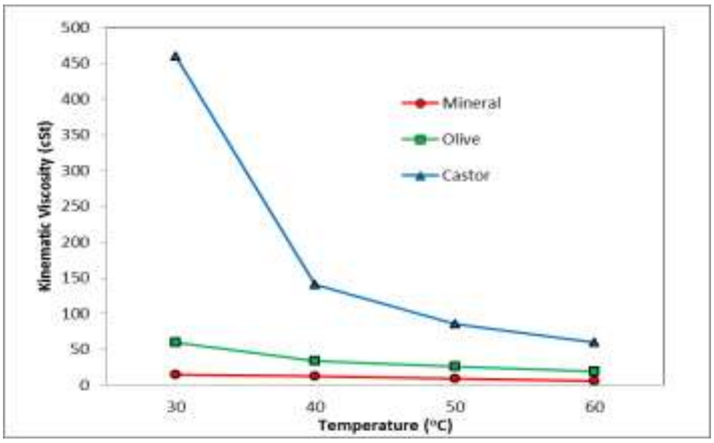


Fig 10: Kinematic Viscosity of Virgin Oils vs. Temperature

The kinematic viscosity of virgin, thermally aged and thermally aged with copper oils can be easily compared with the help of Figure 11.

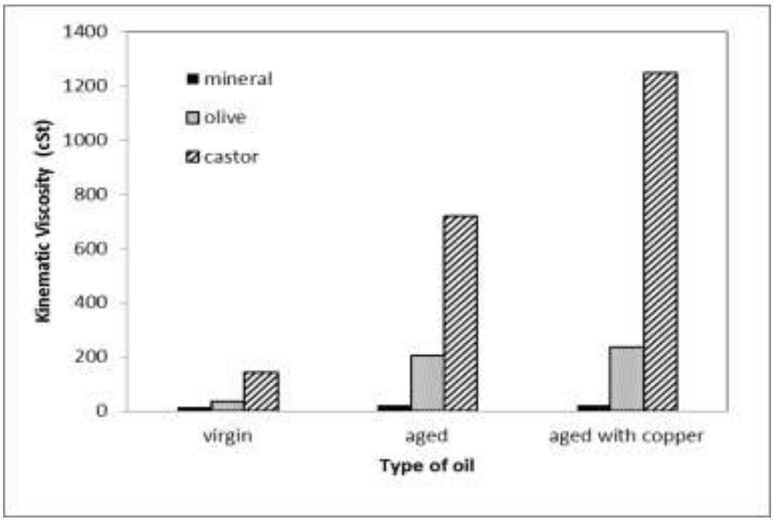


Fig 11: Viscosity of Virgin, Aged and Aged With Copper Oils

For comparison the viscosity of oils at 40°C was considered here. This clearly shows that viscosity of oils increases after aging. This due to oxidation process takes place in the liquids during aging. The molecules of ester are divided into smaller elements during oxidation process and polymerised with the residual molecules, so as to rises the viscosity of oils [10].(Tenbohlen & Koch 2010).

However compared to olive oil, castor oil shows higher viscosity when aged with and without copper. So, chemical treatment is necessary for both vegetable oils to reduce their viscosity. The presence of copper during thermal aging shows a small variation for olive oil, but in castor oil the viscosity of AWC castor oil is nearly twice that of aged castor oil. This may be due to the catalytic reaction of copper with castor oil.

The redwood time obtained at different temperatures for AWC oils can be analyzed with the help of Figure 12. As the oils are going to be with copper during their operation, AWC oils are considered here for comparison. Again this comparison reveals that the time taken by each oil decreases with increase in temperature. The time taken by the castor oil is higher than the other two oils. Even the time taken by AWC castor oil at 60°C is higher than the time taken by olive oil at 30°C. Anyhow when compared to mineral oil the difference is more.

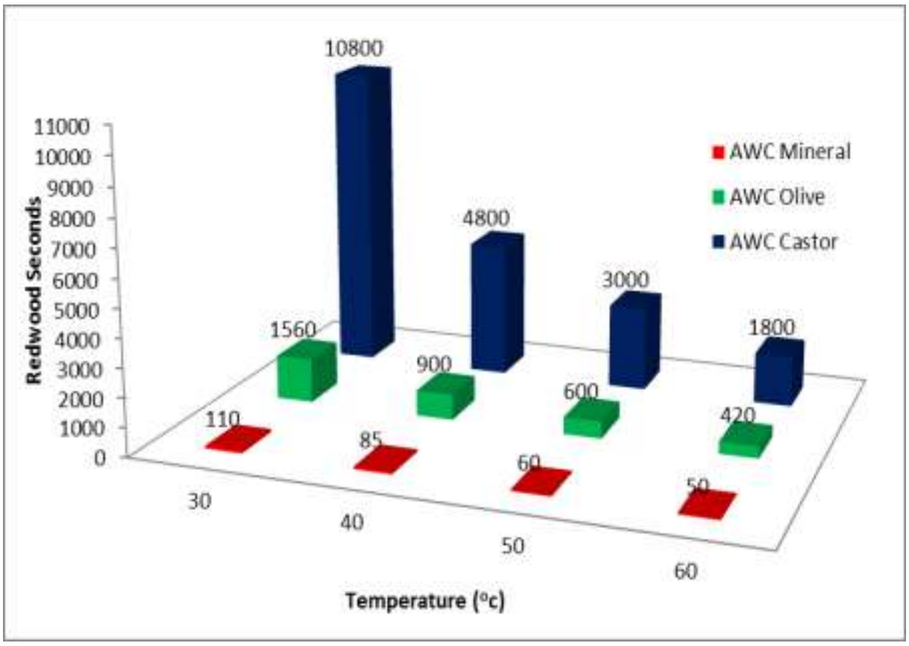


Fig 12: Redwood Seconds vs. Temperature for AWC Oils

4.3. Flash Point

Flash point is the minimum temperature at which the oil will flash when the vapours formed over the surface of the oil is exposed to external source of fire. It is essential that the liquid used as an insulating medium should have very high flash point. Insulating oils with greater flash points are lightly flammable and they are not dangerous when compared to the oils with lower flash points. The flash point reading obtained for virgin, aged and aged with copper oils were compared with the help of Figure 13.

The flash point of virgin olive oil and castor oil is nearly twice that of the value obtained for mineral oil. This assures the enhanced fire resistant capacity of the transformer when the vegetable oils are used as dielectric liquids. After thermal aging of 30 days the flash point of mineral oil is increased about 30^{o}C and it is nearer to the flash point obtained for AWC mineral oil.

In the case of vegetable oils the flash point value reduces after aging, but this value is comparatively higher than mineral oil value. The higher flash point of vegetable oils ensures the safety of the equipment especially for indoor transformers [13]. (Abderrazzaq & Hijazi 2012).

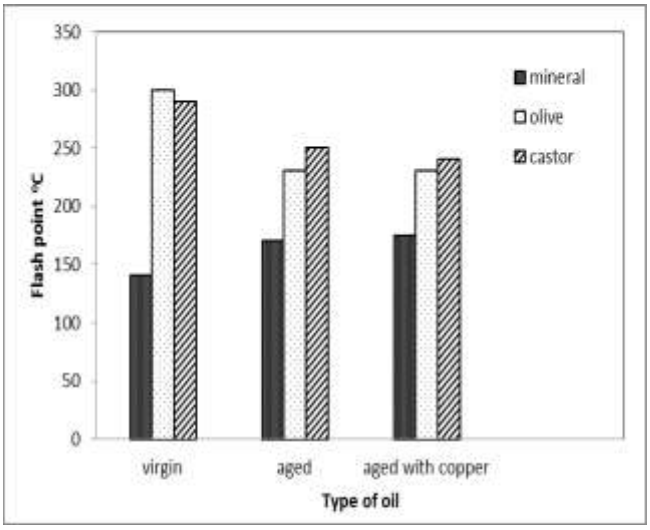


Fig 13: Flash Point Comparison Chart

4.4 Fire Point

Fire point is the minimum temperature at which the inflammable gases formed over the surface of the oil is enough to sustain a steady inflammable gas fire after it is ignited. The fire point of oils was shown in Figure 14. The fire points of virgin and aged vegetable oils are higher than mineral oil. Therefore, olive oil and castor oil will have least problems arises due to low flash point and fire point. Even under higher thermal and loading conditions the vegetable oil will give smoother operations.

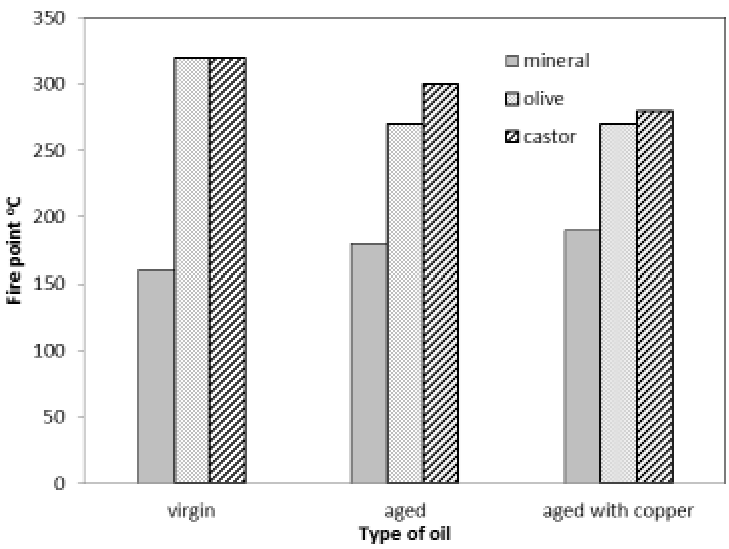


Fig 14: Fire Point Comparison Chart

5. CONCLUSION

In this paper the electrical breakdown voltage strength, physical characteristics such as viscosity, flash point and fire point of extra virgin olive oil and castor oil under unaged and thermally aged conditions were analysed. The results show that the breakdown voltage of vegetable oils are higher than mineral oil even after aging. This is because of chemical changes takes place in vegetable oil during aging.The breakdown strength of castor oil thermally aged for 7 days is very high and after 30 days of aging no breakdown takes place up to 60kV for an electrode gap of 2.5mm. After 30 days of aging the viscosity of castor oil has become so high. Generally, there is no sludge formation with vegetable oils, but there was some solid formation at the edges of oil. The viscosity of vegetable oils are much higher than mineral oil. So to reduce the viscosity of vegetable oils, chemical treatment is necessary. The flash point and fire point of virgin and aged vegetable oils are higher than mineral oil. Therefore, olive oil and castor oil will have least problems arises due to low flash point and fire point. Even under higher thermal and loading conditions the vegetable oil will give smoother operations.

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