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Chemically modified palm kernel oil ester: A possible sustainable alternative insulating fluid

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ABSTRACT

The demand for a sustainable and non-toxic alternative insulating fluid has been on the increase because of the negative environmental impact of mineral-based insulating fluids. Natural ester appeared to be a viable alternative, but it has poor thermo-oxidative properties and higher melting temperature. This report presents the influence of chemical modification on the properties of natural ester-based alternative insulating fluid. Alkyl ester derivatives were synthesized from laboratory purified palm kernel oil. A straight chain alkyl ester was first synthesized to enhance the flow properties of the oil. It was then followed by a process that converts the double bond to an epoxy group. Side-branched ester samples were synthesized from the laboratory synthesized epoxy alkyl ester of palm kernel oil. The chemical modification was performed through esterification reaction involving the epoxy alkyl ester of palm kernel oil and acid anhydrides under nitrogen and in the presence of boron trifluoride etherate as catalyst. The reactions were monitored and the products confirmed using FTIR and GC–MS. The melting point and thermo-oxidative stability of the fluids were examined using Differential Scanning Calorimetry (DSC). The melting point of the ester derivatives was found to reduce with side chain attachment and antioxidant significantly improved the thermal stability. The dielectric behavior and electrical breakdown properties of the ester derivatives were analyzed and compared. The dielectric loss was dominated by mobile charged particles and the charged particles appeared to exhibit faster dynamics compared with purified palm kernel oil. This may be attributed to the mobility of the charges which is related to the viscosity of the esters. The esters possessed excellent breakdown strengths suggest that the processing to optimize the physical properties did not have a negative influence on the electrical breakdown strength. This product may prove useful as an insulation fluid in Electrical Power Transformers.

1. Introduction

The idea of using natural ester fluid for electrical insulation in oil-filled electric equipment was conceived as far back as 1892. The development suffered a setback because the thermo-oxidative stability of the liquid was inferior to conventional transformer oil from mineral oil [1]. Mineral-based dielectric liquid is commonly used in power transformers as they have good insulating and cooling properties as stated in Table 1. However, they are known to be toxic and non-biodegradable. In a quest for a viable alternative to mineral-based insulating fluids in the 90s, vegetable oil was found to have environmental, safety and health benefits [2]. Although recent reports show that natural ester insulating fluid performs very well as an insulant and coolant (see Table 1), its high viscosity has posed a design challenge and its poor thermo-oxidative property has limited its application [2–4]. Seed based oils have two opposing properties; pour point and oxidative stability. These properties are dependent on the degree of unsaturation of the oil. The thermal and oxidative stability of the oil becomes more susceptible to oxidation as the degree of unsaturation progresses from monounsaturation to polyunsaturation [2]. Conversely, the melting and pour points of the oil decrease with increase in the percentage of unsaturated fatty acid content. The unsaturated fatty acids generally have lower melting and pour points than the saturated fatty acids. The high pour point of saturated fatty acid results from its uniform molecular shape which enables the molecules to pack efficiently as it solidifies. Crystal formation is difficult in unsaturated fatty acids because of the bends and kinks introduced by the carbon–carbon double bonds. This limits the ability of the fatty acids to be closely packed. As a result, the more the unsaturation, the harder it becomes for the molecules to crystallize. This will have the consequence of lowering the pour point of the oil [5].

There are two major classes of vegetable oils; one has higher concentration of saturated fatty acids so it is more stable to oxidation but possesses a high melting point. The other has a higher concentration of unsaturated fatty acids, which is highly unstable to oxidation but possesses a low melting point. Efforts have focused mainly on vegetable

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Table 1
Typical properties of conventional transformer oil and vegetable oils.

Properties	Conventional mineral transformer oil	Vegetable oil with saturated fatty acid ≥80%	Vegetable oil with unsaturated fatty acid ≥80%
Viscosity (cSt) at 40 °C	13	29	37.6
Density (kg/m^3) at 20 °C	895	917	886
Pour point (°C)	−40	20	−22
Flash point (°C)	154	225	260
Oxidation onset temperature (°C)	207	282	192
Conductivity (S/m) at 20 °C	10^{-13}	10^{-11}	10^{-10}
Breakdown strength (kV)	45	60	56

oils with higher concentrations of unsaturated fatty acids because of their low melting and pour points. The use of the existing commercial natural ester dielectric fluid (with higher ethylenic unsaturation) is restricted to hermetically sealed transformers to prevent oxidation [3]. Oils with higher concentrations of saturated fatty acids are not often considered, even though they are more resistant to oxidation. This may be because they solidify at much higher temperatures. Abeysundra et al. made an attempt to use purified coconut oil as transformer oil [6], but efforts to reduce the pour point were not successful. Solidification of insulation fluids in transformers could result in the formation of voids during a cold start leading to partial discharges (PD). PD initiation will weaken the insulation and may eventually lead to electrical breakdown. The challenge in using a natural ester as an effective alternative insulating fluid is developing a fluid with low melting and pour points, low viscosity, high thermal and oxidative stability, and excellent dielectric and breakdown property.

The reactive carbon–carbon double bonds of the fatty acid chains of vegetable oils can be deliberately modified using epoxidation process to improve the thermo-oxidative stability and low temperature properties. In this process, the double bonds are reacted with peracetic acid to produce epoxy rings. This process can serve as an intermediate for deriving various bio-based products from vegetable oils [7–11]. Erhan et al synthesized a series of derivatives from soybean oil [12–15]. They produced lubricant based stock from epoxidized soybean oil using acid anhydride of various chain lengths with improved oxidative stability and low temperature properties. The fluid was formulated from epoxidized soybean oil by an acid-catalyzed ring-opening followed by esterification of the dihydroxy derivatives with acid anhydrides to attach a side branched alkyl group. Acyl derivatives of soybean oil of various branch sizes were prepared by Sharma et al. using boron trifluoride etherate as a catalyst to open the epoxy ring and activate the anhydrides simultaneously [16]. Holser prepared carbonated methyl soyates by the introduction of carbon dioxide at the epoxy sites of epoxy methyl soyate at atmospheric pressures [17].

In this paper, an attempt is made to synthesize derivatives of palm kernel oil with optimized properties. Through such synthesis, a new sustainable base-stock may be produced as a viable alternative electrical insulating fluid for high voltage oil-filled electric equipment.

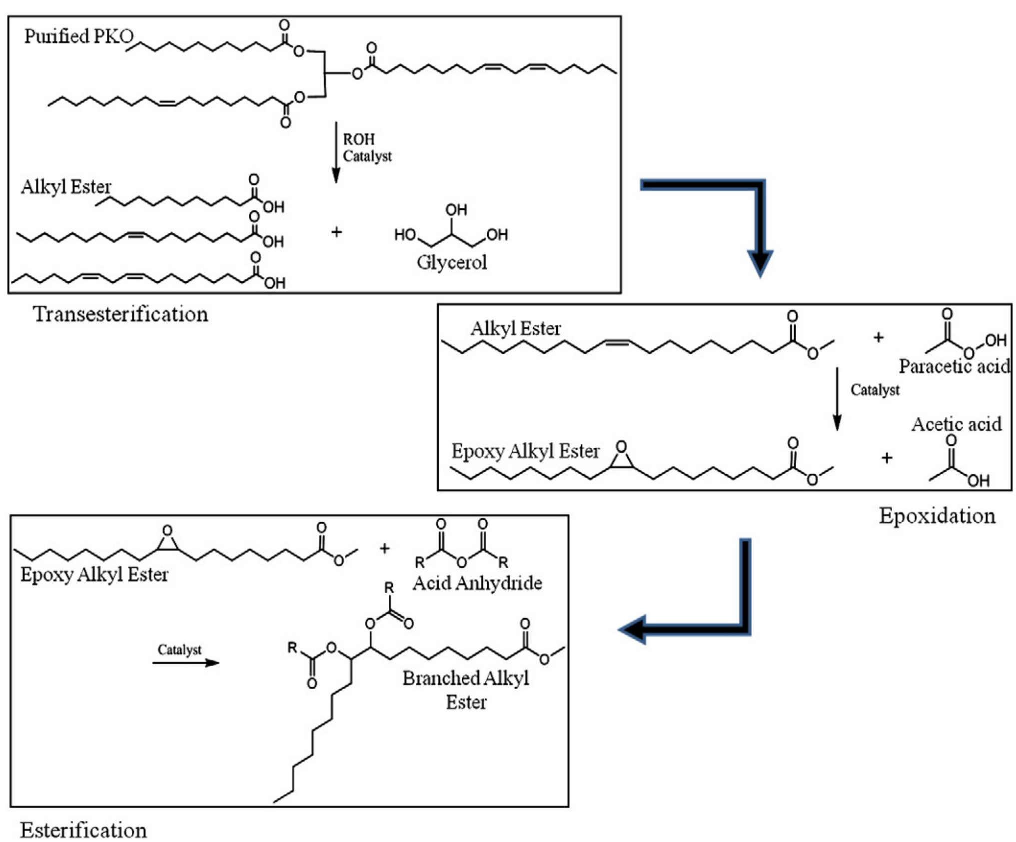

Fig. 1. Reaction scheme.