Selection of a suitable vegetable oil for high voltage insulation applications

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Selection of a suitable vegetable oil for high voltage insulation applications

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Abstract. Many items of high voltage plant employ a liquid both as a dielectric and a coolant. Currently these systems use a mineral oil, however, this suffers from the drawback of being potentially toxic and hence leakages and eventual disposal can be serious issues. To overcome this problem, an increasing trend in the UK is to backfill existing paper/oil cable systems with dodecylbenzene (DDB). This fluid possesses the advantages of improved gas absorption, good dielectric properties and biodegradability; nevertheless it is still derived from crude oil, a non-renewable resource. Vegetable oils offer the added advantage of being renewable although many types are available with very different properties. In order to select a suitable vegetable oil for high voltage applications, a standardised ageing and testing regime is required. In this paper, a wide range of vegetable oils were subjected to controlled laboratory ageing and the resulting aged oils were characterised by a number of analytical techniques. The results from these tests were then used to rank the different oils, and to select the most ageing resistant oil.

1. Introduction

Mineral oil is widely used as a dielectric medium in high voltage plant but can be damaging to the environment, and hence less hazardous replacements are sought [1]. One solution has been to backfill existing paper/oil cable installations with dodecylbenzene (DDB). Whilst DDB has improved gas absorption properties and is biodegradable, its ageing behaviour is far from ideal [2]. However blends of mineral oil and DDB, which might typically result from backfilling a cable, can nevertheless provide an effective replacement for mineral oil [3]. However, both of these oils are synthetic derivatives of crude oil, a non-renewable resource. A more viable long term solution is to seek alternative oils based on renewable resources. To this aim, vegetable oils have already been applied successfully to small transformers in the United States [4]. It is recognised that vegetable oils have poor oxidation stability compared to mineral oils [5] requiring the use of suitable antioxidants [6]. Whilst vegetable oils are all composed of triglycerides [5], many forms are available each with their own unique properties [7]. In this publication, we have explored the ageing behaviour of six vegetable oils together with a commercial dodecylbenzene (DDB) cable fluid. The oils were aged identically, characterized, and then ranked to determine the most suitable oil for inclusion into high voltage plant.

2. Experimental

2.1. Materials and ageing

Table 1 provides a list of the oils used in this investigation; with the exception of DDB and Envirotex oil they are all commercially available food grade oils. To determine the oxidation
resistance of the different oils, they were each used without further treatment and aged in air. Ageing of 20 ml oil samples was undertaken in fan ovens at 135 °C for periods of up to two weeks. Whilst these ageing conditions are not representative of plant conditions, they do provide a consistent basis for comparison of the different oils over a reasonable timescale. Copper was added to selected oils at a fixed surface area of 12.8 cm$^2$ to maintain consistency with previous ageing studies [2, 3]. During ageing, the vials were kept covered, to reduce evaporation losses, but were not sealed.

Table 1: Oils used in this investigation

| Designation   | Description/source                                         |
|---------------|-----------------------------------------------------------|
| DDB           | BICC type C148 batch 5808                                 |
| Envirotemp    | Envirotemp FR3 (Cooper Industries)                        |
| Corn          | Mazola pure corn oil                                      |
| Rapeseed      | Mazola pure rapeseed oil                                  |
| Green olive   | Filippo Berio extra virgin olive oil                      |
| Yellow olive  | Asda, light and mild olive oil                             |
| Sunflower     | Co-op sunflower oil                                       |

2.2. Sample characterisation
Ultraviolet/visible (UV/Vis) spectroscopy was performed in a Perkin Elmer Lambda 35 spectrometer using quartz cells of path length 10 mm. Measurements of oil viscosity were undertaken at room temperature using a Physica Rheolab MC1 testing system fitted with a concentric cylinder test cell (diameter 45 mm, length 115 mm, gap 2 mm). Infrared (IR) spectroscopy was performed on a Nicolet 710 FTIR instrument using KBr windows and a path length of 0.1 mm. Dielectric loss measurements were performed at room temperature, using a parallel cup-plate arrangement (diameter 33 mm, thickness 0.1 mm) connected to a Solartron 1296 dielectric interface linked to a Schlumberger SI 1260 impedance gain-phase analyser.

3. Results
3.1. UV/Vis spectroscopy
On ageing, all oils yellow [2-4] and the absorption edge shifts to longer wavelengths (arrowed, Figure 1a). Ageing in the presence of copper causes the ageing to be accelerated; as a result, the oils yellow more quickly and the absorption edge for any given ageing time is shifted further to the right (Figure 1b). Whilst most of the oils displayed a very similar behaviour, several exceptions to this occurred; absorbance peaks associated with carotene (400-500 nm) and chlorophyll (670 and 610 nm) [8] were observed in virgin (un-aged) green olive oil as expected (Figure 1c) but the peaks diminish after

Figure 1: UV/Vis spectra of (a) rapeseed oil aged without copper, (b) rapeseed oil aged with copper, (c) green olive oil aged with copper.
ageing. Similarly, virgin corn oil also contained traces of carotene but no evidence of chlorophyll. The position of the absorption edge was used, at longer ageing times, where the effects of any carotene present were insignificant, to rank the various oils. The wavelength associated with 50% transmission is considered here. The oils aged without copper display a very similar behaviour (Figure 2a); the observed variations are close to the typical sample to sample variations inherent to this technique (± 20 nm) so it is difficult to draw firm conclusions. However, ageing with copper (Figure 2b) clearly delineates the differences in ageing behaviour. Olive and Envirottemp oils show the least effects of ageing, rapeseed oil has intermediate properties, whereas corn and sunflower oils both show the greatest change in optical properties after ageing. By contrast, DDB shows the largest change in optical properties after ageing with copper, and the smallest on ageing without copper, and hence shows the widest variation in optical properties of all of the oils. Finally, green olive oil appears to age at a somewhat faster rate than yellow olive oil.

![Figure 2: UV/Vis summary plots for oils aged (a) without copper, (b) with copper.](image1)

3.2. Rheometry
The raw data collected by the instrument was shear stress as a function of shear rate. Since the dependence was linear, the gradients were used to estimate the viscosity of each of the oils. Before ageing, all the vegetable oils had a similar viscosity of ~0.05 Pa s, whereas DDB has a much lower viscosity of ~0.006 Pa s. On ageing without copper (Figure 3a), only sunflower oil shows a significantly increased viscosity. On ageing with copper, more subtle differences are noticeable (Figure 3b). In particular, sunflower and corn oil show the greatest increase in viscosity after ageing, followed by rapeseed oil, olive oil and finally Envirottemp oil. This is the same ranking scheme as deduced above and agrees with available reports [9]. By contrast, DDB shows no significant changes in viscosity after ageing.

![Figure 3: Viscosity of (a) oils aged without copper, (b) oils aged with copper.](image2)

3.3. Infrared spectroscopy
On ageing without copper, most of the oils showed little or no change in their infrared spectra after ageing, the exception to this was sunflower oil (Figure 4a), where additional absorbance occurs in the hydroxyl region (arrowed) indicating that oxidation is occurring [10]. On ageing with copper, a small
but measurable amount of oxidation was observed from envirottemp oil (Figure 4b). This increased significantly in rapeseed oil and finally, sunflower oil displayed significant oxidation, in excess of that shown in Figure 4a, indicating the catalytic effects of copper [2-4]. However, in each case, the same characteristic increase in hydroxyl absorbance occurs indicating the same underlying chemistry [10].

To rank the various oils, the absorbance at a fixed wavenumber (3475 cm\(^{-1}\)) was determined. The results confirm that on ageing without copper (Figure 5a) only sunflower oil shows significantly increased oxidation after ageing, as discussed above. Oils aged with copper (Figure 5b) follow broadly the same ranking scheme as that established from the previous two techniques; sunflower oil shows the most dramatic oxidation on ageing, followed by corn oil, then rapeseed oil. Finally, olive and Envirottemp oils both show a small increase in absorbance with ageing time.

Under the current ageing conditions, DDB does not show any detectable oxidation. The use of much larger sample volumes in these experiments, compared to the small volumes used in previous work [2, 3] precludes extensive oxidation from occurring here. Nevertheless, it is clear from the current comparison, where the sample volume and ageing conditions are fixed, that vegetable oils are more susceptible to oxidation than traditional synthetic oils as reported [5, 11].

3.4. Dielectric spectroscopy
The dielectric loss increased in all of the oils after ageing [2, 3] therefore, values at 50 Hz were used to rank the oils. After ageing without copper (Figure 6a) the values were very similar for most of the oils although green olive displays the highest dielectric loss even before ageing, and corn oil also displays a significantly higher dielectric loss compared to the remaining oils. This effect suggests that the presence of carotene and chlorophyll serves to increase the dielectric loss.

As noted previously, ageing with copper (Figure 6b) causes a more significant difference between the oils. Whilst the overall ranking scheme of the six vegetable oils largely agrees with that established from the other techniques (i.e. corn oil shows the greatest increase in dielectric loss, rapeseed oil an intermediate increase and olive and Envirottemp oils the least), under that scheme sunflower oil shows a lower than expected dielectric loss and green olive oil shows an increased
dielectric loss. DDB shows the lowest dielectric loss on ageing without copper and the highest on ageing with copper, thus it exhibits more extreme changes on ageing, in line with its optical behaviour.

![Figure 6: Dielectric loss of (a) oils aged without copper (b) oils aged with copper.](image)

### 4. Conclusions

A wide range of vegetable oils were aged, characterised and then ranked according to their ability to withstand thermal ageing in air. Under this scheme, yellow olive oil appears to be the best food grade oil for inclusion into high voltage plant, offering the best resistance to ageing and the lowest dielectric loss. Over most of the indicators of ageing it performed at least as well as the model Envirotemp oil.

Rapeseed oil offers “intermediate” properties and so may find use in some applications, especially if improved through the use of an antioxidant. Oils to avoid are corn oil and sunflower oil, this is mainly due to their tendency to oxidize much more than the other oils and to thicken on ageing. Whilst such thickening could impair oil circulation in equipment, it may also provide a novel route to designing “self sealing” cable systems.

It is clear from this work that carotene and chlorophyll appear to adversely affect the dielectric properties and therefore such materials should be removed from vegetable oils prior to their use in high voltage equipment. Finally, DDB offers significantly improved oxidation resistance compared to vegetable oils in agreement with established literature, however it is particularly susceptible to copper catalysed reactions and hence its dielectric properties are much worse than any of the vegetable oils after identical ageing in the presence of copper.

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