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# Impact of the Use of Vegetable Oil on the Mechanical Failure of the Cellulosic Insulation of Continuously Transposed Conductors in Power Transformers

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## ABSTRACT

**Natural esters have become of interest for the industry in recent years as dielectric liquids for power transformers, and many studies are focused on their dielectric and chemical properties, and on their influence in the degradation of the solid insulation due to ageing. However, very little is known about their impact on the evolution of the mechanical properties of the paper insulation, which are acknowledged to have a considerable influence in their overall performance and reliability during the operating life of power transformers. This work studies the effects of thermal ageing with vegetable oil in some commercial components which are commonly used in power transformers, such as an insulated continuously transposed conductor (CTC) and samples of thermally upgraded crepe insulation. The changes in the properties of the crepe paper insulation are characterised through the degree of polymerisation and tensile testing. Failure initiation and propagation in the insulation of the CTC is analysed macroscopically. The results are compared with those obtained when using mineral oil, showing that the use of vegetable oil has a protective effect over mechanical properties of the studied types of paper insulation.**

**Index Terms — power transformers, insulation, vegetable oils, accelerated ageing, short circuits, materials testing, mechanical behaviour, failure analysis**

## 1 INTRODUCTION

**THE** most common materials used as solid insulation for the conductors of power transformers are paper and board, due to their adequate dielectric, thermal and mechanical properties. These materials are impregnated in an insulating liquid, which contributes to the dielectric insulation and to the dissipation of the generated heat. During the operating life of a power transformer, the dielectric, chemical and mechanical properties of the paper insulation deteriorate, due to ageing at high temperatures.

The main cause of insulation-related faults in power transformers is the mechanical failure of the paper, as the mechanical properties usually degrade faster than the dielectric ones due to ageing [1]. The stresses and strains caused by electromagnetic forces acting on transformers can cause the breakage of the insulation, which is a mechanical phenomenon, and that can lead to a subsequent electrical breakdown, if the insulation stops fulfilling its dielectric purpose. Besides, the reduction of strength in the paper insulation decreases the mechanical rigidity of the windings, and high mechanical stresses during a short circuit or multiple inrush currents can cause winding movement [2].

The variation of physical-chemical properties that the solid insulation experiences is affected by the use of different types of insulating liquids (namely, mineral oils, vegetable oils or synthetic esters). For many years, the usual insulating liquids for transformers were mineral oils. However, in recent times, other dielectric fluids such as silicone oils, synthetic esters and vegetable oils have become more common [2].

Natural esters are abundant, as they are based on renewable resources and do not depend on fossil raw materials. They are suitable for being used in transformers located in densely populated areas, due to their lower flammability. They also have a higher biodegradability in comparison with mineral oil, and can be used in environmentally sensitive places [3, 4]. When paper is aged at high temperatures, water is generated by the chain scissions in the cellulose by hydrolysis. Moisture content greatly affects the dielectric properties of the solid insulation. However, natural esters consume part of that

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moisture, slowing down that deterioration [3], as will be experimentally proven in this work (see section 3.1).

There are numerous recent studies on the influence of vegetable oils in the chemical and dielectric properties of the transformer insulation, such as [5–9]. Nevertheless, there are only a few which analyse their impact on the mechanical properties of the solid insulation, for instance [10, 11]. Thus, it can be claimed that there is a lack of understanding about how the ageing process with vegetable oils affects the mechanical performance of the dielectric paper in transformer components such as Continuously Transposed Conductors (CTCs), especially for papers different from Kraft type, such as crepe.

In a previous study, [11], some samples of an insulated CTC were extracted from the winding of a core-type transformer. Those CTC samples were impregnated in naphthenic dielectric oil and subjected to accelerated thermal ageing with different durations, to reproduce the process that takes place during the whole operating life of a power transformer. Then, the aged CTC samples were subjected to mechanical bending tests, to obtain an approximate representation of the effects of electromagnetic forces over the windings of an aged transformer. The mechanical failure of the insulation due to bending of the CTC was then analysed. Besides, samples of the same paper grades used in the CTC insulation were subjected to an equivalent ageing process and mechanically characterised in [12, 13].

The purpose of this work is to subject the insulated CTC samples as well as samples of paper insulation to the same ageing conditions as in [11] (temperature and ageing duration), but now impregnated in vegetable oil, in order to evaluate the impact of the use of that insulating liquid on the degradation of mechanical properties. The remainder of this paper is organised as follows: first, the analysed materials and applied methods are reported, see Section 2. The experimental results are presented and discussed in Section 3. Section 4 outlines the conclusions of this study.

# 2 MATERIALS AND METHODS

## 2.1 MATERIALS

The mechanical performance of a commercial CTC of a core-type transformer provided by the company Imefy was studied in [11], see Figure 1. Its insulation consisted of four layers of thin dielectric paper: plain Kraft in the two internal layers (1, 2) and crepe paper in the two external ones (3, 4), whose manufacturing properties are given in Table 1. Paper materials can be considered as three-dimensional orthotropic materials, whose principal directions are the machine direction (MD), cross–machine direction (CD), and thickness direction (ZD).

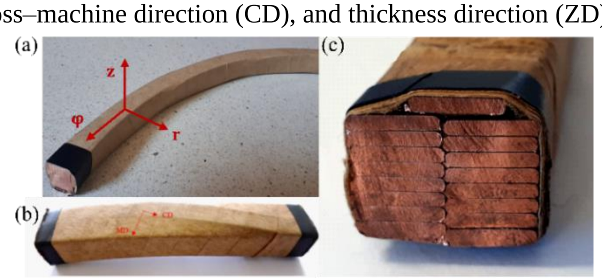


**Figure 1.** (a) Cylindrical coordinate system and main directions of the CTC. (b) Insulated CTC sample with the main directions of the paper material, MD and CD. (c) Cross-sectional view of the CTC.

A commercial natural ester is used as impregnation liquid. The properties of this vegetable oil, derived from sunflower, are listed in Table 2. In [11], the crepe insulation showed a considerably better mechanical performance than the plain Kraft, for the whole considered ageing process. Thus, it is of interest to analyse the impact of the use of vegetable oil in that performance. Samples of the same class of crepe insulation from Table 1 were provided by the company Ahlstrom-Munksjö.

**Table 1.** Manufacturing properties of the studied paper insulation materials.

| PROPERTY | TEST METHOD | PLAIN KRAFT | CREPE |
|---|---|---|---|
| Nominal Grammage ($g/m^2$) | ISO 536 | 62.0 | 80.0 |
| Nominal Thickness ( $\mu m$) | ISO 543 | 82 | 80 |
| Nominal Density ( $kg/m^3$) | ISO 543 | 760 | 1000 |
| Tensile Strength, MD ( $MPa$) | ISO 1924 | 93.5 | 87.5 |
| Tensile Strength, CD ( $MPa$) | ISO 1924 | 33.9 | 25.0 |
| Elongation at break, MD (%) | ISO 1924 | 2 | 15 |
| Elongation at break, CD (%) | ISO 1924 | 4 | 5 |

**Table 2.** Main properties of the vegetable oil used in the experiments.

| PROPERTY | TEST METHOD | AVERAGE VALUE |
|---|---|---|
| Density at 20°C (g/mL) | ASTM D 4052 | 0.91 |
| Viscosity at 100°C (cSt) | ASTM D 455 | 8.5 |
| Viscosity at 40°C (cSt) | ASTM D 455 | 39.2 |
| Viscosity at 0°C (cSt) | ASTM D 455 | 275.9 |
| Boiling point (°C) | ASTM D 92 | 362 |
| Acidity (mg KOH/g) | ASTM D 974 | < 0.06 |
| Water content (mg/kg) | IEC 60814 | 150 |
| Dielectric strength (kV) | IEC 60156 | 65 |
| Loss tangent at 90º, 50 Hz | IEC 60247 | < 0.050 |

## 2.2 EXPERIMENTAL

### *2.2.1 Accelerated thermal ageing*

In this study, 15 CTC samples with a length of 120 mm, see Figure 1b and c, were extracted from the copper coil, dried in an air-circulating oven at 100°C for 3 hours, up to an average final moisture content of 1.473%, measured according to [14]. Four CTC samples were introduced into each of the vessels filled with vegetable oil, see Figure 2a. Those vessels, which will be referred to as 'vessels A' hereafter, were vacuum-sealed and filled with nitrogen in order to create an inert atmosphere.


**Figure 2.** (a) Test pieces in vessels A. (b) Vessels containing the oil-impregnated samples being introduced in the convective oven to start the ageing process.

In addition, paper samples of the same class of crepe insulation used in the two external layers of the CTC insulation, see Table 1, were prepared for mechanical testing, see section

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2.2.2. After drying in the oven, those paper samples were introduced into vessels with some pieces of the copper conductor, which will be called 'vessels B' from now on, with approximately the same mass ratio of copper/paper that exists in the CTC, to include any possible catalytic effect of the copper in the ageing. Vessels B were filled with vegetable oil and subjected to the same process described above.

For comparison purposes, the same initial drying in air-circulating oven, same ratio of 10 g paper/400 g oil in vessels A, same number of pieces of copper conductor in vessels B, and identical ageing states as those considered in [11, 12], where naphthenic oil was used, were applied here. That is: aged into a temperature-controlled oven at 150ºC, see Figure 2b, for 1 week (*State I*), 4 weeks (*State II*) and 9 weeks (*State III*). After those periods, the CTC and paper samples were washed with hexane, to remove the remaining oil, and then dried by exposition to the open air. The ageing temperature of 150ºC was chosen so that the crepe paper insulation reaches aged conditions after a reasonable ageing duration. A lower temperature would have required ageing periods of more than seven months, see [11].

### 2.2.2 Characterisation of the paper insulation

To understand the impact of using vegetable oils on the ageing, the same parameters used to characterise the state of the insulation in were measured here. These are the degree of polymerisation (DP) and several mechanical properties.

The cellulose consists of linear, polymer chains of cyclic, β-D-glucose ($C_6H_{12}O_6$) units. The DP, which has traditionally been used as an indicator of the condition of the paper insulation in power transformers [15], is defined as the number of those units per chain. Those chains break during the operation of the transformer due to the effect of oxygen, moisture and heat. The DP can be measured indirectly through the viscosity of a mixture of paper, deionised water and cupriethylenediamine hydroxide solvent (Cuen) [16]. Here, the DP of the insulation aged in vessels B was measured according to the ASTM D4243 standard in the different ageing states, see section 3.1.

The use of mechanical strength for the determination of the deterioration rate of the paper insulation at different ageing temperatures was firstly proposed by Montsinger. A large number of studies report experimental tensile data (tensile strength or tensile strain at breakage) in different conditions, following standard ISO 1924 [17]. In [11], a finite element (FE) mechanical model implemented in ANSYS AIM Static Structural, enabled to obtain the strain field experienced by the paper insulation in the insulated CTC sample, see Figure 1b, when subjected to a bending force representing the effects of a short circuit, see section 2.2.3. That study suggested that the mechanical failure of the thin paper wrapping of CTCs subjected to bending cannot be explained only from its tensile strength, since the magnitude of the compressive and shear strains of the paper insulation during bending was much higher than those corresponding to the tensile strength. Thus, a method for compressive testing of thin insulation and an indirect method for the estimation of shear properties were proposed in [11].

Regarding shear properties, their direct measurement is not feasible with thin paper, and all the studies are based on approximate methods [11]. The most common one is to infer shear properties from in-plane uniaxial tests at 45º to the MD, which generate a biaxial stress state equivalent to a state of pure shear, see [18–20]. However, studies considering paper materials with similar thickness and grammage to those analysed here, see [21–23], considered that the contribution of the shear strength is maximised, while reducing the effect of normal stress components, with an angle of 35º to the MD.

Here, for the sake of allowing the comparison with the results presented in [13], samples of crepe paper insulation, with their longitudinal dimension at 35º to the MD and with that same geometry, see Figure 3a, were subjected to tensile testing with the strain rate proposed in [17], equivalent to a rate of elongation of 3.33 mm/min, after being aged in vegetable oil. The testing machine, see Figure 3b, records the load, F (N), and the distance between jaws at any instant, L (mm). To obtain stress-strain curves, equations (1) and (2) were used, where $L_0$ (mm) is the initial distance between jaws in the tensile test, $A = w \cdot t$ ($mm^2$) is the cross-sectional area of the paper strip, product of the width by the thickness. The results can be found in section 3.2.

$$\varepsilon\ (\%) = \frac{L - L_0}{L_0} \cdot 100 \tag{1}$$

$$\sigma\ (MPa) = \frac{F}{A} = \frac{F}{w \cdot t} \tag{2}$$

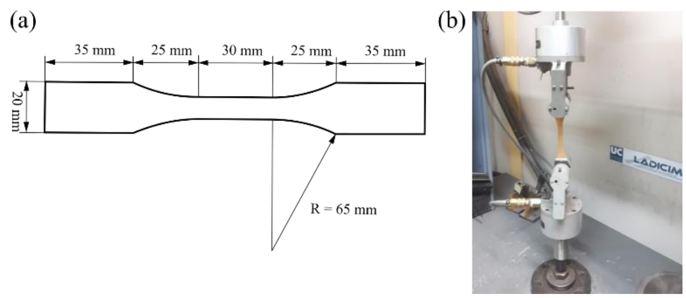


**Figure 3.** (a) Geometry of the paper samples for tensile testing at 35º to the MD. (b) Paper sample aged in vegetable oil being subjected to a tensile test.

### 2.2.3 Three-point bending tests on insulated CTC samples

A short circuit is one of the most extreme mechanical conditions that may affect the conductors in the windings of power transformers and, subsequently, the paper insulation. The electromagnetic forces produced by short circuits can be about 100-400 times greater than the rated ones, and their radial component (see Figure 1a) is predominant in disc-type windings of core-type transformers [24].

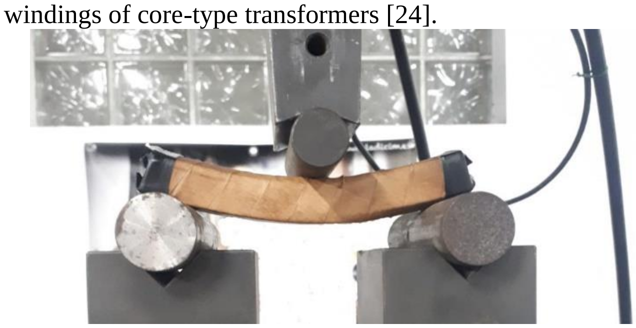

**Figure 4.** Three-point bending test of aged insulated CTC samples.

Here, the effect of electromagnetic forces was represented through a radial force in a three-point bending test over the insulated CTC samples aged in vessels A, see Figure 4. The bending tests were carried out under control of displacement conditions, up to final deflections of 5, 10 and 20 mm, respectively, in order to compare the mechanical failure in the insulation with the experimental results from [11, 12], where

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naphthenic dielectric oil was used for the ageing. The results of these bending tests are presented in section 3.3.

# 3 EXPERIMENTAL RESULTS AND DISCUSSION

## 3.1 DEGREE OF POLYMERISATION (DP) OF PAPER

The results of the DP measurement of the crepe paper insulation aged in natural ester and mineral oil can be seen in Figure 5, where the values are expressed as a percentage of the initial DP when the insulation was not aged. The initial DP of the crepe paper was 886 units, which is catalogued as “good” in [16]. The DP values in mineral oil were obtained after the ageing process described in [11]. The most intense decrease in DP takes place during the first week of ageing, for both insulating liquids, but is more pronounced with the mineral oil than with the ester (53% reduction in DP versus 27%). During the remaining ageing duration, the rates of DP deterioration are approximately similar for both dielectric liquids. After nine weeks, in Ageing State III, the crepe insulation aged in mineral oil and natural ester retain 26.6% and 39.1% of their initial DP, respectively. These results indicate that the vegetable oil tends to slow down the deterioration of the paper insulation due to ageing. This may be due to a greater protection of cellulose when it is impregnated with the natural ester than with the mineral oil. During the ageing tests, the moisture content in the cellulose fell from its initial value, 1.473%, to 0.482% in Ageing State III. On the contrary, moisture of the vegetable oil increased from 100 to 700 ppm. As reported by García et al [8], the natural ester consumed moisture from the cellulose due to the hydrolysis, reducing the ageing rate in comparison with mineral oil.

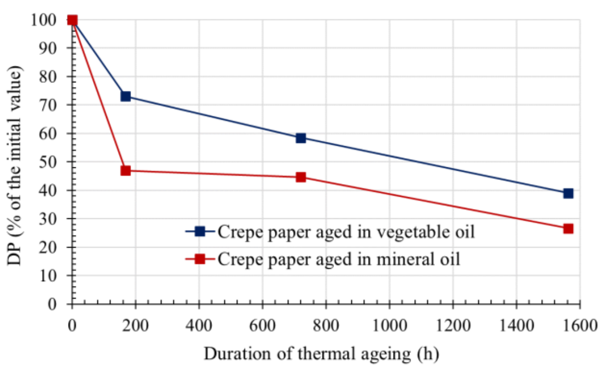


**Figure 5.** Variation in DP of the crepe paper insulation, expressed in % with respect to the initial value, as a function of the duration of thermal ageing.

## 3.2 MECHANICAL PROPERTIES OF THE PAPER INSULATION AGED IN VESSELS B

Crepe insulation samples aged in vessels B were subjected to tensile testing up to fracture. For each ageing state, an average stress-strain curve and the standard deviations were obtained, see Figure 6. The shape of the stress-strain curves resembles those obtained in the case in which the insulation was aged in mineral oil, see [11]. The maximum values of the tensile strength and strain at breakage are summarised in Table 3. These mechanical tests also show the remarkable heterogeneity of the paper material, especially for the strains, which is primarily caused by the nature of its microstructure and, particularly, by the presence of local defects randomly distributed (such as micro cracks or small delaminations) [11]. Crepe paper samples with the same geometry and macroscopical characteristics, subjected to the same ageing process, provided coefficients of variation of up to 26.4% in the strain at breakage, as it was the case for Ageing State II.

**Table 3.** Results of the tensile tests at 35º of MD ± standard deviations for the crepe insulation paper aged in vegetable oil.

| AGEING | $\sigma_{35°}^{max} \pm$ SD (MPa) | $\varepsilon_{35°}^{max} \pm$ SD (%) |
|---|---|---|
| State 0 | 43.6 ± 4.2 | 14.38 ± 0.96 |
| State I | 32.8 ± 3.9 | 10.04 ± 1.40 |
| State II | 30.5 ± 4.1 | 6.24 ± 1.65 |
| State III | 19.4 ± 1.0 | 1.80 ± 0.29 |

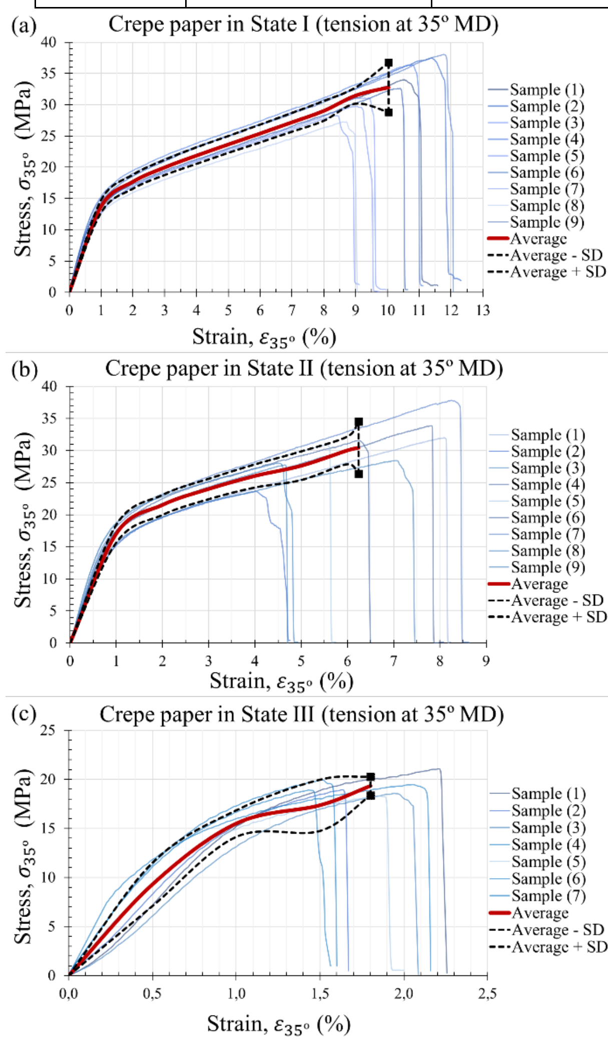


**Figure 6.** Tensile test at 35° MD for the crepe paper aged in vegetable oil, in Ageing States (a) I, (b) II and (c) III.

In Figure 7, the results of the tensile tests at 35º to the MD are compared in the cases in which the crepe paper was aged in mineral oil (see [11]) and in vegetable oil. Figure 7a shows the variation of the tensile strength in those tests. As with the DP, see section 3.1, the most accused reduction in strength occurs in the first week of ageing: $\sigma_{35°}^{max}$ reduces up to 24.8% of its initial value with mineral oil, while this value is still 31.7% with the vegetable oil. When using mineral oil, an increase of strength was appreciated in Ageing State II. The phenomenon of a material subjected to ageing which increases its strength while reducing its ductility has been previously reported for

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other materials, such as steel, aluminium or polymers. This reinforces the hypothesis that the mechanical failure process is controlled by the deformation level instead of by the stress level, as explained more extensively in [12]. However, that behaviour was not observed when ageing with vegetable oil. After 9 weeks of ageing, the reduction of strength was 69.8% with mineral oil and 55.7% with vegetable oil.

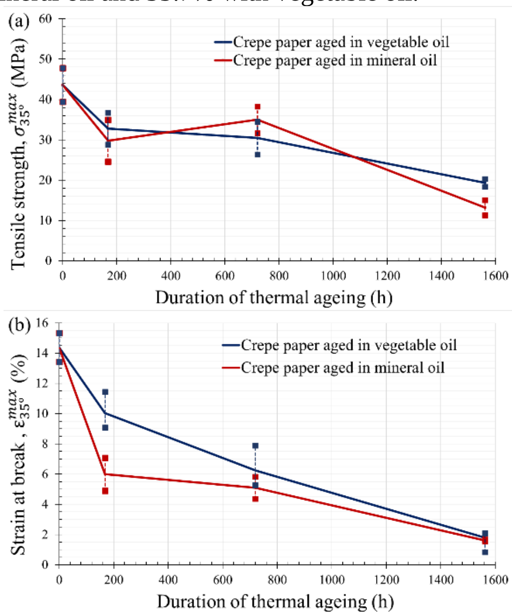


**Figure 7.** Comparison of the (a) tensile strength $\sigma_{35°}^{max}$ and (b) tensile strain $\varepsilon_{35°}^{max}$, for the crepe paper as a function of ageing duration in mineral oil and vegetable oil.

Furthermore, according to Oria et al [11], the reduction in the maximum strain at breakage of the paper insulation seems to affect mechanical failure more than its reduction in strength. Figure 7b shows that, in all ageing states, the strain at breakage of the crepe insulation is higher when using natural ester. The use of ester reduces the deterioration rate of $\varepsilon_{35°}^{max}$, especially during the first week of ageing (58.3% reduction with mineral oil and 30.2% with ester). However, at the end of the ageing duration, the reduction of $\varepsilon_{35°}^{max}$ is only slightly higher with the mineral oil (88.8% versus 87.5%).

### 3.3 RESULTS OF BENDING TESTS ON PAPER-INSULATED CTCS

The curves in Figure 8 show the results of the bending tests over some of the CTC samples aged in vessels A, for different ageing states (I and II) and final deflections (d = 5, 10 and 20 mm). As described in [11], the ageing at 150ºC melts the enamel between adjacent copper layers in the CTC, bonding adjacent layers and resulting in an initial stiffening in the overall response of the conductor to bending. As the displacement gradually increases during the test, that bonding breaks, producing marked steps in the force level withstood by the CTC sample. The green curve in Figure 8 is the average force-displacement curve for CTC samples aged in vegetable oil, while the average response when using mineral oil is the red curve, obtained in [11]. Both curves almost coincide in the elastic part, but the average force that the CTC samples withstand before the plastification of the copper core seems to be slightly higher when using natural ester.

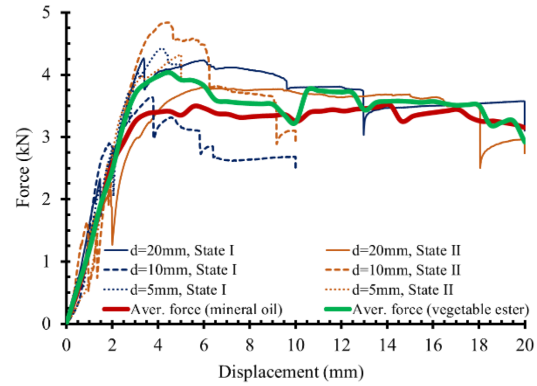


**Figure 8.** Results of bending tests on the CTC samples with different deflections (d) and ageing states.

Regarding the initiation of mechanical failure in the paper insulation, in Ageing State I, for low deformations, such as d = 5 mm, the results were quite similar as when using mineral oil, see [11]. As the paper material is still considerably flexible in that ageing state, it is able to withstand the deformations without breaking, see Figure 9, except in layer 1, which gets stuck to the copper core due to the enamel melting and breaks in the areas of the CTC with higher deformations, see Figure 10.


**Figure 9.** Results for d = 5 mm in Ageing State I, for (a) the crepe paper in layer 4, (b) the Kraft paper in layer 2.

**Figure 10.** Results for d = 5 mm in Ageing State I, for the Kraft paper in layer 1.

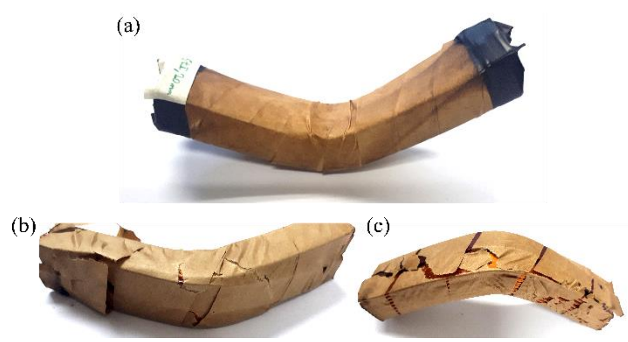


**Figure 11.** Results for d = 20 mm in Ageing State I, for (a) the crepe paper in layer 4, (b) the Kraft paper in layer 2 and (c) the Kraft paper in layer 1.

When d = 20 mm, the deformation level is very high, and only the crepe paper insulation in the external layers (3 and 4) is able to resist it without fractures, see Figure 11a. The fractures in the plain Kraft paper in the two internal layers of the insulation were of the same size at this deformation level and ageing state when using with naphthenic oil, see [11], or vegetable oil, see Figure 11b and c.

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However, the use of vegetable oil showed a protective effect at intermediate deflections, such as d = 10 mm. In that case, when using mineral oil, the crepe insulation was not fractured, small cracks (<5 mm) and big cracks (>10 mm) were produced, respectively, in layers 2 and 1 of the insulation, both made of plain Kraft paper [11]. However, with natural ester, no cracks appeared in the crepe paper, see Figure 12a, nor in layer 2, see Figure 12b; and only small cracks were produced in layer 1 due to the bending, see Figure 13.

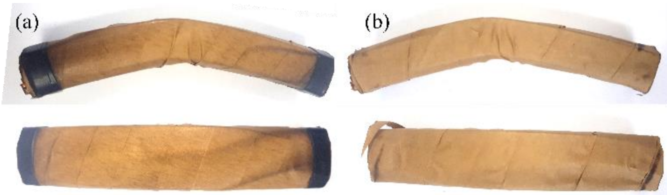


**Figure 12.** Results for d = 10 mm in Ageing State I, for (a) the crepe paper in layer 4, (b) the Kraft paper in layer 2.

**Figure 13.** Results for d = 10 mm in Ageing State I, for the Kraft paper in layer 1.

## 4 CONCLUSIONS

The experimental results presented in section 3 imply that the use of natural ester positively affects the mechanical response of the studied paper insulation to thermal ageing. Both the DP and tensile properties are better during the whole ageing duration when natural ester is used as insulating liquid rather than naphthenic oil. The use of natural ester also seems to protect the insulation of CTC conductors. The present study led to the following conclusions:

- For the thermally upgraded crepe insulation subjected to ageing in the described conditions, see section 3.1, the steepest deterioration of DP occurs during the first week of ageing. The DP reduction is smaller when using natural ester than with mineral oil for the whole ageing duration.
- The tensile tests presented in section 3.2 highlight the wide heterogeneity in the mechanical response of the aged crepe paper insulation, which is a common characteristic of paper materials [25], and has been reported before when ageing in mineral oil ([11–13]).
- The strain at breakage of the crepe insulation obtained from tensile tests oriented at 35º to the MD, see section 3.2, is higher when using vegetable oil than with mineral oil for the whole ageing duration. That effect is more accused at initial-intermediate ageing levels, and reduces as the ageing is deeper.
- When an insulated CTC conductor is subjected to bending, deflections of d = 5 mm are easily endured without mechanical failure, see section 3.3, except when the insulation is extremely aged, see [11]. For deflections higher or equal to 20 mm, deformations are so high that the breakage of the paper insulation usually occurs (specially with the plain Kraft insulation, the crepe insulation is considerably more resistant). Then, the influence of the dielectric liquid at those deformations levels seems to be limited.
- For intermediate bending deformations of the CTC, such as d = 10 mm, the use of natural ester instead of naphthenic oil seems to have a protective effect over the paper insulation, see section 3.3, reducing the size of the produced fractures for the same ageing duration and deformation level.

In summary, vegetable oils seem to have a positive effect on the deterioration of mechanical properties of the thin paper insulation used in the conductors of the windings of power transformers, which can be added to other of their relevant advantages, such as being biodegradable and environmentally friendly. More research is needed to study the impact of using vegetable oils with different insulation products and ageing conditions.

## ACKNOWLEDGMENT

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